CLIMATE AND ENVIRONMENTAL CHANGE IN THE MEDITERRANEAN BASIN
Current situation and risks for the future

First Mediterranean Assessment Report

by MedECC (Mediterranean Experts on Climate and environmental Change)

MedECC
Mediterranean Experts on Climate
and environmental Change

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CLIMATE AND ENVIRONMENTAL CHANGE IN THE MEDITERRANEAN BASIN

First Mediterranean Assessment Report (MAR1)

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MEDECC

The Mediterranean Experts on Climate and environmental Change (MedECC) are an independent network of scientists, founded 2015. MedECC assesses the best available scientific knowledge on climate and environmental change and associated risks in the Mediterranean Basin in order to render it accessible to policymakers, stakeholders and citizens.

To date (September 2020), MedECC counts more than 600 scientific members, all contributing in individual capacity and without financial compensation. MedECC scientists are based in 35 countries, including 19 countries registered as Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention) and 23 countries that are members of the Union for the Mediterranean.

The UNEP/MAP – Barcelona Convention Secretariat, through its Plan Bleu Regional Activity Center, and the Secretariat of the Union for the Mediterranean are working in partnership to support MedECC, and to contribute to establishing a sound and transparent scientific assessment process.

MedECC reports are prepared for use of policymakers and a broader audience. They are developed on the basis of scientific criteria only; their validity is therefore the responsibility of MedECC Report Authors alone. The available knowledge concerning the risks studied by MedECC has significant certain gaps, often due to limited monitoring systems or scientific research capacity – these have been indicated as clearly as possible. Despite best efforts, errors and omissions are nevertheless not unlikely.

THIS REPORT

MedECC has prepared the First Mediterranean Assessment Report (MAR1) on the current state and expected risks of climate and environmental change in the Mediterranean Basin. The report includes a Summary for Policymakers (SPM), which comprises the key messages of the MAR1. A first draft of the MAR1 was prepared in 2019 and underwent expert peer review.

The second draft, revised to take into account review comments, and now supplied with a SPM, has undergone broad consultation with governments, decision-makers and stakeholders in 2020. The particular aim of the consultation was to ascertain that MAR1 findings, as presented in the SPM, are fully comprehensible and unambiguous. While chapter drafts were also supplied with the SPM under review, they served as background information only and were not part of the review.

The MedECC coordinators are very grateful for the expertise, rigor and dedication shown by the volunteer Coordinating Lead Authors and Lead Authors, working across scientific disciplines in each chapter of the report, with essential help from many Contributing Authors.

At the end of the stakeholder consultation, 453 comments for the SPM had been received and were used to revise the SPM wherever this was possible. The stakeholder review was concluded during the online Plenary Session of stakeholders held on September 22, 2020.

MedECC Authors and Coordinators want to thank all reviewers for their time and effort. A record is being kept on the responses to all review comments.

This publication has been made possible through the collaboration of 190 contributors, who are listed in the full report.
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Preferred citation:
MedECC (2020) Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report [Cramer, W., Guiot, J., Marini, K. (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632pp.
ISBN: 978-2-9577416-0-1 / DOI: 10.5281/zenodo.7224821

Cover design: Pandaroo (Péronnas)
Graphs (re)desing and layout: Zen design studio (Marseille)
Copy-editing by Connected Language Services

The UNEP/MAP – Barcelona Convention Secretariat, through its Plan Bleu Regional Activity Center, and the Secretariat of the Union for the Mediterranean are working in partnership to support MedECC. The MedECC Secretariat is supported and funded by UfM, through a grant provided by the Swedish International Development Cooperation Agency (SIDA), hosted by Plan Bleu in Marseille, France.

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FOREWORD

Climate change is possibly the most crucial challenge for the future of the Mediterranean: the pace and magnitude of climate change and its impacts in the region can turn it into a serious stability risk if untamed and not integrated organically in national and regional policy.

In accordance with their respective mandates, the Secretariats of the Union for the Mediterranean (UfM) and of the United Nations Environment Programme / Mediterranean Action Plan – Barcelona Convention (UNEP/MAP) have joined efforts to support the work undertaken by the network of Mediterranean Experts on Climate and environmental Change (MedECC) and its Secretariat, which is hosted by Plan Regional Activity Centre (UNEP/MAP) in Marseille, France.

Despite the pressing need to better understand the current state of play and the present and future risks of climate and environmental change in the Mediterranean, there was until recently a dearth of reliable, robust and scientific data combined with a deficit in knowledge sharing with decision-makers and stakeholders.

Thanks to MedECC, the First Mediterranean Assessment Report (MAR1) now bridges the gap.

The methodology used by MedECC is based on key principles of the Intergovernmental Panel on Climate Change (IPCC) and of the Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). This approach is innovative, but its application was fraught with challenges specific to the Mediterranean region. We commend MedECC for the results achieved.

For the UfM Secretariat, it is clear that MAR1 is a major deliverable of the 1st UfM Ministerial Declaration on Environment and Climate Change; it is also a cornerstone between the first and the second UfM Ministerial Declarations. From the UNEP/MAP perspective, the support to MedECC is a major achievement under the Mediterranean Strategy for Sustainable Development (MSSD), which identifies the establishment of a regional science-policy interface on climate change as a priority (Flagship Initiative). MAR1 will take centre stage in the context of the 22nd Meeting of the Contracting Parties to the Barcelona Convention, which will adopt the UNEP/MAP Medium-Term Strategy (MTS) 2022-2027.

At a time when an unprecedented health crisis having severe impacts on Mediterranean societies and economies, regional cooperation and multilateralism underpinned by robust science have never been more sorely needed. In this vein, MedECC offers a unique synthesis on best available scientific knowledge on climate and environmental changes in the Mediterranean, thus allowing for an evidence-based, basin-wide policy response.

This is also a report of great importance to our partners in the Mediterranean region as MAR1 will inform integrated programming in ways that can improve cooperation to address urgent needs and to inform long-term climate and environmental action. Its findings constitute a foundation for meeting sustainable development needs whilst informing strategic planning and investment at the regional level.

We acknowledge with appreciation MedECC's efforts, which also have an important impact in terms of capacity-building. UfM and UNEP/MAP reiterate their commitment to bolstering MedECC and its linkages with global processes. We will deploy additional support for the best-possible use of MAR1 in the context of the enforcement of the three UN Rio conventions in the region.

Mr. Nasser KAMEL
Secretary General
Union for the Mediterranean

Mr. Gaetano LEONE
Coordinator
UNEP/MAP – Barcelona Convention

Within the mandate given by the Contracting Parties to the Barcelona Convention to Plan Bleu in its role of Regional Activity Centre of the UNEP/MAP system, and in the framework of an agreement with the Secretariat of the Union for the Mediterranean, Plan Bleu has hosted the MedECC Secretariat and supported directly its activities since its creation.

We would like to commend all the scientists who contributed to this report, MedECC Steering Committee and especially its Coordinators and Scientific Secretary for the delivery of this outstanding report. This work would not have been possible without the financial support of the Swedish International Development Cooperation Agency (SIDA), the Principality of Monaco, the French Agency for Ecological Transition (ADEME), the French Ministry of Ecological Transition and Solidarity, the French National Centre for Scientific Research (CNRS) and the French Research Institute for Development (IRD) via the MISTRALS programme, the Aix-Marseille University via the Laboratory of Excellence (Labex) OT-Med, the Advisory Council for the Sustainable Development of Catalonia of the Government of Catalonia (CADS) and the Aix-Marseille Provence Metropole.

Plan Bleu will maintain its support to the MedECC network to disseminate the key MAR1 findings to all stakeholders, including to policymakers through UfM and UNEP/MAP processes; and to dive in the assessment of thematic issues in its next phase of activities.

Mr. Thierry LAVOUX
Président, Plan Bleu

ACKNOWLEDGEMENTS

The MedECC report is the outcome of the work of many people, supported by many institutions. While we cannot mention all of them here, the editors and authors wish to acknowledge and thank the following individuals and institutions who provided their help at different stages of the process: Plan Bleu director, its current François Guerquin, as well as his predecessors Elen Lemaître-Curri and Anne France-Didier, also the Plan Bleu team, in particular Antoine Lafitte, Lina Tode, Sandra Dulbecco and Anna Goubert; the Union for the Mediterranean, its Climate Adviser Arnault Graves, its Senior Deputy Secretary General Grammenos Mastrojeni, its previous Climate Adviser Nicolas Debaisieux, the team of the Union for the Mediterranean Energy and Climate Action, as well as the UfM Communication and Public Affairs Unit; the UN Environment Programme/Mediterranean Action Plan Coordinating Unit, its Coordinator Gaetano Leone and its Programme Management Officer Julien Le Tellier.

We also wish to thank wholeheartedly the reviewers of various drafts of the report – all their comments have been considered carefully even if it was not always possible to accommodate them. The many participants of the Conference "Climate Our Common Future" in Paris 2015 and numerous following scoping meetings made very important contributions to the report.

We received important support from the hosting institutions of several workshops: Mohammed V University in Rabat (Morocco), University of Palermo (Italy), Venice International University (VIU) (Italy), Scientific Centre of Monaco (CSM), Oceanographic Museum of Monaco, National Research Council CNR Congress Center in Milan (Italy) and Aix-Marseille University (France). The Summary for Policymakers (SPM) was crucially refined during a day-long discussion with focal point representatives of the main stakeholders, chaired by Valentina Mauriello and Grammenos Mastrojeni. The report preparation was also supported by the team of the Labex OT-Med (including administrative staff: Sophie Pékar, Barbara Bourlion), the team of AIR Climat (Aurore Aubail and Antoine Nicault), Acterra (Stéphane Simonet), Service Informatique Pythéas (OSU Institut Pythéas, France), Stéphanie Wicha, Aurore Pfitzmann and Marie-Aimée Gros-Rosanvallon.

SUMMARY FOR POLICYMAKERS

Text as approved during Plenary Session of MedECC Stakeholders on September 22, 2020

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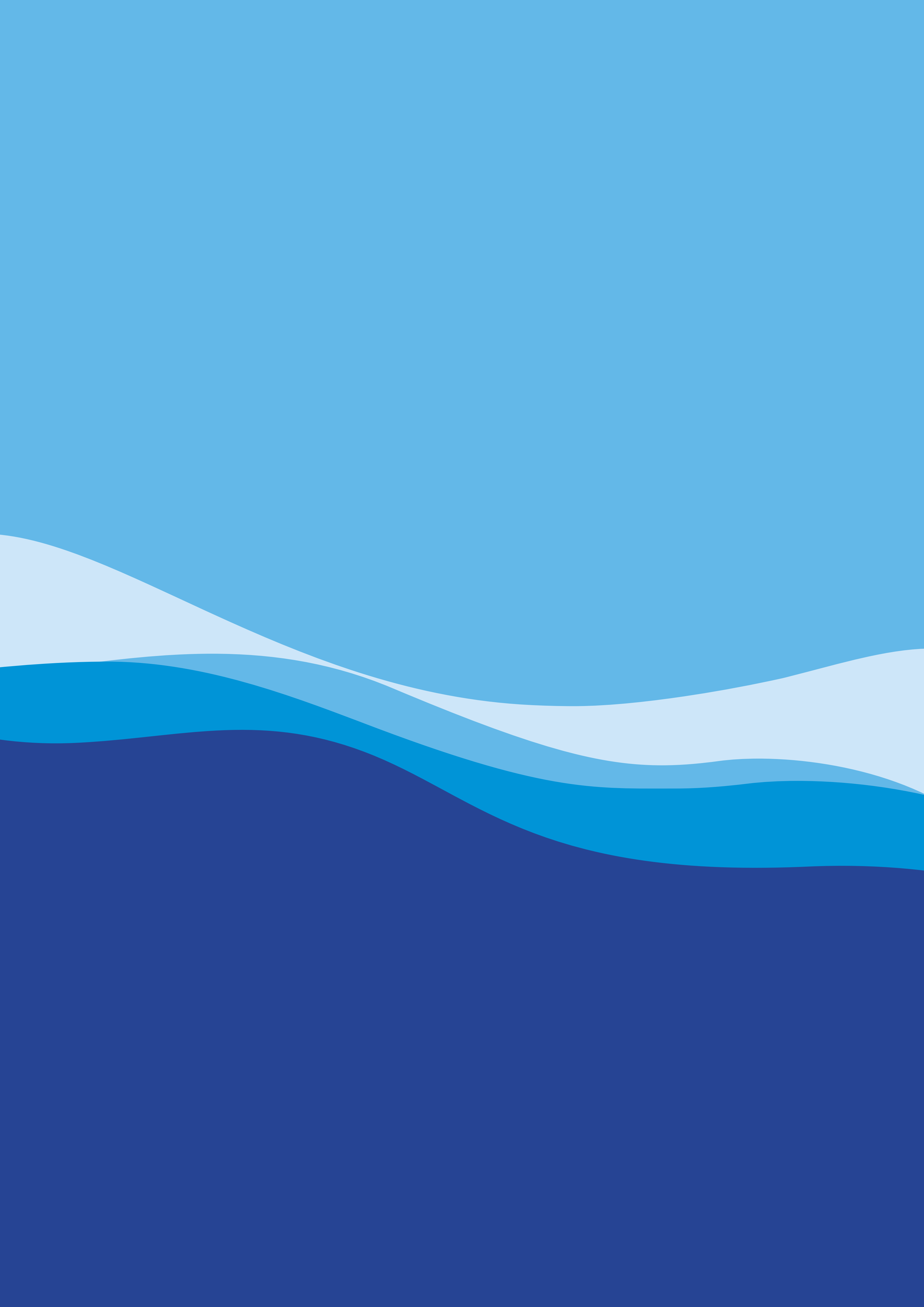
This document should be cited as: MedECC 2020 Summary for Policymakers. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp 11-40, doi:10.5281/zenodo.5513887.*



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Executive Summary: Climate and environmental change in the Mediterranean Basin

Virtually all sub-regions of the Mediterranean Basin, on land and in the sea, are impacted by recent anthropogenic changes in the environment. The main drivers of change include climate (temperature, precipitation, atmospheric circulation, extreme events, sea-level rise, sea water temperature, salinity and acidification), population increase, pollution, unsustainable land and sea use practices and non-indigenous species. In most areas, both natural ecosystems and human livelihoods are affected. Due to global and regional trends in the drivers, impacts will be exacerbated in the coming decades, especially if global warming exceeds 1.5 to 2°C above the pre-industrial level. Significantly enhanced efforts are needed in order to adapt to inevitable changes, mitigate change drivers and increase resilience.

Due to anthropogenic emissions of greenhouse gases, climate is changing in the Mediterranean Basin, historically and projected by climate models, faster than global trends. Annual mean temperatures on land and sea across the Mediterranean Basin are 1.5°C higher than during pre-industrial times and they are projected to rise until 2100 by an additional 3.8 to 6.5°C for a high greenhouse gas concentration scenario (RCP8.5) and 0.5 to 2.0°C for a scenario compatible with the long-term goal of the UNFCCC Paris Agreement to keep the global temperature well below +2°C above the pre-industrial level (RCP2.6). On land and in the sea, heat waves will intensify in duration and peak temperatures. Despite strong regional variations, summer rainfall will likely be reduced by 10 to 30% in some regions, increasing existing water shortages, desertification and decreasing agricultural productivity.

It is virtually certain that sea surface warming will continue during the 21st century by 1 to 4°C depending on the scenario (low or high greenhouse gas emissions) and likely that deep waters will warm more in the Mediterranean than in other oceans in the world. Rising carbon dioxide (CO_2) concentrations lead to seawater acidification, and this trend will continue. The Mediterranean mean sea level has risen by 6 cm over the past 20 years. This trend is likely to accelerate (with regional differences) by the global rate of 43 to 84 cm until 2100, but possibly more than 1 m in the case of further ice-sheet destabilization in Antarctica.

Most impacts of climate change are exacerbated by other environmental challenges such as changing land use, increasing urbanization and tourism, agricultural intensification, overfishing, land degradation, desertification, and pollution (air, land, rivers and ocean). Sulphur dioxide (SO_2) and nitrogen oxide (NO_x) have recently increased drastically, mainly because of shipping activity. Tropospheric ozone (O_3) concentrations increase due to pollution and warming, and high-level episodes will be more frequent in the future. Saharan dust transport is likely to also increase. The Mediterranean Sea is heavily polluted by multiple substances including plastic, emerging contaminants, heavy metals, fecal bacteria and viruses, all with expected increase in the future.

The Mediterranean Sea is invaded by many non-indigenous species, particularly from the Red Sea but also through the Strait of Gibraltar, maritime transport and aquaculture. On land, non-indigenous species are particularly present in regions with high infrastructure and commerce development, including accidentally introduced phytophagous pests which cause damage to crops and forests. These trends are expected to continue in the future.

Agriculture is the largest user of water in the Mediterranean region. Climate change impacts water resources in combination with demographic and socio-economic drivers, reducing runoff and groundwater recharge, water quality, increasing conflicts among users, ecosystem degradation and groundwater salinization in coastal aquifers. Demand for irrigation is expected to increase by 4 to 18% by 2100. Demographic change, including the growth of large urban centers, could enhance this demand by 22 to 74%. There is adaptive potential in the improvement of water use efficiency and reuse. Other important adaptations are changing agriculture practices and promoting the traditional Mediterranean diet, local production and reduction of food waste.

Land and seafood production activities are strongly impacted by climate change, more frequent and intense extreme events, together with higher soil salinization, ocean acidification and land degradation. Crop yield reductions are projected for the next decades in most current areas of production and for most crops. This will potentially be worsened by emerging pests and pathogens. There is large adaptation potential in changing farming practices and management to agroecological methods, also providing important potential for climate change mitigation by increased carbon storage in soils. Marine food production is threatened by unsustainable fishing practices, non-indigenous species, warming, acidification and water pollution, which together may affect species distribution and trigger local extinction of more than 20% of exploited fish and marine invertebrates by 2050. Adaptation will require more rigorous management of fisheries in the Mediterranean. The sustainability of the Mediterranean food sector (from the land and the ocean) also depends on population growth, regional consumer behavior (diet) and the global food markets (which may be affected by environmental crisis elsewhere).

Marine ecosystems and their biodiversity are also impacted by overfishing, warming, acidification and the spread of non-indigenous species from tropical waters. Expected consequences include increased jellyfish outbreaks, mucilage and algal bloom outbreaks, reduced commercial fish stocks, and general biodiversity loss due to altered physiology and ecology of most marine organisms. There is potential for mitigating these impacts through improved conservation within and beyond marine protected areas, more sustainable fishing practices and by reducing pollution from agriculture, urban areas and industry. In coastal systems, sea level rise will impact most infrastructure, aquifers, coastal crops, world heritage and other protected sites, notably in river deltas and estuaries. Increasing nutrient flows towards the sea increase the number and frequency of plankton blooms and jellyfish outbreaks, with negative impacts on fisheries, aquaculture and human health. The multiple levels of land-sea interactions could benefit from the implementation of new approaches of ecosystem-based Integrated Coastal Zone Management and conservation planning.

Land biodiversity changes in multiple ways. In countries of the northern rim, forest area is increasing at the expense of extensive agriculture and grazing, while ecosystems in southern countries are still at risk of fragmentation or disappearance due to clearing and cultivation, overexploitation of firewood and overgrazing. Over the past 40 years, biodiversity changes and species loss have led to homogenization and a general simplification of biotic interactions. Half of wetland area has been lost or degraded, and this trend is expected to continue. Dryland extension and an increase in areas burnt during more frequent wildfires are expected. Adaptation options for land biodiversity include preservation of natural flow variability in Mediterranean rivers and the protection of riparian zones, reduction of water abstraction, modified silvicultural practices, and the promotion of climate-wise landscape connectivity.

Human health is already impacted by high temperatures as well as air and water pollution in the Mediterranean Basin. The combined impacts of expected environmental changes (notably air pollution and climate) increase risks to human health from heat waves, food and water shortages, vector-borne, respiratory and cardio-vascular diseases. These health risks particularly impact disadvantaged or vulnerable populations, including the elderly, children, pregnant women and people with low income. Human security faces new risks from extreme events, particularly along coastal areas. Conflicts caused by scarce resources and human migration are likely to increase due to drought and degrading agricultural and fisheries resources, although socio-economic and political factors are likely to still play a major role.

Mediterranean cities are growing due to increasing population and socio-economic change, notably on the coasts of southern countries. Due to increasing heat stress, the planning and management of cities around to Mediterranean will need to focus more on human health and resilience to environmental change. Impacts of climate change on urban areas are expected to be disproportionally high due to a concentration of population and assets – especially in high-risk prone areas - in combination with hazard-amplifying conditions (e.g., increased runoff resulting from soil sealing, or urban heat island effects). Tourism will likely be affected by climate change through reduced thermal comfort, degradation of natural resources, including freshwater availability, and coastal erosion due to sea level rise and urban development. The net economic effect on tourism will depend on the country and the season.

All Mediterranean countries have significant potential to mitigate climate change through an accelerated energy transition. This will involve phasing down fossil fuel and accelerated development of renewable energies. This ambitious energy transition, reaching beyond the plans and targets announced by governments and policymakers in line with contributions made for the UNFCCC Paris Agreement, requires a significant transformation of energy policies and economic models in Mediterranean countries. While northern rim countries advance towards this transition by gradually diversifying their energy mix, improving energy efficiency and increasing the share of renewable energies, despite investments, some eastern and southern rim countries need support, funding, technology transfer and capacity-building in the framework of the UNFCCC Paris Agreement. Around 2040, the share of renewable energies could triple to reach 13 to 27% under current transition scenarios. Enhanced regional energy market integration and cooperation are crucial to unleashing cost-effective climate change mitigation.

More effective policy responses to climate and environmental changes will require both strengthened mitigation of the drivers of environmental change, such as greenhouse gas emissions, as well as enhanced adaptation to impacts. Poverty, inequalities and gender imbalances presently hamper the achievement of sustainable development and climate resilience in Mediterranean countries. Culture is a key factor to the success of adaptation policies in the highly diverse multicultural setting of the Mediterranean Basin. Aimed at supporting local and vulnerable communities, policies for climate adaptation and environmental resilience need take into account concerns such as justice, equity, poverty alleviation, social inclusion, and redistribution. To support policies for sustainable development with scientific evidence about climate and environmental change, a synthesis of current scientific knowledge, covering most relevant disciplines, sectors and sub-regions is presented by the First Mediterranean Assessment Report (MAR1).

BACKGROUND AND KEY FINDINGS OF THE FIRST MEDITERRANEAN ASSESSMENT REPORT

1 - Background for the assessment

1.1 Global environmental change exacerbates existing challenges for the population living around the Mediterranean Sea, through climate change, land use changes, increasing urbanization and tourism, agricultural intensification, pollution, declining biodiversity, resource competition, and socio-economic trends. Environmental, socio-economic and cultural conditions are highly heterogeneous across the Mediterranean Region *(Section 1.1.1)*, resulting in different manifestations of regional environmental change that require specific adaptation measures as well as enhanced capacity-building. To account for these specificities, a comprehensive risk assessment approach encompassing the entire Mediterranean Basin is needed to provide adequate and timely information as well as data needed for decision makers to design effective mitigation and adaptation strategies. *(Section 1.1.1)*.

1.2 Despite major research efforts across many disciplines and regions, to date, there has been no comprehensive assessment of risks posed by climate and environmental changes in the Mediterranean Basin. Most countries of the Middle East and North Africa (MENA) are likely to face potentially greater risks from climate and environmental changes than other parts of the Mediterranean Basin, but they have limited capacity to monitor important environmental parameters or carry out adequate risk analyses. Effective mitigation and adaptation require integrative studies that go beyond the current knowledge. The main challenges for the Mediterranean are to fill data and knowledge gaps across countries, and to foster the development of high-level climate services, including early warning systems. More research is needed for short- and medium-term projections, as well as large scale programs at the Mediterranean scale to address pressing challenges. *(Section 1.1.2)*.

1.3 The 1st Mediterranean Assessment Report (MAR1) has been developed and drafted in order to provide science-based guidance to multiple actors involved in coming up with a response to climate and environmental changes and to reduce associated risks to communities and natural ecosystems in the Mediterranean region *(Section 1.3.1.4)*. The report was developed by the scientific community, based on publications in scientific journals, for policymakers and other stakeholders through the conclusions in its Summary for Policymakers (SPM), as well as for a broader audience of experts through its detailed technical chapters supporting the SPM. The report is also intended to be communicated more broadly to the public through additional efforts of communication and participatory actions. *(Section 1.3.2)*.

1.4 The report assesses risks for the entire Mediterranean Basin (land and sea), associated with four main drivers of environmental change: climate, pollution, land and sea use and non-indigenous species. Throughout the report, scientific confidence in its findings is indicated based on the consistency of evidence and the degree of agreement of the scientific community, using the terms *"high"*, *"medium"* and *"low"*. *(Section 1.3.3).*

2 - Drivers of environmental change in the Mediterranean Basin

2.1 Climate change

Anthropogenic climate change has been observed for many variables in the Mediterranean Basin during recent decades. For the future, the region is expected to remain among the regions most affected by climate change, particularly when it comes to precipitation and the hydrological cycle.

2.1.1 There is robust evidence that the Mediterranean region has significantly warmed. Basin-wide, annual mean temperatures are now 1.54°C above the 1860-1890 level for land and sea areas, i.e. 0.4°C more than the global average change *(high confidence). (Fig. SPM.1) (Section 2.2.4.1; Box 2.1).*

2.1.2 Multi-model sets of climate simulations show that widespread warming will continue in the Mediterranean during the 21st century *(high confidence). (Section 2.2.4.2, Table 2.1).*

2.1.2.1 Over land, warming will likely be in the range of 0.9 to 1.5°C or 3.7 to 5.6°C during the 21st century, for low (RCP2.6) or high greenhouse gas emissions (RCP8.5), respectively *(high confidence)*. Future regional average warming will exceed the global mean value by 20% on an annual basis and 50% in summer *(high confidence). (Fig. SPM.2) (Section 2.2.4.2).*

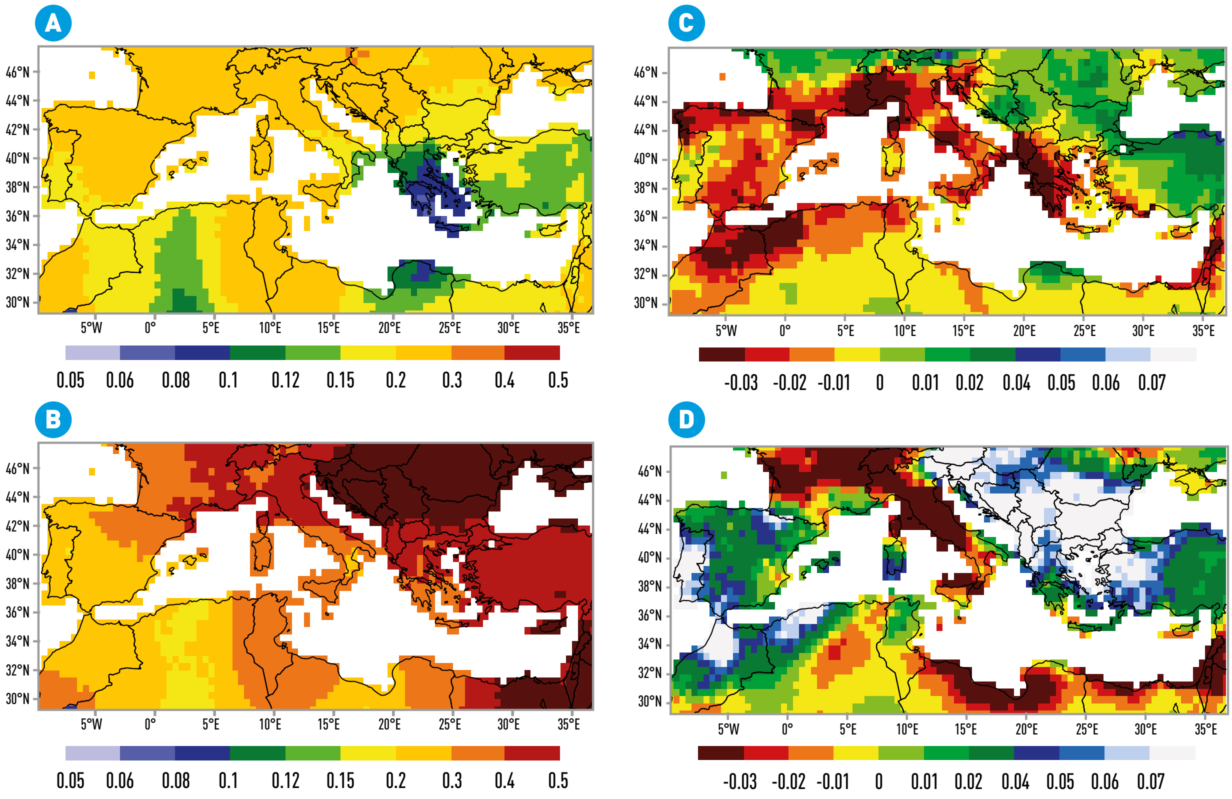

Figure SPM.1 | Observed changes in temperature and rainfall. Recent trends in temperature (A and B, °C decade^{-1}) and rainfall (C and D, mm day^{-1} decade^{-1}) in the Mediterranean Basin over land. Panels A & C average for the period 1950-2018, panels B & D for 1980-2018 (*Fig. 2.5* and *2.8*).

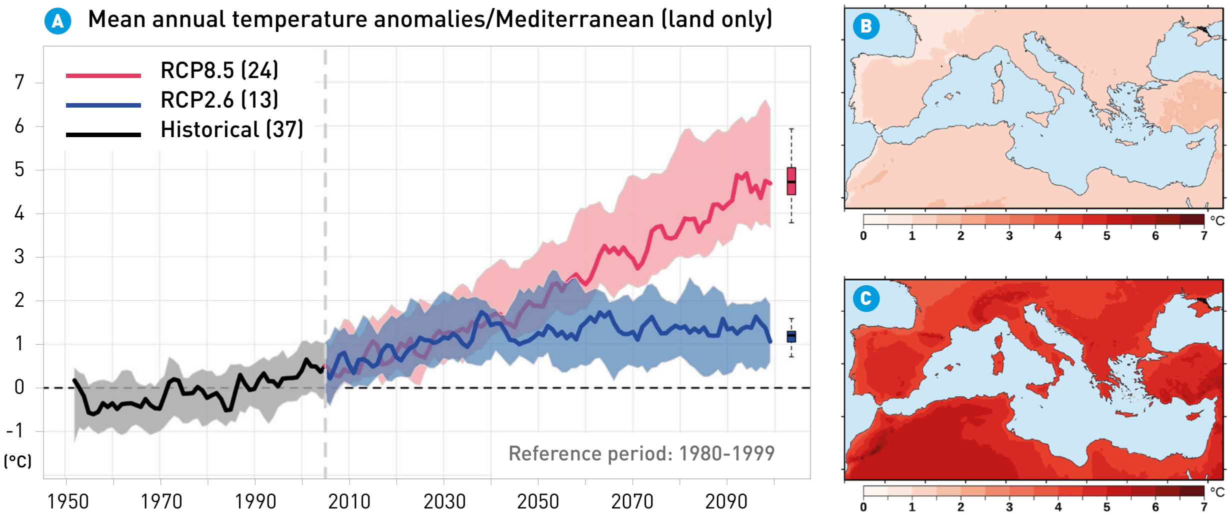

Figure SPM.2 | Projected warming in the Mediterranean Basin over land. Projected changes in annual temperature relative to the recent past reference period (1980-1999), based on the EURO-CORDEX 0.11° ensemble mean, A: simulations for pathways RCP2.6 and RCP8.5, B: warming at the end of the 21st century (2080-2099) for RCP2.6, C: idem for RCP8.5.

2.1.2.2 In the future, warm temperature extremes will increase and heat waves will intensify in duration and peak temperatures. For 2°C of global warming above the pre-industrial value, maximum daytime temperatures in the Mediterranean will likely increase by 3.3°C. With 4°C global warming, nearly all nights will be tropical (nighttime temperature for at least five days above a location-depending threshold) and there will be almost no cold days (below a location-depending threshold) *(high confidence). (Section 2.2.4.2).*

2.1.3 The sign and magnitude of observed land precipitation trends show pronounced spatial variability, depending on the time period and season considered *(medium confidence) (Section 2.2.5.1)*, so that the confidence in the detection of anthropogenic trends in rainfall for the historical past is low.

2.1.3.1 The most evident observed trend is a decrease in winter precipitation over the central and southern portions of the basin since the second half of the 20th century *(medium confidence). (Section 2.2.5.1).*

2.1.4 Models project a consistent decrease in precipitation during the 21st century, for the entire Mediterranean Basin during the warm season (April through September, with the highest magnitude in summer) and in winter for most of Mediterranean, except for the northernmost regions (e.g., the Alps), where wetter conditions are projected *(medium confidence). (Fig. SPM.3) (Section2.2.5.2).*

2.1.4.1 The mean rate of land precipitation decrease among models is 4% per each degree of global warming, which would determine a reduction in the range of 4 to 22% depending on scenario at the end of the 21st century *(medium confidence) (Section 2.2.5.2).* The magnitude of this decrease varies across models, rendering sub-regional projections uncertain.

2.1.4.2 Future climate projections indicate a predominant shift towards a precipitation regime of higher interannual variability, higher intensity and greater extremes (especially in winter, spring and fall, but not in the southern areas, *low confidence*), decreased precipitation frequency and longer dry spells (especially in summer and in the southern countries) *(medium confidence). (Section 2.2.5.2).*

2.1.5 There are no significant trends in the number of observed cyclones in recent decades *(low/medium confidence) (Section 2.2.2.3).* Most future climate projections indicate a decrease in cyclones, especially in winter *(medium confidence). (Section 2.2.2.3).*

2.1.5.1 There is insufficient information for assessing past trends of "medicanes" (Mediterranean hurricanes), but projections indicate decreasing frequency and increasing intensity *(medium confidence). (Section 2.2.2.3).*

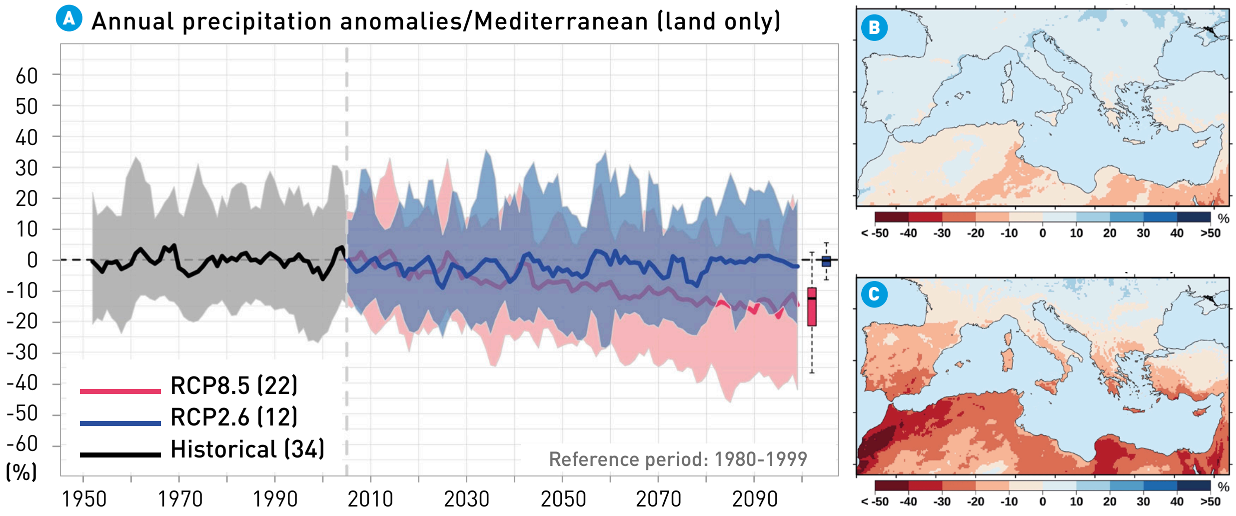

Figure SPM.3 | Projected rainfall change in the Mediterranean Basin. Projected changes in annual rainfall relative to the recent past reference period (1980-1999), based on the EURO-CORDEX 0.11° ensemble mean, A: simulations for pathways RCP2.6 and RCP8.5, B: rainfall anomalies at the end of the 21st century (2080-2099) for RCP2.6, C: idem for RCP8.5.

2.1.5.2 Projections of future wind speeds converge on a limited wind speed reduction over most of the Mediterranean Sea, with the exception of an increase over the Aegean Sea and northeastern land areas *(medium confidence). (Section 2.2.2.4).*

2.1.5.3 Projections suggest a general decrease in mean significant wave height, as well as in the number and intensity of wave extremes, over a large part of the Mediterranean Sea, especially in winter, and storm surges along the coasts *(medium confidence)*, but with no consensus on the most extreme events. *(Section 2.2.8.2).*

2.1.6 Surface solar radiation in the Mediterranean Basin decreased from the 1950s to the 1980s (between -3.5 and -5.2 W m^{-2} $decade^{-1}$) and recovered thereafter (between +0.9 and +4.6 W m^{-2} $decade^{-1}$), consistent with global trends *(very high confidence). (Section 2.2.3.1).* In future climate projections, anthropogenic aerosol loads over the Mediterranean are expected to continue to decrease *(high confidence)*, leading to an increase in surface solar radiation *(medium confidence). (Section 2.2.3.2).*

2.1.7 Observations and most model projections indicate a trend towards drier conditions over the Mediterranean Basin, especially in the warm season and over the southern areas *(medium/high confidence). (Section 2.2.5.3).*

2.1.7.1 Across the Mediterranean Sea, net fresh water loss (evaporation minus precipitation and river runoff) has increased since the last decades of the 20th century *(medium confidence) (Section 2.2.5.3).* The main cause is the strong evaporation increase due to local warming (the estimated rate of evaporation change in relation to warming is about 0.7 mm day^{-1} $°C^{-1}$ (or 25% $°C^{-1}$) over the period of 1958-2006).

2.1.7.2 Net water loss from the sea is expected to increase in the future due to a decrease in precipitation and river runoff and an increase in evaporation *(high confidence). (Section 2.2.5.3).*

2.1.8 In the 20th century a significant reduction in the area and volume of glaciers across high mountains of the Mediterranean has occurred. Deglaciation has generally accelerated in recent decades *(high confidence). (Section 2.2.6.1).*

2.1.8.1 Warming has shifted the occurrence of periglacial processes to higher elevations and degraded permafrost in high mountain environments. Glaciers in the Mediterranean region are projected to continue losing mass in the 21st century until complete disappearance of most mountain glaciers by the end of the century *(very high confidence). (Section 2.2.6.2).*

2.1.8.2 At lower elevation, the snow water equivalent is projected to decline by 25% (10 to 40%) from 1986-2005 to 2031-2050, regardless of the scenario. This will continue with a 30% decrease at the end of the 21st century for a low emission scenario to 80% for high emission scenario *(high confidence)*. *(Section 2.2.6.2)*.

2.1.9 Mediterranean Sea surface waters are warming and deep waters are becoming saltier *(high confidence)*. *(Section 2.2.7.1)*.

2.1.9.1 Since the beginning of the 1980s, average Mediterranean Sea surface temperatures have increased throughout the basin, but with large sub-regional differences in the range between +0.29 and +0.44°C per decade, with stronger trends in the eastern basins (Adriatic, Aegean, Levantine and north-east Ionian Sea), marine heat waves have become longer and more intense *(high confidence)*. *(Section 2.2.7.1)*.

2.1.9.2 The water mass temperature and salinity changes of the water outflowing from the Mediterranean Sea through the Strait of Gibraltar are 0.077°C decade^{-1} and 0.063 psu (practical salinity unit) decade^{-1}, respectively, compared to 2004 *(high confidence)*. *(Section 2.2.7.1)*.

2.1.10 Widespread sea surface temperature increase will continue in the 21st century *(very high confidence)*.

2.1.10.1 During the 21st century, the basin mean sea surface temperature is expected to warm by 2.7 to 3.8°C and 1.1 to 2.1°C under the RCP8.5 and the RCP4.5 scenarios, respectively *(very high confidence)*. The sign of future basin average sea surface salinity change remains largely uncertain and its changes will likely be spatially and temporally heterogeneous *(medium confidence)*. *(Section 2.2.7.2)*.

2.1.10.2 Marine heat waves will very likely increase in spatial extent, become longer, more intense and more severe than today *(medium confidence)*. Under the high emission scenario, the 2003 marine heat wave may become a regular event for the period 2021-2050 and a weak event at the end of the 21st century *(medium confidence)*. *(Section 2.2.7.2)*.

2.1.11 Mediterranean Sea waters have acidified and will continue to acidify along with the global ocean *(medium confidence)*. The Mediterranean Sea is able to absorb relatively more anthropogenic CO_2 per unit area than the global ocean because it is more alkaline and because deep waters are ventilated over shorter timescales *(medium confidence)*. *(Section 2.2.9)*.

2.1.11.1 Sea water surface pH has decreased by -0.08 units since the beginning of the 19th century, similar to the global ocean, with deep waters exhibiting a larger anthropogenic change in pH than typical global ocean deep waters because ventilation times are faster *(medium confidence)*. *(Section 2.2.9.1)*.

2.1.11.2 In 2100, reduction of pH might reach 0.462 and 0.457 units for the western and for the eastern basins, respectively *(low confidence)*. *(Section 2.2.9.2)*.

2.1.12 Mediterranean sea level is rising, similar to global trends, with strong spatial and temporal variation and expected acceleration *(medium confidence)*. *(Section 2.2.8.1)*.

2.1.12.1 Averaged across the Mediterranean Basin, mean sea level has risen by 1.4 mm yr^{-1} during the 20th century and has accelerated to 2.8 mm yr^{-1} recently (1993–2018) *(high confidence)*. *(Section 2.2.8.1)*.

2.1.12.2 Mostly due to global ocean and ice-sheet dynamics, Mediterranean mean sea level rise is projected to accelerate further throughout the 21st century *(high confidence)*. Around 2100, depending on the scenario, the basin mean sea level will likely be 37-90 cm higher than at the end of the 20th century, with a small probability of being over 110 cm *(medium confidence)*. *(Section 2.2.8.2)*.

2.1.12.3 Sea level rise will increase the frequency and intensity of coastal floods and erosion *(high confidence)*. *(Section 2.2.8.2)*.

2.2 Pollution

2.2.1 Across the Mediterranean Basin, ocean and inland pollution are transboundary, ubiquitous, diverse and increasing in both quantity and in the number of pollutants, due to demographic pressure, enhanced industrial and agricultural activities, and climate change *(high confidence)*. *(Section 2.3.1)*.

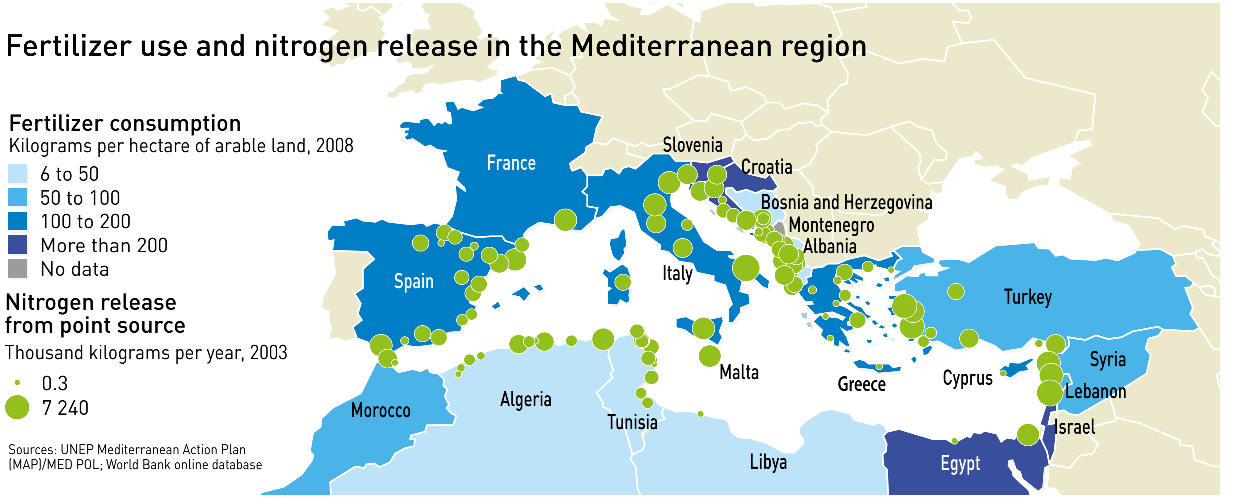

Figure SPM.4 | Fertilizer use and nitrogen release in the Mediterranean Sea (UNEP/MAP/MED POL, 2013).

2.2.2 Pollution of sea water

2.2.2.1 Mediterranean waters are generally oligotrophic (low nutrient), with decreasing levels from Gibraltar eastwards to the Levantine Sea. Several coastal regions are hotspots of human-induced nutrient inputs (Lagoons of Venice and Bizerte, Gulfs of Lion and Gabès, eastern Adriatic and western Tyrrhenian Sea, North Lake of Tunis, Algerian-Provençal Basin and the Gibraltar Strait) *(high confidence) (Fig. SPM.4). (Section 2.3.3.1).*

2.2.2.2 Nutrient enrichment causes eutrophication and may provoke harmful and toxic algal blooms, trends which will likely increase. Harmful algal blooms may cause negative impacts on ecosystems (red-tide, mucilage production, anoxia) and may present serious economic threats for fisheries, aquaculture and tourism. They may also harm human health, since 40% of blooming microalgae are able to produce toxins responsible of different human intoxications. Harmful algal blooms can also occur in freshwater environments. *(Section 2.3.4).*

2.2.2.3 Emerging contaminants (related to recently discovered chemicals or materials) are prevalent across the Mediterranean Basin, and enhanced by increasing inflow of untreated wastewater. These substances may cause disorders of the nervous, hormonal and reproductive system *(high confidence). (Section 2.3.3.5).*

2.2.2.4 The increasing frequency of extreme precipitation events in the north of the Mediterranean increases the supply of faecal bacteria and viruses to the coastal zone *(medium confidence). (Section 2.3.4).*

2.2.2.5 The Mediterranean Sea is one of the most polluted large water bodies globally in terms of plastic and the level of this pollution is expected to increase in the future *(medium confidence). (Section 2.3.2.3).* Even with rigorous reduction of use, plastic debris and their dissolved derivatives will remain a problem since they can take 50 or more years to fully decompose *(medium confidence) (Section 2.3.2.3).*

2.2.3 Air pollution

2.2.3.1 The Mediterranean Basin is among the regions in the world with the highest concentrations of gaseous air pollutants (NO_2, SO_2 and O_3). Its dry and sunny climate, and specific atmospheric circulation patterns enhance air pollution levels *(high confidence). (Section 2.3.3.2)* Emissions of aerosols and particulate matter (PM) into the atmosphere arise from a variety of anthropogenic activities (transport, industry, biomass burning, etc.), but also from natural sources (volcanic eruptions, sea salt, soil dust suspension, natural forest fires, etc.). *(Section 2.3.2.1).*

2.2.3.2 Ships are among the major emitters of SO_2 and NO_x, along with road traffic. Their contribution to transport sector emissions and general air pollution in the Mediterranean Basin is increasing *(medium confidence). (Section 2.3.3.2).*

2.2.3.3 Tropospheric ozone (O_3) concentrations observed in the summer across this region are among the highest in the northern Hemisphere and still increasing in average and with more frequent high-level episodes. They are influenced by Volatile Organic Compounds (VOCs), NO_x emissions and climate. This trend will likely be enhanced by future warming *(medium confidence). (Section 2.3.3.2).*

2.2.3.4 Particular meteorological conditions and natural sources, including the proximity of the Sahara Desert, create specific patterns of aerosol concentrations that may influence particulate matter (PM) concentrations. The occurrence of critically high PM concentrations associated with dust outbreaks is higher in the southern Mediterranean (>30 % of annual days) than in the northern area (<20% of annual days) *(high confidence). (Section 2.3.2.1).*

2.3 Land and sea use change

2.3.1 Landscapes and their use have changed over millennia in the Mediterranean Basin, however the rate of change has increased substantially since the second half of the 20th century *(high confidence). (Section 2.4.1.1).*

2.3.1.1 Urban and peri-urban areas are growing rapidly all over the Mediterranean, especially along the coasts. Urbanization is a major driving force of biodiversity loss and biological homogenization causing landscape fragmentation, loss of open habitats and of the land use gradient, replacing agricultural systems and natural vegetation *(high confidence). (Section 2.4.1.2).*

2.3.1.2 Outside urban areas and areas with intensive agriculture, forest and shrub encroachment, as a consequence of abandoned agro-pastoralism, mainly affects marginal lands, arid and mountain regions, primarily in the north *(high confidence). (Section 2.4.1.1).*

2.3.1.3 In many regions of North Africa and the Middle East (but also on some Mediterranean islands), the dominant land use change process is forest degradation caused by land overexploitation. From the 1980's to the 1990's deforestation has increased by 160% *(high confidence).* (*Section 2.4.1.1* and *2.4.1.2*).

2.3.1.4 Future land use trends depend strongly on regional policies for urbanization, agriculture, forestry and nature conservation. Grassland and pastures will likely continue to further decrease in extension due to rural abandonment, often due to insufficient job opportunities and public services in marginal areas *(medium confidence). (Section 2.4.1.3).*

2.3.2 Marine resource overexploitation and unsustainable fishing practices are the main driver of marine species population decline. *(Section 2.4.2).*

2.3.2.1 Fishing efforts have increased over long periods, but particularly so since the 1990's due to new technologies and higher capacity vessels *(high confidence). (Section 2.4.2.1).*

2.3.2.2 In 2010, the cumulative percentage of collapsed and overexploited stocks exceeded 60% across the Mediterranean Sea *(medium confidence)*. The eastern Mediterranean is the most overexploited sub-basin with the highest number of collapsed species *(medium confidence). (Section 2.4.2.2).*

2.3.2.3 Sustainable management of marine resources requires reduced fishing pressure. The implementation of an ecosystem-based approach may ensure the recovery of both high and low trophic levels and support both ecosystem health and resilience against sea warming *(high confidence). (Section 2.4.2.3).*

2.4 Non-indigenous species

2.4.1 The Mediterranean Sea (and particularly the Levantine Basin) is a hotspot for the establishment of many non-indigenous species *(high confidence). (Section 2.5.1).*

2.4.1.1 Among known marine non-indigenous species introduced over the last 30 years, invertebrates dominate with >58% (mostly mollusks and decapods), primary producers follow with approx. 23% and vertebrates with 18% (mostly fish) *(high confidence). (Section 2.5.1.1).*

2.4.1.2 Most marine non-indigenous species arrive from the Red Sea and Atlantic Ocean, but the highest impact is attributed to those introduced by ships and aquaculture *(high confidence). (Section 2.5.1.2).*

2.4.1.3 The increase in non-indigenous species can be linked to decrease or collapse in populations of native species, and to other ecological changes to the marine ecosystem *(high confidence). (Section 2.5.1.2).*

2.4.1.4 The number and spread of non-indigenous species will likely increase further with increasing shipping activity and the impacts of climate on the ocean *(medium evidence).* Forecasting future establishment of non-indigenous species using species distribution models is challenging. *(Section 2.5.1.3).*

2.4.2 On land, there is a high number of non-indigenous species in human-modified ecosystems and in regions with high infrastructure development *(high confidence). (Section 2.5.2.1).*

2.4.2.1 On land, most non-indigenous species in the region are plants (introduced intentionally as ornamentals), followed by invertebrates. Phytophagous pests, which cause damages to crops and forests, dominate non-indigenous species all over the Mediterranean Basin, accounting for more than a half of the invertebrate species. The main pathways of introduction for vertebrates are accidental escapes *(medium evidence). (Section 2.5.2.1).*

2.4.2.2 With warming, current major non-indigenous species are predicted to shift northwards by 37 to 55 km decade^{-1}, leaving a window of opportunity for new non-indigenous species adapted to xeric conditions. The trend has recently shifted towards increasing numbers of introduced invertebrates and vertebrates. This pattern will very likely continue in the near future, due to increasing air and maritime cargo, where these taxa can be easily transported as stowaways *(medium confidence). (Section 2.5.2.3).*

3 - Resources

3.1 Water

3.1.1 Water resources in the Mediterranean are scarce: resources are limited, unevenly distributed and in some areas not accessible, often mismatching human and environmental needs. *(Section 3.1.1).*

3.1.1.1 Renewable water resources are unevenly distributed among Mediterranean regions (72 to 74% are located in the northern Mediterranean) and so is the spatial distribution of water needs, but with opposite trends. As a consequence, 180 million people in the southern and eastern Mediterranean countries suffer from water scarcity (<1,000 m^3 capita^{-1} yr^{-1}) and 80 million people from extreme water shortage (<500 m^3 capita^{-1} yr^{-1}) *(high confidence). (Section 3.1.1.1).*

3.1.1.2 River discharge is characterized by high temporal - seasonal and inter-annual - variability and groundwater is the main source of freshwater for some Mediterranean countries (Libya, Malta, Palestine, Israel) *(Section 3.1.1.2).* In several cases in southern Mediterranean countries, groundwater resources are drawn from fossil aquifers, i.e. non-renewable resources *(high confidence). (Section 3.1.1.3).*

3.1.1.3 Sustainable water management is complicated by the transboundary nature of many river basins and aquifers, common in Mediterranean countries (18% of total renewable water resources originate outside the territories of the southern Mediterranean, 27% in eastern Mediterranean countries *(high confidence). (Section 3.1.1.1).*

3.1.2 Due to the general scarcity of water resources, conflicts arise from different sectors of water use (agriculture, tourism, industry, people, also biodiversity conservation) *(medium confidence). (Section 3.1.2).*

3.1.2.1 The spatial distribution of water use per sector in the Mediterranean area is heterogeneous. In southern and eastern countries, agricultural use reaches 76-79%. In the northern part, the four sectors are much more balanced (18-36%, *Fig. SPM.5*), with differences between countries. *(Section 3.1.2.1).*

3.1.2.2 The percentage of irrigated land of the total cultivated area in the Mediterranean is about 25% (but more than 70% in Egypt, Israel, Lebanon, Greece), with a strong increase (21%) in recent years *(Section 3.1.2.2).* The trend towards more efficient irrigation systems does not always generate absolute water savings due to the introduction of more water demanding crops (e.g. vegetables) *(medium confidence). (Section 3.1.2.2).*

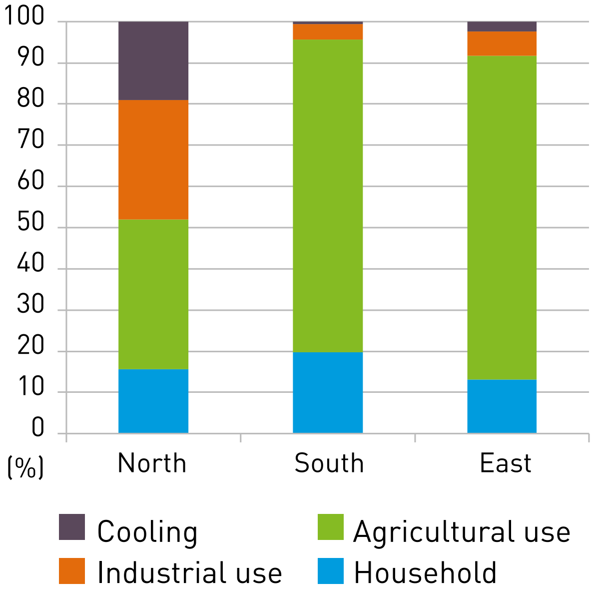

Figure SPM.5 | Total water consumption rates across four main sectors and three sub-regions (data source: AQUASTAT).

3.1.2.3 Tourism activity is at its highest in summer, coinciding with peak demands by irrigated agriculture, creating tensions for water, and this will likely be exacerbated in the future due to climate change *(medium confidence)*. *(Section 3.1.2.3)*.

3.1.2.4 Municipal water use is already constrained in several Mediterranean countries affected by water scarcity, exacerbated by demographic and migratory phenomena, as well as by the limits and obsolescence of water distribution infrastructure *(medium confidence)*. Several northern countries have managed to reduce their municipal withdrawal in absolute values while several southern and eastern countries have the opposite trend *(medium confidence)*. *(Section 3.1.2.5)*.

3.1.2.5 Water-related intersectoral conflicts are likely to be exacerbated in the future because of the interactions between climate change (increasing droughts) and ongoing socio-economic and demographic trends *(medium/high confidence)*. *(Section 3.1.5.2)*.

3.1.3 Disastrous flash floods are frequent in many countries including Italy, France and Spain, affecting mainly the coastal areas, in particular, where population and urban settlements are growing in flood-prone areas. These will likely become more frequent and/or intense due to climate change and surface-sealing *(medium confidence)*. *(Section 3.1.3.3)*.

3.1.4 Climate change, in interaction with other drivers (mainly demographic and socio-economic developments including unsustainable agricultural practices), is likely to impact most of the Mediterranean Basin, through reduced runoff and groundwater recharge, increased water requirements for crops, increased conflicts among users, and increased risk of overexploitation and degradation *(high confidence)*. *(Section 3.1.4.1)*.

3.1.4.1 Impacts of even moderate (1.5 to 2°C) global warming and associated socio-economic pathways are expected to stem from reduced precipitation associated with increased evaporation, leading to a decline in runoff water *(Section 3.1.4.1)*. In many regions, this will likely increase low flow periods in summer and the frequency of no-flow events, and higher drought risks *(Section 3.1.4.1)*. More urban populations are likely to be exposed to severe droughts, and the number of affected people will essentially scale with the temperature increase *(high confidence)*. *(Section 3.1.4.1)*.

3.1.4.2 Aquifer recharge will be strongly impacted by warming and reduced rainfall, particularly in semi-arid areas. At current extraction rates, overexploitation of groundwater is likely to continue having a greater impact on decreasing groundwater levels than climate change *(high confidence)*. *(Section 3.1.4.1)*.

3.1.4.3 Important challenges to groundwater quality in coastal areas are likely to arise from salt-water intrusion driven by enhanced extraction of coastal groundwater aquifers and sea-level rise, as well as from increasing water pollution in the southern and eastern Mediterranean *(medium confidence)*. *(Section 3.1.4.1)*.

3.1.4.4 Impacts of global warming levels higher than 1.5 to 2°C on water resources by the end of the 21st century will be significantly stronger, generating substantially increased risks in the Mediterranean region *(Section 3.1.4.2)*. The probability of more extreme and frequent meteorological, hydrological and agricultural droughts will likely increase substantially, with 5 to 10 times more frequent droughts in many Mediterranean regions *(high confidence)*. *(Section 3.1.4.2)*.

3.1.5 The combined dynamics of climate and socio-economic changes suggest that despite an important potential for adaptation to reduce freshwater resource vulnerability, climate change exposure cannot be fully and uniformly counterbalanced. In many regions, socio-economic developments will have greater impact on water availability compared to climate-induced changes *(low confidence). (Section 3.1.4.2).*

3.1.5.1 Strategies and policies for water management and climate change adaptation are strongly interconnected with all other sectors (e.g., the water-energy-food nexus). Most adaptation and water management strategies rely on the principles of Integrated Water Resources Management (IWRM), which is based on economic efficiency, equity and environmental sustainability, also considering the nexus with agriculture (food production in particular) and energy for building the resilience needed to adapt to climate change. *(Section 3.1.5.1).*

3.1.5.2 Technical solutions are available to improve water availability and the efficient use of water resources. Seawater desalination is increasingly used to reduce (potable) water scarcity in arid and semi-arid Mediterranean countries, despite known drawbacks in terms of environmental impacts on near-coastal marine ecosystems and energy requirements with associated CO_2 emissions. Promising new (solar) technologies are under development, potentially reducing both greenhouse gas emissions and costs *(medium confidence). (Section 3.1.5.2).*

3.1.5.3 Technology is also expected to contribute significantly to the reduction of wastewater volume, its reclamation and reuse and the reduction of impacts on sea water quality. Agricultural, industrial and watering activities present together approx. 70% water reuse potential. The proposal has been made to recharge aquifers with treated wastewater, but critical issues in terms of water quality remain to be resolved *(medium confidence). (Section 3.1.5.2).*

3.1.5.4 Inter-basin transfer of water has been implemented in several large-scale schemes, with high social and environmental costs, and risks of conflict *(low confidence). (Section 3.1.5.2).*

3.1.5.5 Dams for water storage or hydropower exist in most countries, and rivers are diverted for water management in some countries. Large dams often generate social and environmental impacts, such as the destruction of river and wetland ecosystems and the loss of aquatic biodiversity, forced relocation of people and loss of cultural resources. Reductions of these impacts are possible, for example through constructed wetland habitats, and management of fishing and other recreational opportunities and enhanced coordination among countries sharing the same water resources *(low confidence) (Section 3.1.5.2).* Technological developments also allow for the use of underground- or subsurface dams, to contribute to sustainable management of groundwater. *(Section 3.1.5.2).*

3.1.5.6 The strategy of trading commodities (in particular from agriculture) that cannot be produced due to lacking water (virtual water trade) can be considered a form of adaptation. Most Mediterranean countries (e.g., Portugal, Spain, Italy, Greece, Israel, Turkey) have high footprints in terms of national consumption (above 2000 m^3 yr^{-1} $capita^{-1}$) *(low confidence). (Section 3.1.5.1).*

3.1.5.7 Water demand management, i.e. methods used to save (high quality) water, may reduce water consumption or water losses. This includes technical, economic, administrative, financial and/or social measures, with priority for increases in water use efficiency, in particular in the tourism and food sectors and with case-specific solutions integrating traditional knowledge with modern technical achievements *(high confidence). (Section 3.1.5.1).*

3.1.5.8 The reduction of water losses in all sectors of water use in the Mediterranean is crucial for sustainable management and adaptation strategies. Leakage in urban distribution networks and inefficient irrigation technologies are in urgent need of being addressed *(high confidence). (Section 3.1.5.1).*

3.1.5.9 Maintaining the traditional Mediterranean diet and shifting back to a locally produced Mediterranean food in conjunction with a reduction of food waste, could generate water savings in comparison to the present increasingly meat-based diet: 753 l for a locally produced diet and 116 l for less waste of water per capita and per day, in addition to benefits for health (obesity, diabetes) *(high confidence). (Box 3.1.2).*

3.2 Food

3.2.1 Warmer and drier climate conditions, with more frequent and intense extreme events, in combination with higher soil salinization, ocean acidification and land degradation, sea level rise and the emergence of new pathogens pose a threat to most elements of the food production system in the Mediterranean Basin *(high confidence)*.

3.2.1.1 Climate extremes pose a threat to the entire agricultural sector. Crop yield reductions are projected for the coming decades in most current areas of production and for most crops if no adaptation takes place. *(Section 3.2.2.1)*.

3.2.1.2 Maize is the crop most affected by climate change, projected to decline in yield by up to 17% in some countries by around 2050 under RCP8.5 scenario and assuming current agricultural practices *(medium confidence)*; it could become infeasible in regions with limited access to irrigation water *(medium confidence) (Section 3.2.2.1)*. Wheat yield losses of 5% to 22% are also projected because of decreased resilience of production and higher inter-annual variability in 2021-2050 under RCP8.5 scenario with no adaptation. Other water demanding crops, e.g., tomatoes, are also at risk. The production of some currently rainfed crops, such as olives, could become infeasible without irrigation *(medium confidence)*. *(Section 3.2.2.1)*.

3.2.1.3 Increasing atmospheric CO_2 concentrations may help offset yield losses for some crops, such as wheat and barley, but this effect could impact nutritional quality. Beneficial effects of CO_2 are likely limited by water stress conditions as well as by nutrient availability *(low confidence)*. *(Section 3.2.2.1)*.

3.2.1.4 Climate extremes, such as heat stress, droughts, and floods, can cause crop yield losses/failures, crop quality reduction and impacts on livestock *(high confidence) (Section 3.2.1.4)*. These events can also induce long-term socio-economic and landscape changes *(medium confidence)*. *(Section 3.2.1.4)*.

3.2.1.5 Sea level rise will likely impact the agricultural sector by a direct impact on (or loss of) agricultural areas in coastal zones (e.g., in Egypt), along with up to a three-fold increase in the salinity of irrigation water and soil, and retention of sediments that do not reach the coast *(high confidence)*. *(Section 3.2.2.1)*.

3.2.1.6 New and/or re-emerging pests and pathogens may contribute to larger than estimated losses in the agricultural sector. Food quality and security may also be affected by mycotoxigenic fungal pathogens and a higher level of contamination *(medium confidence)*. *(Section 3.2.2.1)*.

3.2.1.7 Total landings from Mediterranean fisheries have declined by 28% from 1994 to 2017 *(Section 3.2.1.3, Fig. 3.22)*. Climate change is projected to heavily affect marine resources in the coming decades. Warming, acidification and water pollution are likely to reduce marine productivity, affect species distribution and trigger local extinction of more than 20% of exploited fish and marine invertebrates by 2050 *(high confidence)*. *(Section 3.2.2.2)*.

3.2.1.8 Perturbations in global markets for agricultural and marine products, potentially caused by environmental change elsewhere, may exacerbate the local impacts of climate change, especially because most Mediterranean countries are net importers of cereal and fodder/feeding products *(high confidence)*. *(Section 3.2.1.5)*.

3.2.2 Adaptation to environmental change will be of key importance to limit and partially offset the impacts of climate change in the food sector *(high confidence)*.

3.2.2.1 Projected yield losses in most crops may be reduced by targeted adaptation strategies, such as crop diversification, adapting the crop calendar and use of new varieties adapted to evolving climate conditions. Strategies based on increased irrigation will have limited applicability in the region. Thus, adapted production of crops such as maize will depend on more drought-resistant varieties *(medium confidence)*. *(Section 3.2.3.1)*.

3.2.2.2 Successful adaptation strategies are based on combining different approaches, i.e. on farming practices (e.g., varieties, rotational patterns, crop diversity, agroforestry) and management (e.g., diversification of income, modifying irrigation practices). Sectoral co-designed climate services may help reduce risks linked to unfavorable climate conditions and extremes *(medium confidence)*. *(Section 3.2.3.1)*.

3.2.3 The food production system on land has the capacity to contribute to greenhouse gas mitigation strategies through nitrogen fertilization optimization, improved water management, better storage of soil organic carbon and carbon sequestration, management of crop residues and agroindustry by-products *(high confidence)*. *(Section 3.2.3.2)*.

3.2.3.1 N_2O emissions in Mediterranean agro-ecosystems can potentially be mitigated by 30 to 50%, through adjusted fertilization (rate and timing). Replacing mineral nitrogen with organic fertilization provides soil and crops not only with nitrogen, phosphorus, potassium and micronutrients, but also enhances organic carbon when using solid fertilizers (i.e., solid manure, compost, etc.), this would be beneficial in many Mediterranean soils with low organic carbon contents *(medium confidence). (Section 3.2.3.2).*

3.2.3.2 Optimized irrigation techniques may decrease greenhouse gas emissions from Mediterranean regions in perennial crops and intensive vegetable cropping systems on paddy soils (water table management) *(medium confidence). (Section 3.2.3.2).*

3.2.3.3 Soil organic carbon content in Mediterranean croplands is responsive to management changes such as organic amendments, cover crops and tillage reductions. There is high potential to enhance soil organic carbon storage through land restoration (as proposed by the "4‰ initiative" proposed 2015 by France during the UNFCCC COP21). Organic fertilizers, tillage reduction and residue retention are effective practices in herbaceous systems. Woody systems, in which the carbon storage potential is higher, can benefit from maintaining a soil cover and use of agro-industry byproducts, such as composted olive mill waste, as a source of organic matter *(medium confidence). (Section 3.2.3.3).*

3.3 Energy transition in the Mediterranean

3.3.1 From 1980 to 2016, primary energy consumption in the Mediterranean Basin steadily increased by approx. 1.7% yr^{-1}, mostly due to changing demographic, socio-economic (lifestyle and consumption) and climate conditions *(high confidence). (Section 3.3.2.1: Fig. 3.25).*

3.3.1.1 The current level of Mediterranean greenhouse gas emissions is approx. 6% of global emissions, close to its proportion of the world population. International climate policy agreements demand an accelerated energy transition in the countries of this region to enable secure, sustainable and inclusive development. *(Section 3.3.1).*

3.3.1.2 The contribution of oil to energy production has remained stable between 1995 and 2016, while that of coal has gradually decreased. Primary energy production from natural gas has doubled, while the contribution of nuclear power and renewable energy sources contribution has risen by about 40% *(high confidence). (Section 3.3.2.1, Fig. 3.28).*

3.3.1.3 While northern rim countries advance towards the transition by gradually diversifying their energy mix, improving energy efficiency and increasing the share of renewable energies, despite recent investments, some eastern and southern rim countries lag behind in these developments *(high confidence). (Section 3.3.3.2).*

3.3.2 Projected trajectories for energy demand over the next few decades in the Mediterranean Basin differ significantly between the northern and the eastern/southern rim countries *(high confidence). (Section 3.3.3.2).*

3.3.2.1 Energy demand in the north has decreased by 8% since 2010, due to moderate population growth, increasing efficiency and a stable economy, and is expected to continue to decrease. In 2040, northern Mediterranean energy demand would be 22%, 10% and 23% lower than 2015 levels, for three stylized energy policy scenarios ("transition" - TS, "reference" - RS, and "proactive" - PS), respectively *(medium confidence). (Section 3.3.3.2).*

3.3.2.2 Southern Mediterranean countries have undergone sustained economic and population growth over recent decades. Energy demand is thus expected to continue increasing and to reach 55% (TS), 118% (RS) and 72% (PS) by 2040 when compared to 2005 *(medium confidence). (Section 3.3.3.2).*

3.3.3 Climate change in the Mediterranean is expected to impact energy production (due to impacts on infrastructure) and energy use (by decreased heating demand and increased cooling needs). *(Section 3.3.2.3).*

3.3.3.1 Losses in power generation are projected due to warming in the region, with only marginal impact if global warming does not exceed 2°C (losses <5%), but rapid deterioration beyond 2°C (losses >5% reaching 10% at specific locations) *(low confidence). (Section 3.3.3.5).*

3.3.3.2 Traditional hydropower and thermoelectric power usable capacity is expected to decline, due to decreased streamflow and increased water temperature, leading to a 2.5 to 7% decrease in hydropower by 2050 and 10 to 15% decrease in thermopower by 2050 (ranges indicate RCP2.6 vs. RCP8.5 estimates vs 1971-2000) *(high confidence). (Section 3.3.3.5).*

3.3.3.3 Weather and climate variability, as well as extreme events, cause significant impacts on the availability and magnitude of renewable energy generation. With the increase of the share of renewable energies, the electricity transmission system will be more exposed to weather variations and may be threatened by specific weather conditions that are usually not considered as extremes *(medium confidence). (Section 3.3.2.3).*

3.3.3.4 With warming, all Mediterranean countries will experience a net increase in energy demand for cooling. The change in average daily peak electric load from 2006-2012 to 2080-2099 under RCP4.5 climate change scenarios is up to 4-6% (Balkans) and 8-10% under RCP8.5 (Balkans, Spain, Portugal) *(high confidence). (Section 3.3.3.6, Fig. 3.50).*

3.3.4 The Mediterranean Basin has significant potential for additional renewable energy production, on land and in the ocean. These include wind, solar, hydro, geothermal and bioenergy as well as energy generation by waves and currents *(high confidence) (Section 3.3.2.2).* There is also potential for high energy efficiency gains *(high confidence). (Section 3.3.3.2).*

3.3.4.1 Thermal energy from biomass (mainly wood residues and waste) currently exceeds use of all other renewable energies, mainly for the production of heat or fuel (less for electricity). Overall production of energy from solid biomass is currently 1.56 PW, varying considerably between countries and mainly concentrated on the northern rim. The production of firewood has increased by about 90% in north Africa over the last 60 years and has recently returned to its 1960's level in southern Europe, after a significant reduction from 1973 to 2009 *(medium confidence). (Section 3.3.2.2).*

3.3.4.2 Although fossil fuels are expected to remain the dominant component of the energy mix until 2040, renewable energies will overtake natural gas and coal and become the second most used energy source in the Mediterranean Basin. In 2040, the share of renewable energies would triple to reach 27% in TS, 13% in the RS and 24% in PS (scenarios "transition" - TS, "reference" - RS, and "proactive" - PS) *(high confidence). (Section 3.3.3.3).*

3.3.4.3 Among the various renewable energy technologies, solar is expected to grow at the fastest pace in both sub-regions. End usage of solar thermal energy, in particular solar water heaters, has high potential in the south and is efficient with a good return on investment *(medium confidence). (Section 3.3.3.3).*

3.3.4.4 The potential for energy efficiency enhancements is substantial in the Mediterranean Basin, particularly in the south *(high confidence).* Overall, energy intensity is decreasing in the region, largely related to shifts in the buildings, industry and transport sector *(high confidence). (Section 3.3.3.2).*

3.3.5 By further improving energy efficiency and deploying renewable energies on a large scale, the entire Mediterranean region can reduce tensions on energy security for importing countries, improve opportunities for exporting ones and reduce energy costs and environmental damage for the whole region. Embarking on an energy transition path will also help improve social welfare in the region and contribute to job creation, among other positive externalities *(medium confidence). (Section 3.3.3).*

3.3.5.1 Given socio-economic development and climate change, an important gap between energy supply and demand is expected, particularly in southern and eastern rim countries. This challenge can be met by rapid restructuring of the energy sector, and particularly further accelerated integration of renewable energies *(medium confidence). (Section 3.3.4.2).*

3.3.5.2 Advantages/measures of the energy transition include: (i) drastic reduction of per capita greenhouse gas emissions, (ii) return on investment in renewable energies, which may lead to savings of up to 54% in energy costs for a given country, and (iii) establishment of a CO_2 emissions trading market which will provide economic incentives for investments in renewable energies *(medium confidence). (Section 3.3.4.2).*

3.3.5.3 Despite electrification rates of almost 100% in southern and eastern rim countries, the energy dynamics of these countries are largely unsustainable in the long term, as a result of a highly subsidized electricity market (with some exceptions, e.g., Turkey) leading to a systemic misallocation of resources, population growth, increasing urbanization and expected socio-economic changes in the region, and global warming *(high confidence). (Section 3.3.4.3).*

3.3.5.4 A change in domestic energy policies, including reforming the energy pricing mechanisms, and/or the introduction of tax and regulatory incentives may be needed in some southern and eastern rim countries to reduce the cost disadvantage of renewable energies compared to fossil fuels *(medium confidence). (Section 3.3.4.2).*

3.3.5.5 Regional energy market integration and cooperation are needed to unleash cost-effective climate change mitigation. *(Section 3.3.4.5).* Cross-border regulations require the convergence of national regulations to allow interconnections to work effectively. Investment regulation requires the design and development of infrastructure that will be needed for promoting international complementarities and technical standards *(high confidence). (Section 3.3.4.5).*

3.3.6 Mediterranean islands experience specific threats, challenges and opportunities in the context of global change and energy transition. Geographical and socio-economic singularities of Mediterranean islands put additional pressure on water and energy, leading to resource depletion and environmental degradation, threatening sustainable development, especially during the high touristic season when population doubles for some *(high confidence). (Box 3.3.2).*

3.3.6.1 On most islands, energy demand is set to increase, due to socio-economic trends including tourism, but also due to expected increase in the use of energy-intensive desalination techniques *(medium confidence). (Box 3.3.2).*

3.3.6.2 Enhancement of hydropower is limited on most Mediterranean islands, but there is important potential for wind power and hydrogen generation *(medium confidence). (Box 3.3.2).*

4 - Ecosystems

4.1 Marine ecosystems

4.1.1 Mediterranean marine ecosystems are unique due to their high number of endemic species, but they are also highly vulnerable to local and global pressures including environmental change. *(Section 4.1.1.1).*

4.1.1.1 The Mediterranean Sea represents the highest proportion of threatened marine habitats in Europe (32%, 15 habitats) with 21% being listed as vulnerable and 11% as endangered. This threat includes several valuable and unique habitats (e.g., seagrasses and coralligenous), supporting an extensive repository of biodiversity. Despite covering only 0.82% of the planet's ocean surface, the Mediterranean Sea hosts 18% of all known marine species *(high confidence). (Section 4.1.1.1).*

4.1.1.2 Over millennial time-scales, productivity in the overall oligotrophic Mediterranean Sea responds rapidly to short and long-term changes in nutrient input, either from rivers, winds or upwelling activity, all of which modify the benthic-pelagic ecosystems by extending into the entire food chain *(high confidence). (Section 4.1.1.2).*

4.1.1.3 Tropical non-indigenous species are spreading into the Mediterranean through current warming trends, causing "tropicalization" of marine fauna and flora *(medium confidence). (Section 4.1.1.1).*

4.1.1.4 Acidification in Mediterranean waters will likely impact the marine trophic chain, from its primary producers (i.e., coccolithophores and foraminifera) to corals and coralline red algae *(medium confidence). (Section 4.1.1.1).*

4.1.1.5 Climate change and direct human activities impact the integrity of marine ecosystems by disturbing plankton ecology, increasing jellyfish outbreaks, reducing fish stocks, and more generally causing changes in physiology, growth, reproduction, recruitment and behavior in marine organisms *(medium confidence). (Section 4.1.1.1).*

4.1.2 The combination of various ongoing climate drivers of environmental change (e.g., sea warming, ocean acidification, and sea level rise) has numerous detectable effects on marine organisms

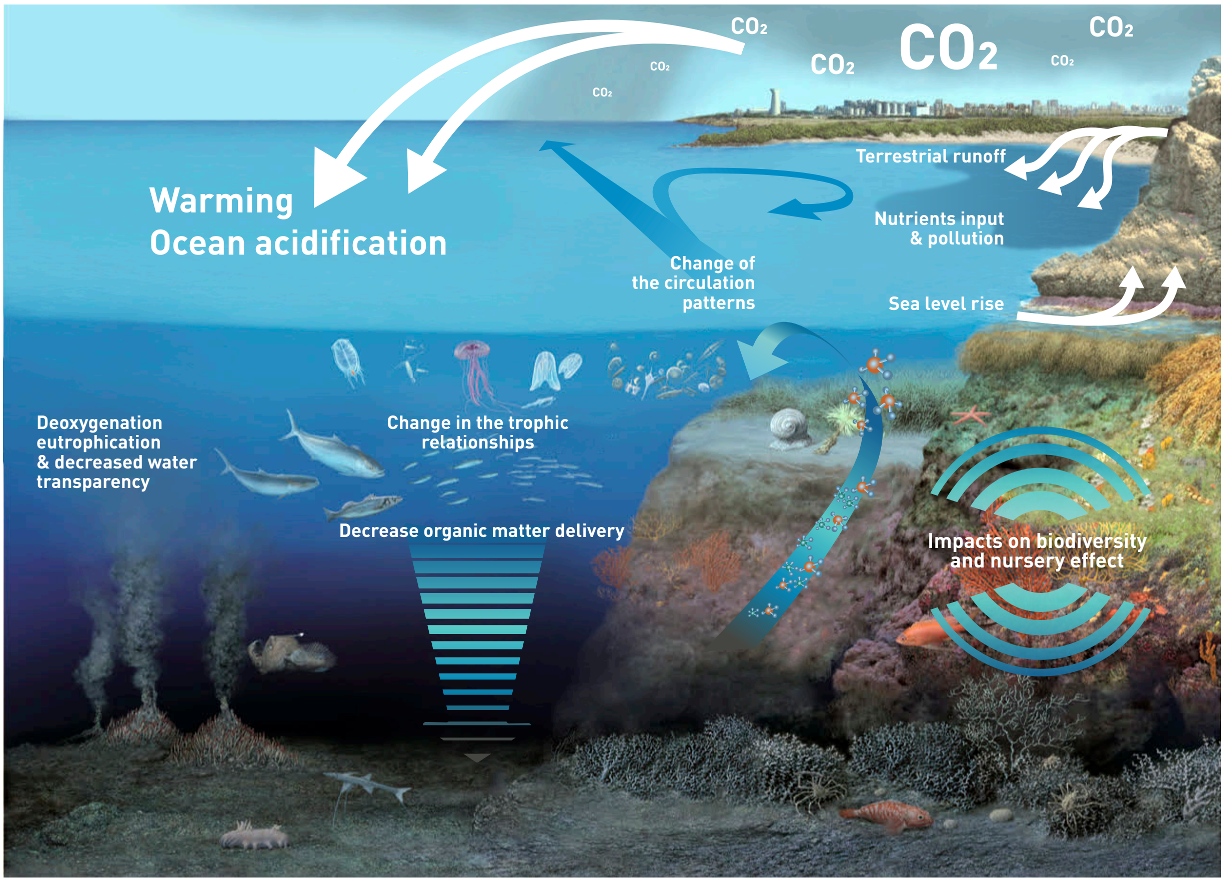

Figure SPM.6 | Climate change drivers potentially affecting marine pelagos and benthos in the Mediterranean Sea.

acting at individual, population, and ecosystem scales. Expected future impacts include major reorganizations of the biota distribution, species loss, decrease in marine productivity, increase in non-indigenous species, and potential species extinctions *(medium confidence) (Fig. SPM.6). (Section 4.1.2.1).*

4.1.2.1 Projections for high emission scenarios show that endemic assemblages will be modified by 2041-2060 and among 75 Mediterranean endemic fish species, 31 will likely extend their geographical range, while 44 will likely reduce it *(medium confidence).*

4.1.2.2 Alterations of natural habitats for commercially valuable species are likely to occur, resulting in many repercussions on marine ecosystem services such as tourism, fisheries, climate regulation, coastal protection, and ultimately on human health *(medium confidence). (Section 4.1.2.2).*

4.1.2.3 In general, small pelagic species, thermophilic and/or exotic species of smaller size and of low trophic levels, could benefit from environmental change. Large-sized species, often with commercial interest may find conditions for survival reduced *(medium confidence). (Section 4.1.2.1).*

4.1.3 Adaptation strategies to reduce environmental change impacts on marine ecosystems need to occur in conjunction with climate mitigation and pollution reduction policies and actions. *(Section 4.1.3.4).*

4.1.3.1 Due to the diversity of marine community responses to climate change and other stressors in different sub-basins, wider monitoring coverage is needed to improve knowledge of the different adaptation processes that characterize and best suit each zone *(high confidence). (Section 4.1.3.1).*

4.1.3.2 All measures that improve marine ecosystem health, resilience or biodiversity have the potential to delay and reduce the adverse effects of climate drivers. These include more sustainable fishing practices, reducing pollution from agricultural activity, sustainable tourism and more effective waste management *(high confidence). (Section 4.1.3.4).*

4.1.3.3 Marine protected areas can provide an "insurance" role for biodiversity if they are placed in locations with limited vulnerability to ocean acidification and climate change *(medium confidence)* *(Section 4.1.3.4)*. While marine protected areas cannot halt climate change and its consequences, such as ocean acidification, they are an important tool for enhancing the resilience and adaptive capacity of ecosystems *(high confidence)*. *(Section 4.1.3.2)*.

4.1.3.4 Developing practical management actions that take into consideration the uniqueness of each species and their responses towards different drivers is crucial to increasing their resilience and plasticity in the context of climate change *(high confidence)*. *(Section 4.1.3.3)*.

4.2 Coastal ecosystems

4.2.1 The coastal zone, i.e. the area in which the interaction between marine systems and the land dominate ecological and resource systems, is a hotspot of risks, especially in the MENA region *(high confidence)*. *(Section 4.2.1.1)*.

4.2.1.1 Alterations of coastal ecosystem regimes (lagoons, deltas, salt marshes, dune systems, etc.) due to climate change and human activities affect the flow of nutrients to the sea, the magnitude, timing and composition of plankton blooms, significantly increase the number and frequency of jellyfish outbreaks, and could have negative impacts on fisheries *(high confidence)*. *(Section 4.2.1.1)*.

4.2.1.2 In addition to hosting a wide diversity of wild faunal and floral species, coastal ecosystems are also often used as aquaculture platforms (i.e., fish, shellfish cultures, etc.), and the pressures on them may have significant consequences on their usages *(medium confidence)*. *(Section 4.2.1.1)*.

4.2.1.3 Seagrass meadows in the Mediterranean Sea cover 1.35 to 5 million hectares, between 5 and 17% of the worldwide seagrass habitat. The current loss rate of seagrass is approx. 5% in the Mediterranean. Even in the remaining Posidonia meadows, almost half of the surveyed sites have suffered net density losses of over 20% in 10 years *(medium confidence)*. *(Section 4.2.1.1)*.

4.2.1.4 The rapid spread of non-indigenous fish species represents a serious problem for trophic networks and fisheries in coastal areas, due to the local extinction of species that are preys of these generalist fish *(high confidence)*. *(Section 4.2.1.1)*.

4.2.2 In the future, environmental change, particularly warming, decreasing nutrient replenishment, and ocean acidification, are expected to cause changes in plankton communities at different levels, from phenology and biomass to community structure *(medium confidence)* *(Section 4.2.2.1)*. Negative impacts are also expected to affect fish, corals and seagrass meadows, while non-indigenous species are expected to be favored *(medium confidence)*. *(Section 4.2.2.1)*.

4.2.2.1 Sea level rise impacts coastal wetlands and estuaries, while reduced precipitation and prolonged droughts will reduce the water discharge and sediments flow of Mediterranean rivers and catchments. Mobile coastlines are likely to retreat or disappear because of the effects of erosion due to the accelerated rise in sea level, with the most severe impacts affecting the least mobile species *(medium confidence)*. *(Section 4.2.1.1* and *4.2.2.2*).

4.2.2.2 Mediterranean coasts are expected to suffer further severe disturbance due to intensive urbanization and other land uses, which could worsen as land availability decreases and population growth continues. In the future, coastal storms and floods, probably more frequent and intense, will have adverse impacts on ecological balances, as well as human health and well-being, particularly in Mediterranean coastal cities *(medium confidence)*. *(Section 4.2.2.3)*.

4.2.3 Developing more integrated approaches would support adaptation policies for the entire Mediterranean, involving ecosystem-based management of coastal areas, identifying synergies and conflicts, as well as integrating local knowledge and institutions. *(Section 4.2.3.6)*.

4.2.3.1 Suitable adaptation policies include (i) reducing pollution from runoff, both from agriculture, industry and waste management, (ii) defining policies to limit or prevent acidification and (iii) moving aquaculture operations to areas protected from critical acidification levels *(high confidence). (Section 4.2.3.1).*

4.2.3.2 Early Detection and Rapid Response has been recognized as a key aspect for non-indigenous species management. Efficient public awareness campaigns disseminating information to local communities may help to quickly detect unwanted non-indigenous species, together with formalized early warning systems (*medium confidence). (Section 4.2.3.3).*

4.3 Terrestrial ecosystems

4.3.1 Terrestrial biodiversity changes in the Mediterranean Basin over the past 40 years have occurred more quickly and extensively than in most other regions in the world. Urbanization and the loss of grasslands are key factors in ecosystem degradation across the region. Since 1990, agricultural abandonment has led to a general increase in forested area of 0.67% yr^{-1} across the basin, with significant variations between northern and southern shores of the Mediterranean. *(Section 4.3.1.2).*

4.3.1.1 Since about 1980, biodiversity changes have occurred more quickly and extensively in different Mediterranean species groups and habitats than before. Species loss is marked by a general trend of homogenization (loss of vulnerable and rare species) recorded in several species groups, and also by a general simplification of biotic interactions (loss of specialized relationships) *(high confidence) (Section 4.3.1.2).*

4.3.1.2 In all Mediterranean mountain regions, subalpine species move to higher altitudes wherever this is possible *(medium confidence). (Section 4.3.1.2).*

4.3.1.3 Almost all countries in the northern sub-region have undergone increase in forest area due to the decline of extensive agriculture and agro-pastoral systems, with rates around 1% yr^{-1} in Italy, France and Spain. In the southernmost areas, semi-natural ecosystems are more at risk of fragmentation or disappearance due to human pressure from clearing and cultivation, overexploitation of firewood and overgrazing *(high confidence). (Section 4.3.1.2).*

4.3.1.4 Agro-system biodiversity has declined dramatically since the early 1950s due to the intensification of agriculture, leading to an increase of highly modified agroecosystems and simplified agricultural landscapes *(high confidence).* Traditional and extensive agricultural practices, including agro-ecological methods, generally help maintain high biodiversity levels *(medium confidence). (Section 4.3.1.2).*

4.3.1.5 Over the last five decades, agricultural production has increasingly been impacted by loss of pollinators, with an increase by a factor of three in the number of crops requiring the intervention of pollinators *(medium confidence). (Section 4.3.1.2).*

4.3.1.6 Mediterranean drylands have a significant and specific biodiversity value, with most plants and animals highly adapted to water-limited conditions. *(Section 4.3.1.2).* European Mediterranean drylands are undergoing an overall increase in the percent of arid area in response to climate change and extensive land abandonment. Almost 15% of the humid Mediterranean domain has been replaced by more arid area since the 60s, while arid area has remained stable *(medium confidence). (Section 4.3.1.2).*

4.3.1.7 Freshwater ecosystems offer many important ecosystem services (e.g., water supply for drinking, agriculture and industries, water purification, erosion control, recreation, tourism and flood mitigation) (*Section 4.3.1.2*: freshwater ecosystems). 48% of Mediterranean wetlands were lost between 1970 and 2013, with 36% of wetland-dependent animals in the Mediterranean threatened by extinction *(high confidence). (Section 4.3.1.2).*

4.3.2 Drier climate and increased human pressure are expected to cause significant impacts on terrestrial biodiversity, forest productivity, burnt area, freshwater ecosystems and agro-systems during the 21st century *(medium confidence). (Section 4.3.2).*

4.3.2.1 All factors considered, a general reduction of forest productivity in the medium- and long-term is likely associated with higher mortality and dieback, particularly for species or populations growing in water-limited environments,

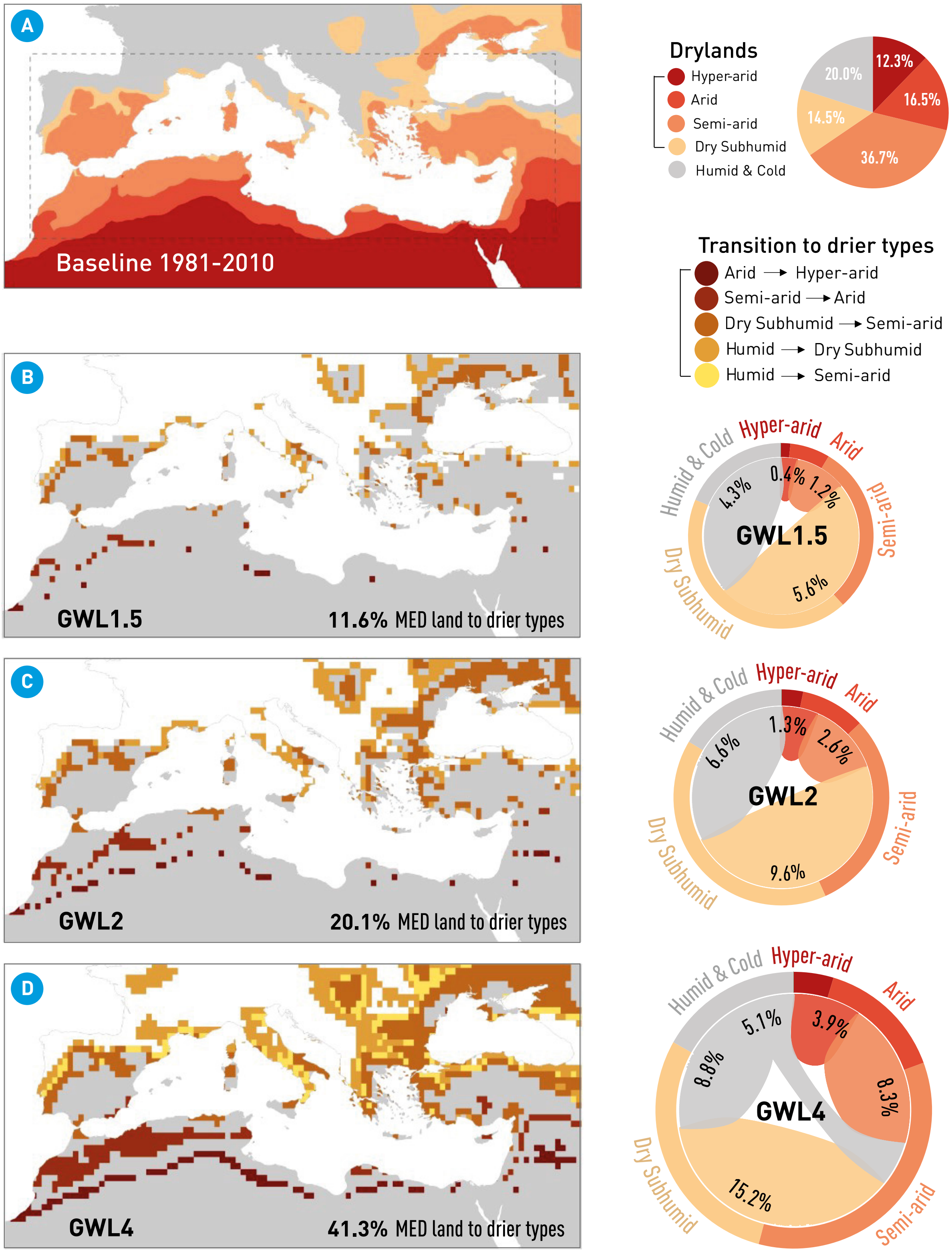

Figure SPM.7 | Distribution of drylands and their subtypes based on observations for the 1981-2010 period. Areal cover of drylands per subtype is estimated within the boundaries of the Mediterranean SREX region (dashed line). (B, C, D) Distribution of projected dryland transitions for three Global Warming Levels (GWLs: +1.5°C, +2°C and +4°C above preindustrial levels), relative to the baseline period. Grey shaded areas in (B), (C) and (D) are drylands of the baseline period. Chord diagrams denote the areal extent of projected transitions in each dryland subtype for each GWL (proportional to the total extent of land changing to drier types) *(see Section 4.3.2.4, Fig. 4.15)* which constitute the majority of Mediterranean forests *(medium confidence). (Section 4.3.2.1).*

4.3.2.2 An increase in wildfires, and hence burnt area is projected in Mediterranean Europe under most global warming scenarios. Burnt area could increase across the region by up to 40% for 1.5°C warming and up to 100% from current levels for 3°C warming at the end of the 21st century *(high confidence). (Section 4.3.2.1).*

4.3.2.3 Most Mediterranean drylands will likely become drier and their extent is expected to increase across the region. Global warming projections of 1.5°C, 2°C and 4°C above pre-industrial levels correspond to 12%, 20% and 41% increases in dryland area respectively *(medium confidence) (Fig. SPM.7). (Section 4.3.2.3).*

4.3.2.4 For freshwater systems, projections suggest decreased hydrological connectivity, increased concentration of pollutants during droughts, changes in biological communities as a result of harsher environmental conditions, and a decrease in biological processes like nutrient uptake, primary production, or decomposition. Increased pressure by users on the shrinking water resources will likely aggravate impacts on river ecosystems *(medium confidence). (Section 4.3.2.5).*

4.3.3 For most ecosystems, management options exist that can enhance resilience under environmental change. *(Section 4.3.3).*

4.3.3.1 Promotion of "climate-wise connectivity" through permeability of landscapes, conservation or creation of dispersal corridors and habitat networks may all facilitate the upward migration of lowland species to mountains in order to adapt to new climate change conditions *(medium confidence). (Section 4.3.3.2).*

4.3.3.2 Promotion of more adequate forest management taking into account local conditions and future projections can improve the adaptation of Mediterranean forests to warmer climates (e.g., mixed-species forest stands, thinning, management of understory). The management of spatial heterogeneity in landscapes can help reduce fire extent under climate warming *(low confidence). (Section 4.3.3.1).*

4.3.3.3 Preserving the natural flow variability of Mediterranean rivers and streams and wide riparian zones, along with reductions in water demand may assist adaptation of freshwater ecosystems to future environmental change *(medium confidence). (Section 4.3.3.5).*

5 - Society

5.1 Development

5.1.1 For this report, sustainable development seeks to address the needs of current and future generations, utilizing natural resources in ways that preserve and sustain them, and ensure equitable access to them in the present and the future. If losses in well-being are to be avoided for future generations, sustainability strategies will need to improve well-being and environmental sustainability at the same time. *(Section 5.1.1.1).*

5.1.2 Due to the growing impact of climate change on population, institutional response is increasingly needed, at a local, national and international level. This means mitigating, adapting and regulating the action of business and other multinational enterprises, and taking into account human rights issues. *(Section 5.1.1.2).*

5.1.2.1 Climate-proofing infrastructure across the entire Mediterranean region is necessary to withstand present and future climate change impacts in the coming decades. Investments in research and development greatly reduce the costs of adaptation *(high confidence). (Section 5.1.1.3).*

5.1.2.2 The Mediterranean has a rich history as well as exceptional natural and cultural landscapes, which attracted more than 360 million tourists in 2017. In the past 20 years, the gross domestic product contribution from the tourism sector has steadily increased by 60% in Mediterranean countries. Climate change will likely impact the thermal comfort of tourists during the main season. Sea-level rise will likely affect beaches and cultural heritage sites *(high confidence) (Section 5.1.1.3).*

5.1.2.3 A significant part of Mediterranean tourism is oriented towards outdoor activities, which if unmitigated, are at risk of further degrading natural resources, including freshwater availability *(high confidence). (Section 5.1.1.3).*

5.1.2.4 Mediterranean tourism has a major role for employment throughout the region, and has the potential to become more resilient to climate change than the overall economy. Sustainable tourism can secure significant employment and help offset the negative economic impact of climate change *(medium confidence). (Section 5.1.1.3).*

5.1.3 Poverty, inequalities and gender imbalances relate both directly and indirectly to the achievement of sustainable development in Mediterranean countries. The presence of these imbalances, both relative and absolute, hampers economic development, de facto blocking parts of society from the benefits of higher standards of living *(Section 5.1.1.3).*

5.1.3.1 The loss to human development due to inequality over the past few years (2010 to 2017) is consistently more significant in southern Mediterranean countries than northern Mediterranean countries *(high confidence). (Section 5.1.1.3; Box 5.1.1).*

5.1.3.2 Gender inequalities are significant in Mediterranean countries, ranked between the 18th position and the 159th (out of 164) in the global ranking of the Gender Development Index *(high confidence). (Section 5.1.1.3; Box 5.1.2).*

5.1.3.3 Climate change education means active participation of the community, especially children and youth as agents of change and enhanced collaboration between education policymakers and researchers to set the basis of educational policy and actions in scientific knowledge and expertise *(medium confidence). (Section 5.1.1.4).*

5.1.4 The expected increasingly extreme climate conditions and pollution of the Mediterranean Basin are likely to result in economic vulnerabilities and risks of higher intensity than in other European regions. *(Section 5.1.2).*

5.1.4.1 Higher intensity and more recurrent flash-floods with higher mortality in the eastern Mediterranean directly affect agriculture, commerce, tourism and industry *(medium confidence). (Section 5.1.2).*

5.1.4.2 The effect of sea level rise, together with changes in storm features is likely to seriously affect port operations, slowing down trade operations and productivity levels *(medium confidence). (Section 5.1.2).*

5.1.4.3 The economic impact on tourism depends on the country and the season. Some adaptation to warming can be achieved by spreading out tourism offers to the spring and autumn. Northern Mediterranean regions could experience climate-induced tourism revenue decreases of up to -0.45% of gross domestic product per year by 2100 *(medium confidence). (Section 5.1.2).*

5.1.4.4 Economic costs due to droughts (e.g., on food security) may exceed those caused by earthquakes or floods *(low confidence). (Section 5.1.1.3).*

5.1.5 The success of adaptation strategies will involve consideration of the specific regional climate conditions, in sectoral, political and socio-economic contexts by ensuring dialogue between stakeholders, through cooperative structures, knowledge transfer and monitoring progress to support regular reviews of policy objectives and the inclusion of new scientific information when it becomes available. *(Section 5.1.3).*

5.1.5.1 The variants of sustainable urban growth represented by sustainable cities, resilient cities, green cities or low carbon cities bring opportunities to create pathways for transformative and sustainable urban development *(high confidence). (Section 5.1.3.1).*

5.1.5.2 Stronger pollution and greenhouse gas emissions control instruments can be deployed. Institutional approaches may facilitate internalization of externalities. Command and control instruments may have an action on production inputs, emission outputs, location or production techniques. Economic incentive (market-based) instruments include taxes, liability payments, emission permits, subsidies etc. *(Section 5.1.3.2, Table 5.3).*

5.2 Human health

5.2.1 Environmental change has already led to a wide range of impacts on human health in Mediterranean countries, and most trends are likely to continue. *(Section 5.2.1.1).*

5.2.1.1 Direct impacts are related to exposure to extreme events as heat waves and cold spells, floods and storms. Interaction with environmental systems leads to indirect impacts such as changes in water availability and quality, in food availability and quality, rising air pollution including pollution from forest fires, and changing patterns of vector-, food- and water-borne diseases *(high confidence). (Section 5.2.1.1).*

5.2.1.2 Population vulnerability to the impacts of environmental and climate change is strongly influenced by population density, level of economic development, food availability, income level and distribution, local environmental conditions, pre-existing health status, and the quality and availability of public health care *(high confidence). (Section 5.2.2).*

5.2.1.3 Vulnerable Mediterranean populations include the elderly, the poor, and people with pre-existing or chronic medical conditions, displaced people, pregnant women and babies. People who are disadvantaged due to a lack of shelter, clean water, energy or food are more at risk from extreme events *(high confidence). (Section 5.2.2).*

5.2.2 Heat waves are responsible for high mortality rates causing tens of thousands of premature deaths, especially in large cities and among the elderly. Heat-related morbidity and mortality has been partially reduced in recent years by more efficient protection of people *(high confidence) (Fig. SPM.8). (Section 5.2.3.1).*

5.2.2.1 Most Mediterranean cities are compact and densely populated and have experienced

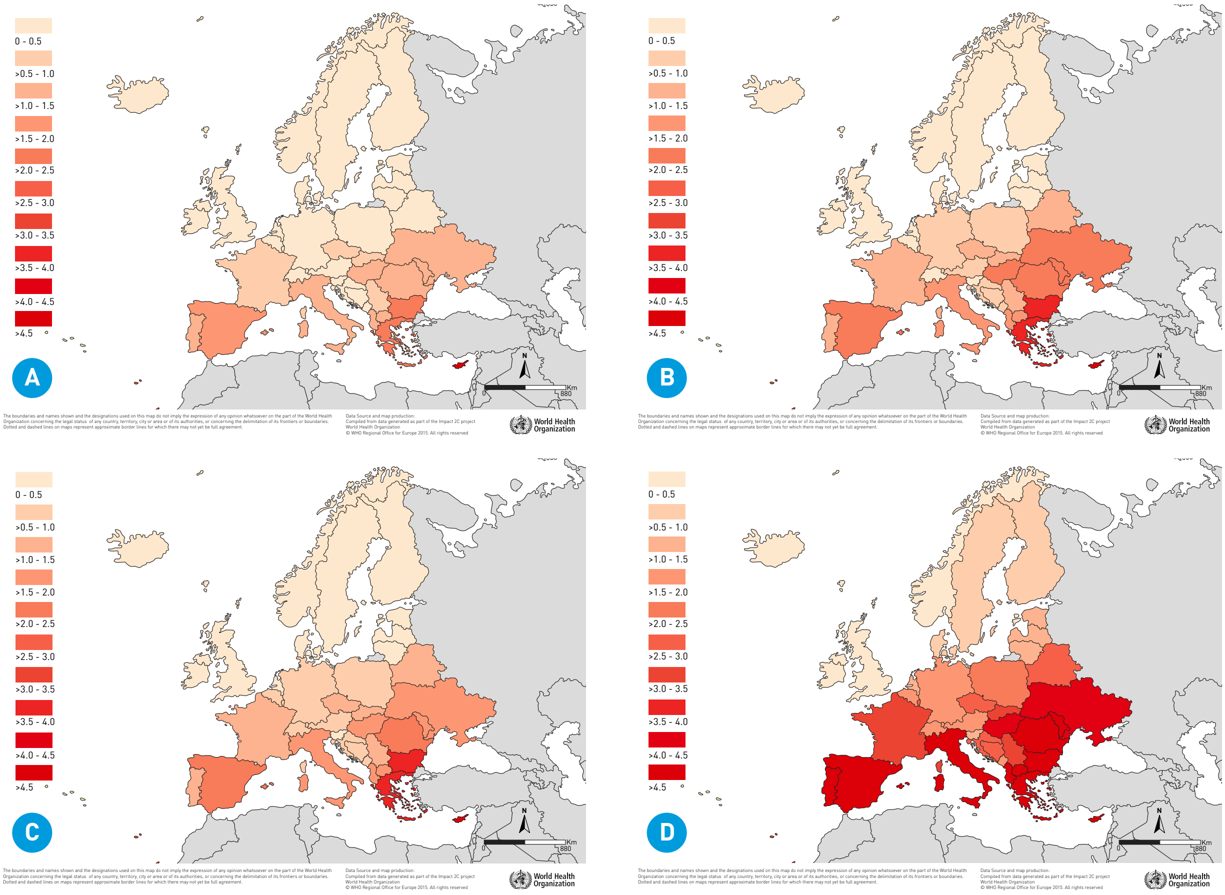

Figure SPM.8 | Attributable fraction of heat-related deaths during summer with different climate scenarios by country in Europe. A) RCP4.5 in 2050; B) RCP8.5 in 2050, C) RCP4.5 in 2085 and D) RCP8.5 in 2085 (Kendrovski et al., 2017).

strong impacts from extremely high temperatures on their population *(medium confidence). (Section 5.2.3.1).*

5.2.2.2 In recent decades, mortality rates due to heat stress have been reduced through national plans and alert systems that have raised risk awareness and avoidance among the population *(high confidence). (Section 5.2.3.1).*

5.2.2.3 The European population at risk for heat stress is expected to increase (4% annually) in the coming years and could increase to 20 to 48% by 2050, depending on different combinations of socio-economic scenarios. Vulnerability varies between regions and the Mediterranean region will be among the most affected. Annual mortality attributable to heat in Mediterranean Europe will increase by a factor of 1.8 and 2.6 for moderate (RCP4.5) or high (RCP8.5) global warming levels, respectively, by the middle of the 21st century, while by the end of the century the increase will be by a factor of 3 and 7 respectively *(high confidence). (Section 5.2.5.2).*

5.2.2.4 The impact of heat on mortality will be more influenced by socio-economic factors due the impacts on vulnerability than by the exposure to high temperatures *(medium confidence). (Section 5.2.5.2).*

5.2.3 Despite the rise in mean temperature, cold waves are not likely to disappear *(high confidence).* Moderate cold-related risk will remain a temperature-related risk throughout the 21st century, in combination with risks due to pathogenic agents *(low confidence).* (*Section 5.2.5.3* and *5.2.3.4*).

5.2.4 Environmental changes in the Mediterranean Basin will likely exacerbate risks for vector-borne disease outbreaks in the Mediterranean region, since warmer climate and changing rainfall patterns (together with landscape management) may create hospitable environments for mosquitoes, ticks, and other climate-sensitive vectors, particularly for the West Nile Virus, Chikungunya and Leishmaniasis *(medium confidence). (Section 5.2.3.3).*

5.2.4.1 Projections for 2025 show an elevated risk for vector-borne diseases in the Mediterranean. By 2050, the West Nile Virus high-risk areas are expected to expand further and the transmission seasons will extend significantly *(medium confidence). (Section 5.2.5.4).*

5.2.4.2 Future changes in the habitability of the Mediterranean Basin for vector-based disease vectors and pathogens vary geographically and will significantly modify the extent and transmission patterns in the area. A significant reduction of habitat suitability for the tiger mosquito Aedes albopictus (vector for chikungunya and dengue) is projected for the middle of the 21st century in southern Europe and the Mediterranean related to significant increase in summer temperatures *(high confidence). (Section 5.2.5.4).*

5.2.4.3 With rising average temperatures and increasing frequency and length of heat waves, a rising number of cases of food-borne illness must be expected for business-as-usual scenarios, unless education, epidemiological surveillance and enforcement (related to food safety) are intensified *(high confidence). (Section 5.2.5.4).*

5.2.5 Every year, around one million fatalities are attributed to outdoor and indoor air pollution in the European and eastern Mediterranean regions. *(Section 5.2.4.1).*

5.2.5.1 Synergistic impacts are observed between ozone levels, particulate matter concentrations and climate, especially during heat wave days, with high temporal and spatial variability with a 1.66% increase in mortality for each 1°C temperature increase on low ozone level days and an increase of up to 2.1% on days with high ozone levels. Reducing the exposure to particulate matter improves the life expectancy of Europeans by about 8 months *(high confidence). (Section 5.2.4.1).*

5.2.5.2 Exposure to forest fire smoke and pollutants of natural origin, such as Saharan dust, is related to increased mortality, respiratory and cardiovascular diseases with variable impacts depending on age *(medium confidence). (Section 5.2.4.2).*

5.2.5.3 Ozone-related morbidity and mortality is expected to increase by 10-14% from 2021 to 2050 in several Mediterranean countries. The combined influence of O_3 and PM2.5 (particulate matter with a diameter of less than 2.5 μm) will increase European mortality by 8-11% in 2050 and by 15-16% in 2080 compared to the year 2000 *(medium confidence). (Section 5.2.5.5).*

5.2.6 Climate change and extreme events have a negative impact on mental health for people who experience loss of homes, destruction of settlements and damage to community infrastructure *(medium confidence) (Section 5.2.4.3).* Displacement may lead to adverse health outcomes, especially for vulnerable population groups as well as those who suffer from chronic diseases *(medium confidence). (Section 5.2.4.4).*

5.2.7 Prevention plans related to human health should be developed further by specifically considering climate change risks. Most mitigation and adaptation measures for climate change offer synergies with other public health issues, notably air pollution. Mediterranean countries need to enhance cross-border collaboration, as adaptation to many of the health risks (e.g., vector-borne diseases, droughts, migration) requires collaboration across borders and also across the different parts of the basin *(low confidence). (Section 5.2.6.2).*

5.3 Human security

5.3.1 Human security is a condition that exists when the vital core of human lives is protected, and where people have the freedom and capacity to live with dignity *(medium confidence). (Section 5.3.1.1).*

5.3.1.1 Environmental and climate change constitutes a threat to the enjoyment of economic, social and cultural rights, acting as a risk multiplier and a key crosscutting issue for multiple aspects of human rights and international justice. *(Section 5.3.2.2).*

5.3.1.2 There is a substantial divide between Mediterranean countries when it comes to individual circumstances and the specific impacts of environmental change on security, which depend on climate but also geographical, social, cultural, economic and political conditions. *(Section 5.3.1.1).*

5.3.2 Recent human migration (mostly within southern and eastern countries of the Mediterranean Basin but also between the South and the North) can partially be attributed to environmental change, but other drivers such as economic and political factors are usually more important. While slow-onset environmental and climate-related events have significantly affected human well-being in some areas, adaptation is usually possible for reducing the need for human migration. In contrast, fast-onset events with associated environmental degradation (such as storms and floods) have likely led to migration, mostly temporary and over short-distances *(medium confidence). (Section 5.3.2.3).*

5.3.3 Climate fluctuations have likely played a role in the decline or collapse of ancient civilizations, probably involving situations of increased violent conflicts. For the contemporary period, several studies indicate a link between armed conflict and environmental change, but other scholars disagree *(low confidence). (Section 5.3.2.4; Box 5.3.1)*

5.3.3.1 Negative weather shocks such as dry spells occurring during the crop growing season by reducing agricultural production and income may increase the continuation and intensity rather than the outbreak of civil conflicts, especially in regions with agriculturally-dependent and politically excluded groups. Several recent studies identify a link between higher food prices caused by climate change and urban social unrest in Africa. Rising food prices are considered to have played a significant role in the Arab Spring unrest across North Africa and the Middle East in 2011, although such forms of violence are mostly triggered by a complex set of political and economic factors rather than only by higher food prices caused by climatic change *(low confidence). (Section 5.3.2.4).*

5.3.3.2 For conflict, the impact of expected future environmental change remains rather speculative. However, recent historical experience makes it likely that severe and rapid climate change could further exacerbate political instability in the poorest parts of the Mediterranean Basin *(medium confidence). (Section 5.3.3.2).*

5.3.3.3 Knowledge is limited regarding how natural disasters interact with and/or are conditioned by socio-economic, political, and demographic contexts to cause conflict. Future research remains necessary. *(Section 5.3.5).*

5.3.4 Parts of the rich Mediterranean cultural heritage, notably many UNESCO World Heritage Sites, are directly threatened by sea-level rise or other aspects of environmental change. There is an urgent need for mitigation and adaptation as a large number of world heritage sites are already at risk today. By 2100, flood risk may increase by 50% and erosion risk by 13% across the Mediterranean region *(high confidence). (Section 5.3.3.1).*

5.3.5 Culture is a key factor to the success of environmental change adaptation policies in the highly diverse multicultural setting of the Mediterranean Basin. Climate adaptation policies have the potential to infringe on human rights in the Mediterranean region if they are disconnected from concerns such as justice, equity, poverty alleviation, social inclusion, and income redistribution *(high confidence). (Section 5.3.4.1).*

6 - Managing future risks and building socio-ecological resilience in the Mediterranean

6.1 Although national governments have an important role to play in reducing the burden of climate change on human health, it is at the local scale that most actions and measures are taken. These measures include (but are not limited to) the improvement of housing and infrastructure, the education and awareness-raising of the most vulnerable communities, the implementation of early warning systems, the strengthening of local emergency and healthcare services, and the general improvement of the adaptive capacity of the community and local institutions *(high confidence). (Section 6.2.2).*

6.2 Sustainable water security measures require integrated approaches which include water saving technologies, such as new equipment in irrigation agriculture and households, often complemented by improved water efficiency, multi-scale storages, use of unconventional water sources stemming from recharging wastewater or sea water desalinization. Some of these measures may cause environmental impacts due to soil contamination, energy consumption or coastal ecosystem degradation *(high confidence). (Section 6.3.3).*

6.3 Adaptation of Mediterranean agriculture to water scarcity will benefit from more sustainable approaches. Many studies on no tillage and agroforestry in the Mediterranean show that these practices may have positive effects on the soil by keeping more water, therefore enhancing yields, especially in water-stressed years *(Section 6.4.3).* These strategies also have benefits for climate mitigation, since conservation agriculture emits less greenhouse gases and enhances soil carbon sequestration and storage *(medium confidence). (Section 6.4.2).*

6.4 Anticipated changes in fire regimes can have significant impacts on natural and social systems. These impacts can be exacerbated by some of the current fire suppression policies, such as deployment of prescribed fire over large tracts of land *(Section 6.5.3).* Transformative changes in fire management practices in the Mediterranean countries are necessary for reducing risk and vulnerability and increasing natural and societal resilience, e.g., development of socio-economic sustainable activities that ensure low overall landscape risk *(medium confidence). (Section 6.5.4).*

6.5 Land Degradation Neutrality is a conceptual framework to halt the loss of land due to unsustainable management and land use changes. Its purpose is to maintain the land resource base so that it can continue to supply ecosystem services while enhancing the resilience of the communities that depend on the land. This concept, endorsed by the UNCCD Parties and the sustainable development goals (SDG), just starts to be applied, but could beneficially be extended to further Mediterranean areas *(low confidence). (Section 6.6.4).*

6.6 Interconnections between hazards may result in consecutive and compound events that can lead to non-linear increases in the magnitude of individual events, thus challenging the resilience of populations living in floodplains. Good practices in flood management include development of dedicated early warning systems, construction of check dams, improvement of drainage systems in urbanized areas, emergency management plans in addition to urban planning for resilience and strategic retreat and nature-based solutions, such as reforestation in upstream areas, floodplain restoration and bank erosion protection, and adequate agricultural practices for retaining water *(medium confidence). (Section 6.8.2).*

6.7 Sea-level rise will lead to increases in coastal-flood and erosion risk along the entire Mediterranean coast. Proactive adaptation to these hazards is essential for maintaining the functions of coastal zones. Coastal adaptation practices can be classified in the following broad categories: Protect, accommodate, advance, and retreat. Nature-based protection solutions, i.e. beach and shore nourishment as well as dune or wetland restoration, is becoming a more common alternative to hard structures. Flood fatalities are reduced as societies are learning to live with flood hazards *(medium confidence). (Section 6.9.2).*

6.8 Tourism and recreation, red coral extraction, and fisheries (both capture and aquaculture production) are the sectors that are most vulnerable to sea acidification *(Section 6.11.1)*. Recruitment and seed production present possible bottlenecks for shellfish aquaculture in the future since early life stages are vulnerable to acidification and warming *(Section 6.11.1)*. As an example, seagrasses may provide "refugia" from ocean acidification for associated calcifying organisms, as their photosynthetic activity may raise pH above the thresholds for impacts on calcification and/or limit the time spent below some critical pH thresholds *(medium confidence). (Section 6.11.4).*

6.9 Although the level of non-indigenous species arrivals will likely remain high in northern countries in the coming decades, their presence will likely increase substantially in southern and eastern countries where biodiversity may be high but capacity to manage non-indigenous species is low. In such places, unmanaged non-indigenous species may threaten human livelihoods *(Section 6.12.1)*. Only few non-native species succeed in establishing in their new locations and gaining importance, but those that do can result in billions of dollars in costs *(medium confidence). (Section 6.12.2).*

6.10 Only few Mediterranean cities have local climate plans that consider mitigation and adaptation in a joint manner. There is an urgent need for more integrated local climate plans. Cities, in particular, need to become more resilient to environmental change as impacts will be disproportionally high in these locations due to a concentration of population and assets in combination with hazard-amplifying conditions (e.g., increased runoff through soil sealing, urban heat island effect). This requires knowledge exchange and promotion of ambitious action against climate and environmental change and new approaches to urban development *(medium confidence). (Section 6.13).*

1

INTRODUCTION

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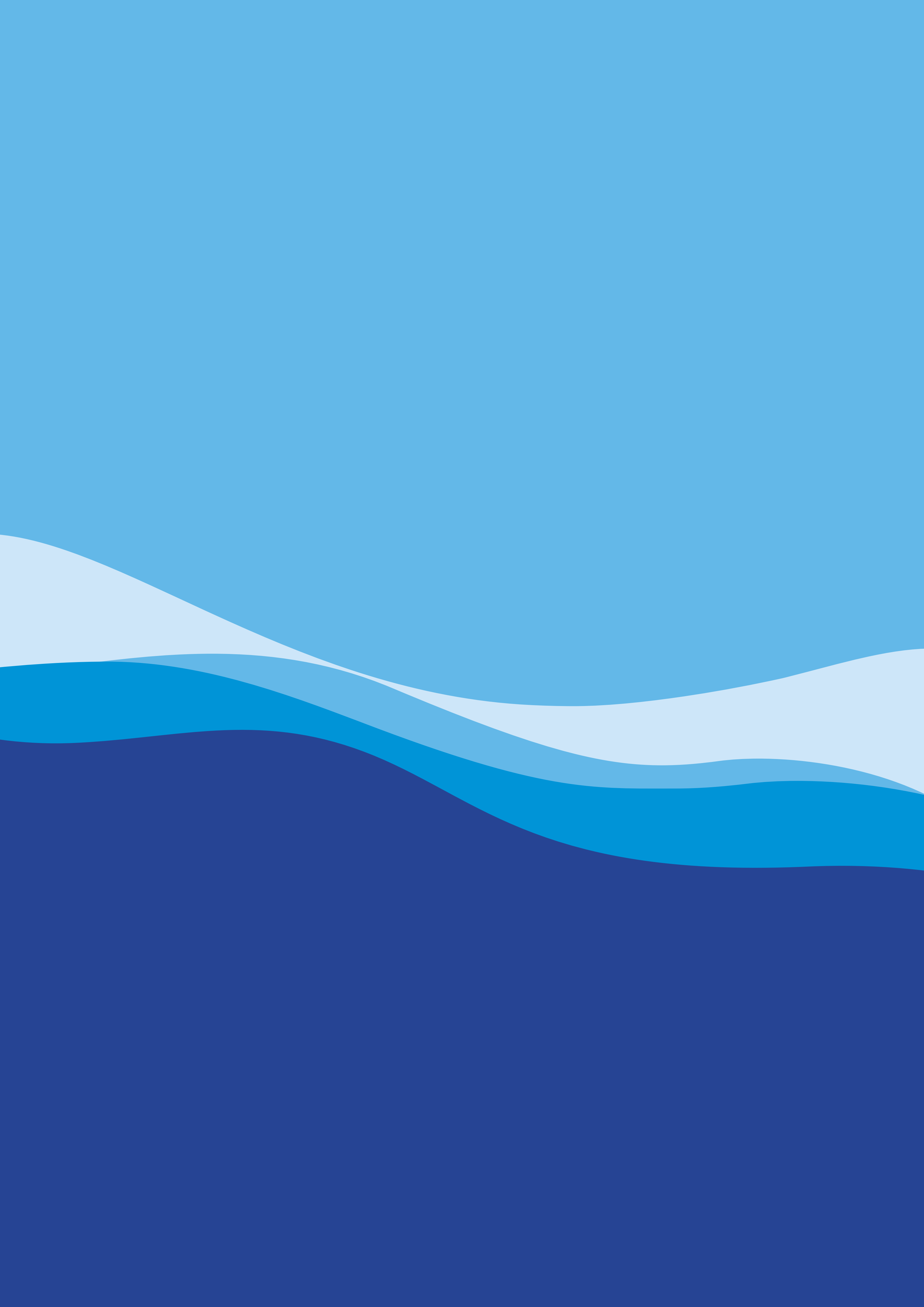
This chapter should be cited as: Lange MA, Llasat MC, Snoussi M, Graves A, Le Tellier J, Queralt A, Vagliasindi GM 2020 Introduction. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 41-58, doi:10.5281/zenodo.7100592.*



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1.1 The Mediterranean Basin: a region affected by accelerating climate and environmental change

1.1.1 What do we know about the Mediterranean Basin and what do we need to know?

The Mediterranean Basin is considered one of the cradles of civilization (Abulafia 2011; Sağlamer 2020). Its rich cultural and scientific heritage dates back to the Egyptian and Mesopotamian empires, followed by the remarkable accomplishments of Greek thinkers and philosophers and the no less ingenious scientists, engineers and architects of the Roman Empire. Throughout the history of the last several millennia, people, communities and societies have learned to adapt to and master environmental conditions that have often been adverse, and which frequently caused severe damage to human lives and environmental integrity. But it has not only been their ability to adapt to changes in natural conditions that has protected Mediterranean societies from severe impacts. As time has gone on, there has been a steadily growing body of knowledge and understanding of the underlying causes and the usual course of such changes, based on careful and long-term observations and analysis. It is no surprise then that we now know a lot about the changes and variations in environmental conditions that we observe today. But neither the level of observation nor the level of knowledge is the same, whether for the entire region, or for all environmental issues, or for their integration with the socio-economic system. Added to this lack of homogeneity is the complexity of the region, both in terms of climate and environment, and culture and socio-economics (Zamora Acosta and Maya Álvarez 1998; Woodward 2009; IEMed 2015).

During the second half of the 20th century and up to the present day, numerous scientific projects have studied the changing environment of the Mediterranean Basin and its adjacent regions (for a compilation of such research activities, see *Appendix A.4.1*). The capacity for systematic observation of the environment has increased substantially, followed by the development of conceptual and numerical models of the changing atmosphere and ocean, as well as of other environmental changes and their impacts. Through the work done by large numbers of scientists, we have gained not only a more complete understanding of past changes but have also learned to generate projections of future climate and environmental change with increasing confidence in the reliability of the results. Projections of such changes into the future are key for the mitigation of risks to human livelihoods (Bolle 2003; Lionello 2012; Navarra and Tubiana 2013; Luterbacher et al. 2016).

As a first assessment, based on various sources of information, Cramer et al. (2018) have shown that the Mediterranean Basin is at risk of suffering from levels and rates of climate and environmental changes now and in the foreseeable future that exceed global mean values. This applies to changes in temperatures, precipitation and the frequency and magnitude of extreme weather events, but it also implies changes in land and sea use, pollution, air quality and other factors. Average annual mean temperatures in the Mediterranean Basin have risen by 1.5°C since pre-industrial times (1861-1890), approx. 0.4°C above the global average *(Chapter 2)*, due to a combination of local drivers (e.g., land use changes) and changes on a global scale that affect the Mediterranean Basin through various modes of tele-connectivity (Lionello et al. 2014).

Although droughts have been a common experience for most of the history of the Mediterranean, the recently observed decline of seasonal precipitation for parts of the Basin *(Chapter 2)* presents new and significant challenges for Mediterranean communities. While most climate models show remarkable agreement in the expected decrease in Mediterranean rainfall, there are also some results indicating significant differences in magnitude and sign for these changes. Even if future global warming is limited to 2°C, as prescribed by the UNFCCC Paris Agreement, summer rainfall risks being reduced by 10-30% in some regions. Such a decrease will enhance existing water shortages and increase irrigation demand for agricultural productivity, particularly in countries on the southern rim of the Basin (Vautard et al. 2014). Climate change, population growth, increasing domestic needs and pressure from tourism, new industries and urban sprawl may see irrigation demand rise by 26-92% by the end of the 21st century (Fader et al. 2016). Although frequently addressed by policymakers, irrigation and food security remain a sensitive issue that needs additional research (Grafton et al. 2018; WWAP 2019). Research into the extent to which local landraces can cope with projected climate changes without significant loss of productivity should be a priority (FAO 2015). More aridity exacerbates ongoing desertification, with strong socio-economic impacts on farmers (UNEP/MAP 2016). The interlinkages between resources have been addressed through the concept of the Water-Energy-Food Nexus (e.g., Hoff 2011; Kennou et al. 2019), but they still present unresolved challenges. Since the impacts of climate change are likely to include the degradation of agricultural water resources and loss of fertile soils, enhanced efforts to adapt agricultural and other land systems to climate change are necessary to ensure food security and rural livelihoods (UNEP/MAP 2016). Despite this reduction, extreme precipitation events are expected to intensify in a large part of the region. Therefore, flood socio-economic and environmental impacts should be added to those produced by water scarcity (Tramblay and Somot 2018).

Primarily caused by global processes, including thermal expansion of sea water and accelerated melting of ice sheets in Greenland and Antarctica, sea level is projected to increase more strongly than previously estimated (DeConto and Pollard 2016; IPCC 2019). This will have repercussions for the Mediterranean Sea, as well. For the recent past, in which sea level has been monitored by satellite altimetry (1993-2018), Mediterranean sea level has increased up to 2.8 ±0.1 mm yr^{-1}, which is consistent with global sea level trend (3.1 ±0.4 mm yr^{-1}) (Cazenave and WCRP Global Sea Level Budget Group 2018). At a sub-regional level, by the end of the 21st century (2080-2099) the projected rise in the average sea level of the Mediterranean Basin with respect to the present climate (1980-1999), is estimated to be 37 cm, 45 cm, 62 cm and 90 cm under RCP2.6, RCP4.5, RCP8.5 and high-end greenhouse gas emission scenarios, respectively (Somot et al. 2016; Jordà et al. 2020).

Coastal regions around the Mediterranean Basin are densely populated. Due to the near absence of tides in much of the Mediterranean, many cities and coastal infrastructures are built close to current mean sea levels. They are therefore particularly vulnerable to future sea level rise. Paired with an increasing frequency of storm surges, these cities and infrastructures face enhanced risks of flooding. Sea level rise will lead to loss of arable lowlands, notably in intensively used river deltas such as those of the Nile, the Po and elsewhere, with adverse consequences for agricultural activities and food security. A related problem is the intrusion of seawater into coastal aquifers (seawater intrusion), which renders these aquifers unsuitable for human consumption and for most agricultural purposes (Hegazi et al. 2005). Enhanced uptake of atmospheric CO_2 has led to a significant increase in seawater acidity of the Mediterranean, which is set to continue (Tsimplis et al. 2013; Palmiéri et al. 2015). Acidification has serious consequences for organisms that produce carbonate shells and skeletons and for marine ecosystems throughout the Mediterranean Basin (Gattuso et al. 2015; Palmiéri et al. 2015).

Beyond climate change, the Mediterranean Basin also experiences environmental challenges due to changing land and sea use, agricultural intensification and urban sprawl, increasing pollution and declining biodiversity. Due to drought, land use change, and high temperatures, the area affected by forest fires could increase by approx. 40% up to ~100% relative to recent levels, generally proportional to warming (Turco et al. 2018). Likewise, warming in combination with overfishing risk causing the local extinction of more than 20% of exploited fish and marine invertebrates by 2050 (Jones and Cheung 2015).

These examples show that climate change, in combination with other challenges, will likely not only affect ecosystems on land and in the ocean, but also create risks for the services they provide and therefore ultimately the ecological basis for the well-being of people in the Mediterranean Basin. Combined with current changes in lifestyle, e.g., the switch to a more urbanized life-style and a more processed animal-based diet, in particular southern Mediterranean countries in particular are at risk of increasing their dependence on food imports and trade from elsewhere (CIHEAM 2014; UNEP/MAP 2016). Landraces are likely to be lost as farmers replace them with other landraces, or improved varieties, that are better adapted to the new conditions (FAO 2015). Some scholars argue that this trend could be mitigated by boosting a return to the traditional Mediterranean diet, with significant health benefits for all Mediterranean people including their visitors (Serra-Majem et al. 2011).

Climate and environmental changes and their impacts imply risks for human security in the Mediterranean region (Karmaoui 2016; Rigaud et al. 2018). These changes are added to escalating conflict and insecurity in some African and Eastern countries that are leading thousands of people to flee, taking their chances on unseaworthy boats across the Mediterranean. Public health is already affected by multiple facets of climate and environmental change, including enhanced and more frequent (urban) heat waves, increasing air pollution (higher risk of cardiovascular or respiratory diseases), and increased spread of disease vectors (West Nile virus, dengue, chikungunya) (Kuglitsch et al. 2010; Negev et al. 2015; Orru et al. 2017). Environmental change is also increasingly recognized as a relevant factor for socio-economic risks (e.g., famines) in situations of instability and conflict. Synergistic effects between societal, economic and environmental factors should also be considered, as well as the relevance of globally connected socio-economic structures (Le Roy Ladurie 2004, 2006). For instance, droughts, floods or other extreme events in agricultural regions elsewhere may lead to market disturbances and may affect prices, trade, production and security in the Mediterranean too.

1.1.2 An integrated Mediterranean risk assessment for sustainability

Considering this incomplete compilation of examples for current understanding of global and environmental changes in the Mediterranean Basin, one might get the impression that much is known already. However, impressive as it may seem, most environmental research conducted so far in the region is primarily driven by disciplinary and sectoral investigations. A more comprehensive, systemic and holistic approach to interrelated processes and components would likely make useful contributions to environmental decision-making in the Mediterranean Basin. So far, an adequate and comprehensive assessment of risks posed by climate and environmental changes in the Mediterranean Basin is lacking (Cramer et al. 2018).

The absence of integrated studies comes in addition to the painful lack of monitoring and risk analysis capacity in southern and eastern countries of the Mediterranean Basin. There are few, but strong indications that these countries potentially face larger risks from climate and environmental changes, compared to northern countries, while commanding significantly scarcer financial resources to effectively adapt to their impacts (IPCC 2014).

This report cannot replace a full and integrated research-based risk assessment in the terms outlined above. It rather aims at providing an assessment of current knowledge such as it emerges out of the existing body of research. While the assessment is designed and carried out as a regional study, its results may also provide useful conclusions on a global scale. Global environmental change inevitably has distinct regional manifestations. Similarly, processes and changes on the regional level will have consequences for global processes. The MedECC network sees this regional assessment as a possible "bridge" between the global and the national to local scale, essential for the advancement of mitigation and adaptation strategies. Such a bridge appears to have particular potential in the Mediterranean context, since this region is at a crossroads between Africa, Europe and (Western) Asia. The importance of the regional dimension has been emphasized in the context of the implementation of the 2030 Agenda and the Sustainable Development Goals (SDGs). The 2030 Agenda recognizes regional dimension and regional governance as playing a crucial role in translating sustainable development policies into concrete actions at the national level (UN 2015; UN-SDSN 2018).

Mitigation of the processes underlying climate and environmental change and adaptation to their unavoidable impacts represent a priority for public and private decision makers concerned with the future of communities and environmental integrity in the Mediterranean Basin. Effective mitigation and adaptation require investigations that go beyond current knowledge. Looking at the current state of the Mediterranean, we note the following challenges and needs:

- A substantial gap between knowledge and understanding of climate and environmental change between the northern-rim countries and most of the southern- and eastern-rim countries of the Mediterranean Basin.
- A disparity of observational data and monitoring systems between the North versus the South and the East, which calls for an intensification of observations and the creation of observational networks, notably in the MENA region.
- Research on short- and mid-term weather and climate predictions, including seasonal forecast ing to better manage water resources and agriculture, is being carried out in some Mediterranean countries. The results of such studies have the potential to be applied more broadly.
- Despite some initiatives (e.g., the Mediterranean Climate Outlook Forum - MedCOF), the level of climate services offered by the scientific communities in most Mediterranean countries remains insufficient. Such services can be decisive in providing vital information on short-term to intermediate climate trends to planners and decision makers involved in agricultural and water policies.
- The implementation of more advanced early warning systems may enable better preparation for extreme events and other climate-related risks that usually affect the Mediterranean region. Such systems need to be based on

and accompanied by an adequate societal and individual risk awareness (see the recommendations of UNISDR 2015).

- Large-scale programs are needed (or should be strengthened) in eastern and southern Mediterranean countries to address pressing multi-factorial challenges such as land degradation and desertification, ultimately focusing on increased resilience to change as well as the reinforcement of ecological transitions to more sustainable resource use.
- In order to address these issues, a comprehensive scientific synthesis and assessment report is required. This report should include recent trends, likely future developments, and consequences of climate and environmental changes on natural systems, the economy, and human well-being in the Mediterranean Basin.

The overarching goal of this report is to provide such a synthesis, based on existing knowledge in the scientific literature. The work has been carried out by the Mediterranean Experts on Climate and environmental Change (MedECC) aiming for a comprehensive synthesis of current scientific knowledge that covers all relevant disciplines, sectors and sub-regions. The assessment considers three major interconnected domains, namely resources (water, food & energy), ecosystems (marine, coastal and land), and society (development, health and security). Although the target audience of this assessment is decision makers and policymakers, anyone interested in the Mediterranean can benefit from it. After completion of this first assessment, there is a desire to develop a platform for constructive science-society-policy dialogue.

1.2 The Mediterranean Experts on Climate and environmental Change (MedECC)

1.2.1 Goals, basic structure and first accomplishments of MedECC

MedECC's main, overarching goal is to provide a state-of-the-art risk assessment on climate and environmental changes and their impacts across the Mediterranean, based on existing scientific knowledge, with the following specific objectives:

- To activate and engage the scientific community working on environmental and climate changes in the Mediterranean Basin;
- To provide comprehensive updated and consolidated scientific knowledge on these changes and make it accessible to policymakers, key stakeholders and the general publi in a process which facilitates ownership of scientific knowledge;
- To identify possible gaps in the current understanding of environmental and climate changes and their impacts in the Mediterranean;
- To help build capacity of scientists from southern and eastern Mediterranean countries to international levels and standards by encouraging training, research and development efforts in these countries in the context of the Paris Agreement;
- To bridge the gap between research and decision-making, contributing to the improvement of policies at all levels;
- To contribute to future reports of the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) or similar assessments in the Mediterranean Basin. MedECC has an important role to play in the work of the IPCC, as it is contributing to the Sixth Assessment Report (AR6) with a cross-chapter paper dedicated for the first time to the Mediterranean.

MedECC's work therefore focuses on two complementary directions:

- Publishing a scientifically robust assessment and synthesis of environmental and climate changes and their impacts in the Mediterranean Basin, based on currently available research;
- Building a science-policy interface on these changes and their impacts in the Mediterranean and thereby providing a scientifically sound basis for decision-making.

1.2.2 Principles and processes of work in MedECC

Since the founding of MedECC, two scientists at the French National Centre for Scientific Research (CNRS) coordinate the development and work of the network. Central to the governance of MedECC is its Steering Committee (SC, *Fig. 1.1*) which

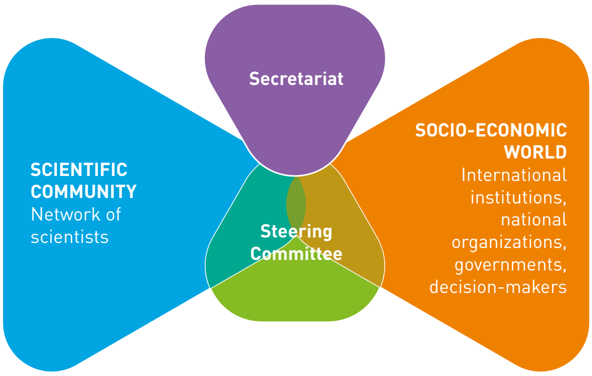
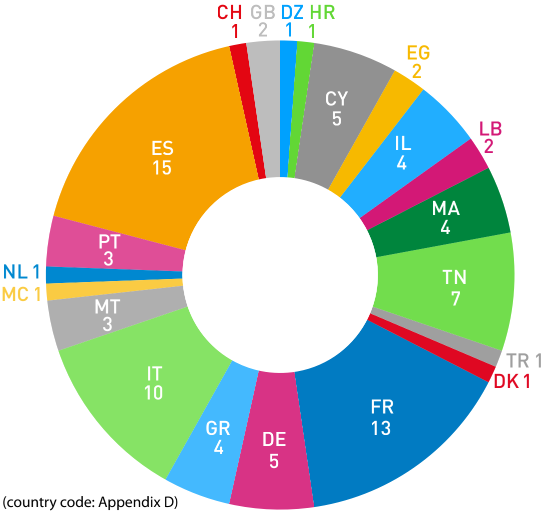


Figure 1.1 | **Structure and functioning of MedECC.**

met for the first time in April 2016 in Barcelona, Spain. The SC is currently composed of 20 members from 11 countries *(Appendix A.4.1)*, including 16 scientists in a personal capacity (representing environmental sciences, political sciences and economics) and 4 representatives of policymaking bodies: the United Nations Environment Programme/Mediterranean Action Plan – Barcelona Convention Secretariat (UNEP/MAP) and its Plan Bleu Regional Activity Centre, the Secretariat of the Union for the Mediterranean (UfM), and the Advisory Council for the Sustainable Development of the Government of Catalonia (CADS). More details on the work and accomplishments of the SC can be found in *Appendix A.4.1.2.*

MedECC work is carried out by an open and inclusive network of scientific experts to support decision-making through accurate and accessible information on current and future environmental and climate changes and their impacts in the Mediterranean Basin. The network currently comprises more than 600 scientists from 35 countries who contribute in a personal capacity on a voluntary basis. Members of the network do not primarily represent an institution or country.



(country code: Appendix D)

Figure 1.2 | **Distribution of MAR1 Coordinating Lead Authors and Lead Authors by country.**

The added value of the work of MedECC lies in the large geographical and thematic scope addressed (see below) and the comprehensive involvement of more than 86 Coordinating Lead Authors (CLAs) and Lead Authors (LAs) from 21 countries participating in the drafting of the report *(Fig. 1.2)*. 27 (31%) are based in southern and eastern Mediterranean countries and 31 (36%) are women. In total, 190 authors from 25 countries contributed to the report (CLAs, LAs and Contributing Authors - CAs). Appendix A.4 provides more information about the steps of MAR1 as well as the duties of the different players involved in report preparation. By providing information on the assessment/synthesis process underlying MAR1, we aim to address both institutional stakeholders/organizations as well as individuals interested in the organization of MedECC and its work.

1.3 The First Mediterranean Assessment Report (MAR1): A synthesis of knowledge on risks from climate and environmental change in the Mediterranean Basin

1.3.1 Report scope and objectives

1.3.1.1 Geographic scope

Located at the crossroads of three continents, the Mediterranean region is unique in its historical and geographical specificities, as well as its natural and cultural heritage. While the Mediterranean Sea is a well-defined water body, limited by the Strait of Gibraltar, the Dardanelles Strait and the Suez Canal *(Fig. 1.3)*, various definitions are used for the land boundaries of the Mediterranean region.
In political terms, the United Nations Environment Program Mediterranean Action Plan (UNEP/MAP[1])

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[1] https://www.unep.org/unepmap/

Figure 1.3 | Geography, physiography and landscapes of the Mediterranean Basin
(Source: GRID-Arendal)²

covers 21 riparian countries, which are Contracting Parties (CPs) to the Barcelona Convention (excluding Jordan and Portugal, which are not riparian countries sensu stricto, and Gibraltar/UK and Palestine, which are not currently CPs but have observer status). The population of this so-defined Mediterranean region is about 480 million inhabitants (EEA 2020). From a geopolitical point of view, the Union for the Mediterranean (UfM³), created in 2008, embodies a much wider spatial scope of 43 countries (all the countries of the European Union and 15 countries in the southern and eastern Mediterranean).

For much of the physical assessment by MedECC, we adopt a simple regular latitude-longitude box (29°N to 47.5°N and 10°W to 39°E, *Fig. 2.1)*, which includes some regions with non-Mediterranean climates, such as the Alps, the Eastern Balkans or part of the Sahara. This definition of the Mediterranean region is similar to the MED zone adopted in IPCC-AR4 (IPCC 2007), and slightly larger than in IPCC-AR5 (IPCC 2013) and the ongoing AR6 assessment.

The Mediterranean Sea is a relatively small, semi-enclosed sea with limited exchange to the global ocean through the Strait of Gibraltar, located at the western end of the Mediterranean, the linkup between the Mediterranean and the Black Sea through the Bosphorus and Dardanelles and the connection to the Red Sea through the Suez Canal in the South-East *(Fig. 1.3)*. The Mediterranean Sea can be divided into two sub-basins: the Western and the Eastern Mediterranean, which are in turn made up of a series of various small basins (Amblàs et al. 2004). The Mediterranean region includes 75 coastal watersheds and 224 coastal administrative regions, with a total of 46,000 km of coastline (UNEP/MAP 2016).

The topographic, geographic and socio-economic structures of Mediterranean landscapes are heterogeneous. Their current shapes are the result of centuries of interactions between natural forcings and diverse human activities, both past and present.

The coastal area comprises a large set of ecosystems that deliver valuable services to people, including lagoons, estuaries, deltas, coastal plains, wetlands, rocky shores and nearshore coastal areas, seagrass meadows, coral communities, frontal systems and upwellings, seamounts, and pelagic

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[2] https://www.grida.no/resources/5931

[3] https://ufmsecretariat.org/

systems. Most of these systems are very sensitive to human and climate forcing. Wetlands represent 1.7-2.4% of the total area of Mediterranean countries (Tour du Valat 2012). The most extensive coastal wetlands are found in estuaries like that of the Po (Italy), Nile (Egypt), Rhône (France) and Ebro (Spain) rivers.

Other elements of Mediterranean heritage are the nearly 15,000 islands and islets dotted throughout the basin, some of which are particularly vulnerable. The largest islands are Sicily, Sardinia, Corsica, Cyprus, and Crete, and the major island groups include the Balearics off the coast of Spain and the Ionian, Cyclades, and Dodecanese islands of Greece. In total, the islands' coastlines comprise around 19,000 km, or more than 41% of the Mediterranean coastline (Emmanouilidou 2015). In terms of land surface, islands represent only 4% of the land area of the whole Mediterranean Sea Basin (Kolodny 1974). The small islands (less than 10 km^2), are particularly valuable in terms of biodiversity. Since many of them are uninhabited or weakly impacted by human activities, they constitute valuable "life laboratories" for assessing the sole impacts of climate change. Since 2005, the Mediterranean Small Islands Initiative (PIM[4]) has been working to improve knowledge and management of these territories, as well as raising awareness of the importance of local populations for the preservation of these fragile territories.

The Mediterranean is also complex in terms of its socio-political settings. For millennia, the Mediterranean has been a unique geographical space but – except for the Roman Empire – it has been a politically, economically and culturally divided region. While its geographical scope has remained unchanged over the past 5,000 years of human history, the modes of government in countries and regions have been in permanent flux (Brauch 2010).

Approximately one-third of the Mediterranean population is concentrated along its coastal regions. Meanwhile, about 250 million people reside in coastal hydrological basins. In the southern region of the Mediterranean, around 120 million inhabitants are concentrated in coastal hydrological basins, where environmental pressures have increased (EEA 2020). In addition, around 360 million international tourists visited the Mediterranean countries in 2017 (UNWTO 2019). Approximately half of these arrivals - 170 million - are in Mediterranean coastal areas, exacerbating the human pressures in coastal zones, and generating a 40% increase in marine litter, particularly during the summer season (Galgani et al. 2014).

The variety of cultures, policy and governance approaches and the diversity of social systems have led to very different levels of socio-economic development and ecological footprints of the Mediterranean states between the north and the south (Raleigh et al. 2008; IPCC 2014; Rigaud et al. 2018; GRID 2019). Per capita income levels are three to five times higher in southern European countries (France, Italy and Spain, in particular), compared to countries on the southern and eastern shores of the Mediterranean Sea. While important progress has been made in the South and the East over the last twenty years, instability and significant inequalities persist. This north-south dichotomy is at the heart of the climate change issue, as it exacerbates imbalances by having greater impacts on lesser-developed countries, which have limited capacities to deal with the impacts and possible adaptation measures.

Due to the complexities and heterogeneities of topographic, geographic and socio-economic structures in the Mediterranean Basin, regional, sub-regional, national or local scales are considered where appropriate and where data and information are available. For instance, the spatial separation of drivers has been considered at the level of ecosystems (open ocean, deltas, river basins, wetlands, drylands, etc.). Impacts of environmental change are sometimes quite localized but concern a large number of domains. They are complex to understand and require studies and simulations at reduced spatial scales, associated with high degrees of uncertainty. Best practices with regard to mitigation and adaptation measures are usually reported at the local level, as adaptation measures are generally implemented at a territorial scale where end-users and decision makers are more engaged.

1.3.1.2 Scenarios and reference periods

Different periods and time windows have been selected by climatologists and adopted by IPCC to monitor and record changes in climate conditions throughout Earth history along the different reports. In order to quantify human impacts with respect to an "unperturbed" reference state (ideally the climate just before human activities started to

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[4] http://initiative-pim.org/

demonstrably change the environment at global scale) a practical approach to identifying impacts and their characteristics is needed *(Chapter 2)*.

Instrumental observations of temperature are available mainly since the second half of the 18th century but only in some European countries. In the IPCC AR5 report, the 1850-1900 period is considered as the best approximation for an unperturbed state, but, it is not named pre-industrial. It has nonetheless been kept as the reference for the pre-industrial period in the IPCC Special Report on the Impacts of Global Warming at 1.5°C (SR15) (IPCC 2018) *(Section 2.2.1)*.

Climate modelling and climate projections adopted the practice of describing future changes with respect to a recent baseline (during which validation of models is supported by a large amount of instrumental observations). Because of the long residence time of carbon dioxide in the atmosphere, the human influences on the current trajectory of a changing climate appear to be irreversible for decades to centuries, even if significant mitigation measures are implemented immediately (Millar et al. 2006). Thus, given the dynamics of the natural climate system and the superimposed changes humans are causing, the 21st century is an important transitional time for undertaking both mitigation and adaptation actions. In order to be able to propose future climate projections considering various possible socio-economic trajectories and climate policy pathways, we follow the IPCC scenario approach. Although results based on multiple IPCC scenarios are reported in MAR1, we mostly focus on two options which encompass the range of IPCC-AR5, CMIP5 and CORDEX simulations: the "business as usual" scenario (RCP8.5, for an explanation of the RCPs see *Box 2.2*) and the optimistic scenario closest to the UNFCCC Paris Agreement target (RCP2.6). These scenarios were also chosen due to model projection availability constraints at the regional scale. Where more recent studies are not available, the assessment also considers studies based on the older IPCC SRES approach (Nakićenović 2000) *(Section 2.2.1)*.

1.3.1.3 Adapting to climate and environmental change

Climate change adaptation is a necessity, possibly an opportunity, but many definitions exist and the nature and effectiveness of adaptive responses is critically influenced by the framing of adaptation responses (Wise et al. 2014). The IPCC AR5 has framed adaptation as a "process of adjustment to actual or expected climate and its effects in order to either lessen or avoid harm or exploit beneficial opportunities" and also emphasizes that there is "increasing recognition that an adequate adaptive response will mean acting in the face of continuing uncertainty about the extent of climate change and the nature of its impacts" (IPCC 2014). Other authors emphasize how the increasing climate pressure recalls the need to shift rapidly from incremental to transformative adaptation (Rickards and Howden 2012; Vermeulen et al. 2013). Adaptation can be understood as a set of actions which "adjust to" a new situation (e.g., change date of seeding), which recalls a "technical fix" approach, or as a "structural coupling dynamic process", where social learning is the main process informing decisions at any critical point of an ongoing adaptive pathway (Collins and Ison 2009). In the latter framing, the assumption is that no single group has clear access to understanding the issues and their resolutions, hence the difficulties in securing the active and broad-based engagement of stakeholders, and the facilitated spaces for "learning to adapt" become crucial. Adaptation can be operationalized as part of pathways of change and response, which implies the reorganization of institutional structures that are likely to lead to more sustainable trajectories (Rickards and Howden 2012).

The design of adaptation pathways can emerge from the integration of capacity-based (i.e., bottom-up) approaches with impact-based (i.e., top-down) approaches (Vermeulen et al. 2013). The same authors show that when the signal-to-noise ratio of the changing climate is low, i.e., the noise associated with natural weather variability is higher than the changing climate signals, the capacity to respond can basically rely on "no-regret" or "win-win" approaches resulting in incremental adaptation practices, such as short-term investments on higher water storage capacity or use of water-saving technologies, which can also respond to weaknesses emerging from the usual climate uncertainty. When climate shifts are stronger, impact-based decisions can more effectively inform systemic or transformative adaptation pathways, even when uncertainty of future predictions is relatively high (Vermeulen et al. 2013).

1.3.1.4 Toward a systemic approach

As previously emphasized in this chapter, a large amount of scientific material (data, publications, reports, etc.) is available for various Mediterranean areas (from localities to countries or marine sub-basins), for different periods of various durations, for different compartments (atmosphere, soil, continental or sea water, etc.) and on different topics (chemical composition, physical characteristics, ecosystems, human activities, etc.). New data from satellite providers are essential for those regions with poor instrumental coverage, but also to provide a complete overview of the Mediterranean Region (e.g., GEO-Cradle, geocradle.eu, the COPERNICUS and Digital Africa systems, or the Integrated Geospatial information Frameworks, IGIF). All of these elements contribute to the overall understanding of the impacts of climate and environmental changes in the Mediterranean. The fact that advanced research is so complex that it requires very focused and specialized studies makes it difficult to achieve the objective of having an overall integrated understanding of the functioning of the Mediterranean environment, of the modifications due to local human activities and of the evolutions related to global changes. A holistic approach is however of major importance in order to better understand the interactions between these multiple elements, and then provide a robust scientific basis to develop and implement sustainable and effective policies.

This systemic approach has been successfully adopted for decades by scientists contributing to the IPCC by developing more and more refined global climate models. Nevertheless, these models are not designed to address all processes that determine the evolution of the Mediterranean environment and socio-ecosystems under both climate change and other environmental processes caused by human activity.

The development of an integrated Mediterranean model with the spatial and temporal resolution suitable for comprehensively resolving the relevant processes has to be a long-term target for the scientific community. Such an approach could provide answers to the concerns of policymakers related to sustainable development strategies in the Mediterranean region. At present, MedECC aims to initiate the process by providing a first synthesis of the state of knowledge in the various scientific fields that need to be considered and brought together in order to move one step forward in this direction.

1.3.1.5 MedECC MAR1 as a policy support instrument

Given the stated goals and objectives of MedECC, MAR1 is intended to support policies in deriving mitigation and adaptation strategies, particularly in the context of Mediterranean cooperation under policies of the European Union, Arab League, EU-Africa and EU-Asia cooperation, North African Unions, Maghreb and Mashriq. To provide adequate support, MAR1 has been inspired by other science-policy interfaces such as the IPCC and IPBES, aiming to provide an unbiased, scientific view of climate and environmental change, its various, multi-sectoral impacts and the risks they imply for society.

The MedECC MAR1, by summarizing existing findings and results, aims to highlight their policy relevance without being policy-prescriptive.

The MedECC MAR1 is designed to address the needs of multiple actors involved in providing a response to climate and environmental changes and risks in the Mediterranean region. The primary target users of the report are governments and policymakers at all levels, the UfM and the UNEP/MAP at the regional level, and more broadly, the comprehensive system of intergovernmental processes pursuing different aims, including the three "Rio Conventions" (UNFCCC, CBD, UNCCD) and the Ramsar Convention (and their financial instruments), as well as IPCC, IPBES and the Commission on Generic Resources for Food and Agriculture (CGRFA). Other important end-users include the scientific community, major economic decision makers and the private sector, the education sector, civil society and non-governmental organizations (CSOs and NGOs). MedECC aims to build close relationships with various media in order to help guide the interpretation of its report and to ensure that the public is provided with objective and unbiased information about MAR1.

MAR1 contributes to meeting the need for an advancement and implementation of regulatory instruments aiming to reduce greenhouse gas emissions and emissions of pollutants to mitigate climate and environmental changes in the Mediterranean Basin. The scoping and drafting of the report involved ample consultation of completed or ongoing assessments of comparable nature like the IPCC and IPBES assessment reports and builds on the existing relations between MedECC and other groups. Findings of MAR1 will be directly employed for the drafting of a Mediterranean Cross-Chapter Paper in the forthcoming IPCC Sixth Assessment Report *(Appendix A.1)*.

1.3.2 Methodology

The drafting of MAR1 entailed a collective and iterative review, synthesis, analysis and judgment of available scientific knowledge. The entire assessment is supported by scientific references; no additional research has been undertaken by MedECC. In some cases, a new analysis of data was conducted using existing models to address specific questions and to identify knowledge gaps to be addressed by other initiatives and research programs.

The report is primarily based on peer-reviewed literature (in English or other languages) but selected non-peer reviewed literature was also considered (such as institutional or government reports, national statistics, etc.) in which case the authors carefully checked the quality of the references included to justify their inclusion. A scientific literature database was maintained by the MedECC Secretariat and was made available to all report authors.

Drafts of the report have been subject to a dual scientific review allowing suggestions and amendments by scientific experts. A first internal review of the First Order Draft (FOD) involving the SC and the authors of the report was carried out, and the Second Order Draft (SOD) was submitted to external scientific reviewers.

The main body of MAR1 is accompanied by a Summary for Policymakers (SPM), which undergoes an approval procedure organized with the UNEP/MAP – Barcelona Convention Secretariat and its Plan Bleu Regional Activity Centre, through their Focal Points and/or the Members of the Mediterranean Commission on Sustainable Development (MCSD), as well as with the UfM Member State representatives within the regional Climate Change Expert Group (CCEG).

1.3.3 Communicating uncertainties and results

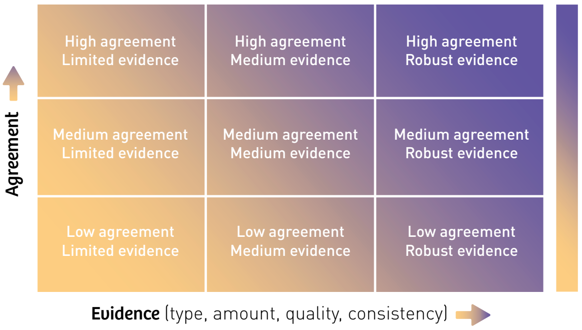
Communication of the findings of MAR1 aims to also adequately communicate scientific uncertainties and confidence in the material used. For this purpose, three different target groups are differentiated:

- the scientific community; all of the main conclusions will be supported by robust literature and/or evidence following the AR5 IPCC (IPCC 2013) criteria to communicate the uncertainty of findings;
- policymakers and stakeholders; conclusions for them will be summarized in the MAR1 Summary for Policymakers; considering the strong relationships with key institutions such as UNEP/MAP and UfM, main questions and key messages will be discussed with them prior to final publication, in order to take their views and the advice of the MedECC SC into account;
- the public at large, mainly, but not exclusively, those living in Mediterranean countries; the main challenges and opportunities will be communicated to them; in so doing, we will progress from MAR1's strictly "informative" role towards a more "participatory" and "responsible" one, in order to further understanding and acceptance of measures aimed to cope better with climate and environmental changes in the Mediterranean region.

The approach of the MAR1 report meets the call made by the United Nations program on the Sustainable Development Goals as well as the concessions proposed after the COP 21 under the UNFCCC (Paris Agreement), in particular SDG 17 "Strengthen the means of implementation and revitalize the global partnership for sustainable development" (Partnerships for the Goals).

Following the AR5 IPCC (IPCC 2013), the metrics for communicating the degree of certainty in key findings (notably on climate drivers) will be the following:

- **Confidence:** confidence in the validity of a finding, will be based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement; confidence is expressed qualitatively and its level will be based on the evidence (robust, medium and limited) and the agreement (high, medium and low). A combination of different methods, e.g., observations and modelling, is important



High agreement Limited evidence	High agreement Medium evidence	High agreement Robust evidence
Medium agreement Limited evidence	Medium agreement Medium evidence	Medium agreement Robust evidence
Low agreement Limited evidence	Low agreement Medium evidence	Low agreement Robust evidence

Figure 1.4 | The basis for the confidence level is given as a combination of evidence (limited, medium, robust) and agreement (low, medium and high) (Mastrandrea et al. 2011).

for evaluating the confidence level. There is flexibility in this relationship; for a given evidence and agreement statement, different confidence levels could be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. *Fig. 1.4* shows how the combined evidence and agreement results in five levels for the confidence level used in this assessment. Confidence should not be interpreted probabilistically, and is distinct from "statistical confidence".

Term	Likelihood of the outcome
Virtually certain	>99% probability
Extremely likely	>95% probability
Very likely	>90% probability
Likely	>66% probability
More likely than not	>50% probability
About as likely as not	33-66% probability
Unlikely	<33% probability
Extremely unlikely	<5% probability
Exceptionally unlikely	<1% probability

Table 1.1 | Likelihood terms associated with outcomes used in MAR1 (from IPCC 2013).

- **Uncertainty:** quantified measures of uncertainty in a finding will be expressed probabilistically, i.e., based on a statistical analysis of observations or model results, or on expert judgement. The qualifier "likelihood" provides calibrated language for describing quantified uncertainty. It can be used to express a probabilistic estimate of the occurrence of a single event or of an outcome, for example, a change in a given climate parameter, an observed trend, or a projected change lying in a given range. Statements made using the likelihood scale may be based on statistical or modelling analyses, elicitation of expert views, or other quantitative analyses. Where sufficient information is available, it is preferable to avoid the likelihood qualifier in favor of the full probability distribution or the appropriate probability range. *Table 1.1* shows the list of "likelihood" qualifiers to be used in this report.

1.3.4 Report structure

The outline for the MAR1 report was approved by the MedECC Scientific Committee during its meeting on May 24, 2018 in Marseille, France. MAR1 consists of a Summary for Policymakers, six main chapters and several appendices, as follows:

- Summary for Policymakers, including an Executive Summary.
- This chapter, Chapter 1, **"Introduction"**, frames the motivation and main components of the MedECC Assessment.
- Chapter 2, **"Drivers of change"**, focuses on the physical, bio-chemical and human drivers of climate and environmental changes, distinguishing between climate, pollution, land/sea use and management, and invasive species. Based on these drivers, the analyses in Chapters 3-5 all consider past trends and current situation, projections, vulnerabilities and risks, adaptation, knowledge gaps and research needs.
- Chapter 3, **"Resources"**, assesses the state of knowledge for major resource challenges: water, food and energy in three sub-chapters describing each of these resources.
- Chapter 4, **"Ecosystems"**, assesses the state of knowledge for marine, coastal and terrestrial ecosystems.
- Chapter 5, **"Society"**, addresses major issues of development, health and human security under climate and environmental change.
- Chapter 6, **"Managing future risks and building socio-ecological resilience"**, discusses options for more sustainable policies given the risks identified in *Chapters 3-5*. It describes the future risks associated with climate change in Mediterranean countries, and critically reviews a range of examples of adaptation and mitigation, promoting their synergies, as well as cooperation and networking among Mediterranean countries for building resilience.
- Supplementary information is given by the appendices, which include the information on MedECC partners and related research activities, the institutional context of MedECC, the main steps in MAR1 preparation, maps of projected temperature and precipitation changes for the Mediterranean Basin, the lists of acronyms and country codes.

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DRIVERS OF CHANGE

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This chapter should be cited as: Cherif S, Doblas-Miranda E, Lionello P, Borrego C, Giorgi F, Iglesias A, Jebari S, Mahmoudi E, Moriondo M, Pringault O, Rilov G, Somot S, Tsikliras A, Vila M, Zittis G 2020 Drivers of change. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 59-180, doi:10.5281/zenodo.7100601.*

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2 Drivers of change

Executive summary

Climate drivers

During recent decades, observations of several variables provide evidence of the ongoing anthropogenic climate change in the Mediterranean region, particularly increase of mean and extreme temperatures, and dry environmental conditions. Climate projections show that the region will among the most affected regions by climate change, specifically regarding precipitation and the hydrological cycle, but also mean warming and heat extremes (in both the terrestrial and marine environment), sea level rise and sea water acidification.

Basin-wide, annual mean temperatures are now 1.5°C above the preindustrial level. In the last decades dry conditions have become more frequent and a large reduction of glaciers across high mountains of the Mediterranean has occurred at a progressively increasing pace. Mediterranean Sea waters have become warmer and saltier, Mediterranean sea level has risen at a rate (1.4 mm yr^{-1}) similar to the global trend at centennial scale.

In the future, the regional average warming will exceed the global mean value by 20% and it might reach 5.6°C at the end of the 21st century in the RCP8.5 high emission scenario. Heat waves and warm temperature extremes will intensify. Total annual precipitation is expected to decrease over most of the region (the average reduction rate is approximately 4% per each degree of global warming). However, magnitude and spatial distribution of changes are uncertain, because of differences among models. Dry conditions will be further enhanced by increasing evapotranspiration over land. At the same time, the inter-annual variability of the hydrological cycle will increase, with longer dry spells especially in the southern areas. Extreme precipitation events will become more intense over large parts of the northern Mediterranean areas.

Mediterranean mean sea level is projected to be at the end of the 21st century in the range from 20 to 110 cm higher than at the end of the 20th century, depending on the level of anthropogenic emissions. Sub-regional and local relative sea level rise will be further modulated by vertical land motions and regional circulation features (with deviations in the order of 10 cm from the basin average). Therefore, though in the future milder marine storms are expected, coastal hazards, floods and erosion will increase, because of mean sea level rise.

Widespread seawater warming will continue. Annual mean surface temperature will increase 2.7-3.8°C and 1.1-2.1°C in one century under the RCP8.5 and the RCP4.5 scenarios, respectively. Marine heat waves will become longer, more intense than today and their spatial extent will increase. Seawater acidification will continue, with a pH reduction that might larger than 0.4 units at the end of the 21st century.

Pollution

Across the Mediterranean Basin, ocean and inland pollution are ubiquitous, diverse and increasing in both quantity and in the number of pollutants, due to demographic pressure, enhanced industrial and agricultural activities, and climate change.

Mediterranean seawater is generally oligotrophic (low nutrient), with decreasing levels from Gibraltar eastwards to the Levantine Sea. Several coastal regions are hotspots of human-induced nutrient inputs. This nutrient enrichment causes eutrophication and may provoke harmful and toxic algal blooms, whose frequency will likely increase. Harmful algal blooms may cause negative impacts on ecosystems and may represent serious economic threats for fisheries, aquaculture, tourism and human health.

Emerging contaminants are well present across the Mediterranean Basin, and enhanced by increasing inflow of untreated wastewater. These substances may cause disorders of the nervous, hormonal and reproductive system. And the increasing frequency of extreme precipitation events in the north of the Mediterranean increases the supply of fecal bacteria and viruses to the coastal zone. The Mediterranean Sea is one of the most polluted large water bodies globally in terms of plastic and the level of this pollution is expected to increase in the future.

The Mediterranean Basin is among the regions in the world with the highest concentrations of gaseous air pollutants (NO_2, SO_2 and O_3). Its dry and sunny climate, and specific atmospheric circulation patterns enhance air pollution levels. Ships are among the major causes of increasing SO_2 and NO_x emissions in this region.

Emissions of aerosols and particulate matter (PM) into the atmosphere arise from a variety of anthropogenic activities. Particular meteorological conditions and natural sources, including the proximity of the Sahara Desert, create particular patterns of aerosol concentrations that may influence particulate matter PM concentrations. The occurrence of critically high PM concentrations associated with dust outbreaks is higher in the southern Mediterranean (>30% of the annual days) than in the northern area (<20% of the annual days).

Land and sea use change

Landscapes and their use have changed over millennia in the Mediterranean Basin, however the rate of change has increased substantially since the second half of the 20th century, with rapid growth of urban and peri-urban areas leading to loss of biodiversity and habitats. Abandonment of agro-pastoralism (which will likely continue in the future) is causing unmanaged shrubs forest development in marginal lands, arid and mountain areas in European countries, while land overexploitation is causing widespread forest degradation in areas of North Africa and the Middle East. Future land use trends depend strongly on regional policies for urbanization, agriculture, forestry and nature conservation.

Marine resource overexploitation and unsustainable fishing practices have increased in time and are the main drivers of the population decline of several species. Presently, more than 60% of marine stocks have collapsed or are overexploited. Sustainable management of marine resources requires the reduction of fishing pressure.

Non-indigenous species

The Mediterranean Sea (and particularly the Levantine Basin) is a hotspot for the establishment of many non-indigenous species (invertebrates, primary producers, and vertebrates), whose arrival and increase are linked to the decrease or collapse in populations of native species. Most marine non-indigenous species enter the Mediterranean Sea from the Red Sea and Atlantic Ocean, but those introduced by ships and aquaculture produce the largest impact on the environment. The number and spread of non-indigenous species will likely further increase with increasing shipping activity and impacts of climate change on the Mediterranean water masses.

Mediterranean land areas currently host a high number of non-indigenous species (mostly plants and invertebrates) in human-modified ecosystems and in regions with high infrastructure development. Most invertebrate species are phytophagous pests that cause damages to crops and forests. Future warming is predicted to induce a northward shift at a speed of 37-55 km decade^{-1} of current major non-indigenous species and determine a window of opportunity for new non-indigenous species adapted to dry environments. The presently increasing trend of the numbers of introduced invertebrates and vertebrates (the latter generally caused by accidental escapes) will very likely continue, as they can be easily transported also as stowaways in air and maritime cargo.

Interaction among drivers

When ecosystems and societal sectors are threatened by multiple, co-occurring drivers, climate change, pollution, land and sea use change, and non-indigenous species can interact. Interactions cause effects that can be additive/cumulative, synergistic or antagonistic and result in alteration, intensification, and even in generation of new impacts. Examples of new threats are increase of flood events, due to a combination of climatic and land use changes, desertification, which is the result of increasing aridity and exploitation of resources, and wildfires, affected by forest encroachment and heat waves, among many other interactions.

2.1 Introduction

This chapter describes characteristics and evolution of human-induced and natural factors that cause changes in the Mediterranean Basin ecosystems and human systems. In order to cover most major risks for people and biodiversity, four broad domains of change drivers are considered: climate change and variability, pollution, land and sea use changes and non-indigenous species. These factors correspond to the concept of "direct drivers", which was introduced in the Millennium Ecosystem Assessment (MEA 2005; Nelson et al. 2006), that unequivocally influence processes in ecosystems and can be identified and measured to differing degrees of accuracy.

Anthropogenic climate change is already affecting the environment and societies in the Mediterranean region. Warming is unequivocal, and there are emerging signs of changes of the hydrological cycle and other climate variables *(Section 2.2)*. Climate models indicate a trend towards a warmer and drier environment, seawater warming, with more intense warm extremes both over land and in the sea, and regional increase of sea level *(Section 2.2)*. The Mediterranean region is likely very vulnerable to climate change and many components of its terrestrial and marine environment are already under stress *(Section 2.2)*.

Atmospheric and water pollution can be driven by many factors, which affect all the compartments of the environment: water, air and soil/sediments. Pollutants can migrate from one media to another. There is a wide range of pollutants that can be biological (e.g., bacteria or insects), chemical (e.g., pesticides, trace metals) or physical (e.g., particulate matter) (*Section 2.4-6* and *Chapters 3* and *4* of this report).

Changes in land and sea use changes are considered among the major direct drivers of environmental change worldwide, but their characteristics vary, depending on each region, even at very local scale. Mediterranean terrestrial landscapes and ecosystems show different patterns of change on northern and southern shores, due to urbanization, coastal development, evolving agricultural and farming practices, including their abandonment. The overexploitation of the Mediterranean Sea resources poses a particular threat due to its intrinsic geographical limits *(Section 2.4)*.

Non-indigenous species are profoundly affecting terrestrial and marine ecosystems in the Mediterranean and their impact is not only measurable in biodiversity alterations, but also in human health and economic damages *(Section 2.5)*.

There is no strict consensus of the grouping of the drivers into the categories that have been adopted in this report. More condensed or more articulated lists can be found in the scientific literature. Our four categories include all physical, chemical and biological factors that directly act on the Mediterranean environment, with a substantial correspondence with those used in the recent IPBES 2018 regional reports (Bustamante et al. 2018; Elbakidze et al. 2018; Nyingi et al. 2018; Wu et al. 2018b).

The level or rate of change of direct drivers can be influenced or altered by indirect drivers (MEA 2005; Nelson et al. 2006). Indirect drivers are grouped in categories such as demographic, economic, sociopolitical, cultural, religious, technological, legislation and financial drivers. In turn, indirect drivers are distinguished in "endogenous" and "endogenous" drivers, whose magnitude can and cannot be influenced/altered by the decision-makers, respectively. Whether a driver is exogenous or endogenous depends on the organizational level and on the spatial and temporal scale. The concepts of indirect and direct drivers roughly match those of driving forces and pressures in the Drivers–Pressures–State–Impacts–Responses (DPSIR) framework, which was initially developed by the European Environmental Agency (EEA 1999).

Understanding of indirect drivers is essential for the benefit of the environment. It is the action on indirect drivers by policymakers and stakeholders that can effectively manage the risks posed to the environment and human societies by climate change, pollution, land and sea use changes and arrival of non-indigenous species. However, this is a quite different topic with respect to the content of this chapter. Mechanism and tools influencing direct drivers are considered in other parts of this report. The scope of this chapter is the assessment of the state of knowledge of physical, chemical, and biological factors, of their present status, past and future evolution in the Mediterranean Basin.

2.2 Climate change

2.2.1 Framing

There is no universal definition of the land boundaries of the Mediterranean region *(Chapter 1)*. In this section, and also for much of this report, we adopt a simple regular latitude-longitude box (29°N to 47.5°N and 10°W to 39°E, *Fig. 2.1*), which includes some regions with other than Mediterranean climates, such as in the Alps, the Eastern Balkans or part of the Sahara. This definition of Mediterranean region is similar to the MED zone adopted in IPCC-AR4 (IPCC 2007), and slightly larger than in IPCC-AR5 (IPCC 2013a).

In order to provide a spatially refined assessment, we define sub-regions over land and over sea by using smaller rectangular boxes. Over land, the European sub-regions follow the definition proposed during the PRUDENCE European project (Christensen et al. 2002) *(Fig. 2.1)*, and we define new sub-regions (inspired by Nabat et al. 2015b) for the Middle East and Africa. Over the sea, 4 sub-regions are defined using the natural strait delimitations *(Fig. 2.1)*, the Western Mediterranean Sea (MEDW) between the Gibraltar Strait and the Sicily Strait, the Adriatic Sea (ADR) north of the Otranto Strait, the Aegean Sea (AEG) north of the Cretan Arc Straits and the Eastern Mediterranean Sea (MEDE) for the remaining.

When assessing future climate change, it is important to specify the reference period to which climate projections are compared, along with future "time slices". In MAR1 we use 20-year long time periods following standard IPCC practice. This length of time period is sufficient to smooth part of the high-frequency natural climate variability that can otherwise mask the forced trend, but it is short enough to assume that climate does not change much during the 20 years covered. For the reference period, we choose the latest years of the 20th century (1980-1999). This choice is a compromise related to the observation and model data availability at the Mediterranean scale. IPCC has traditionally chosen the pre-industrial

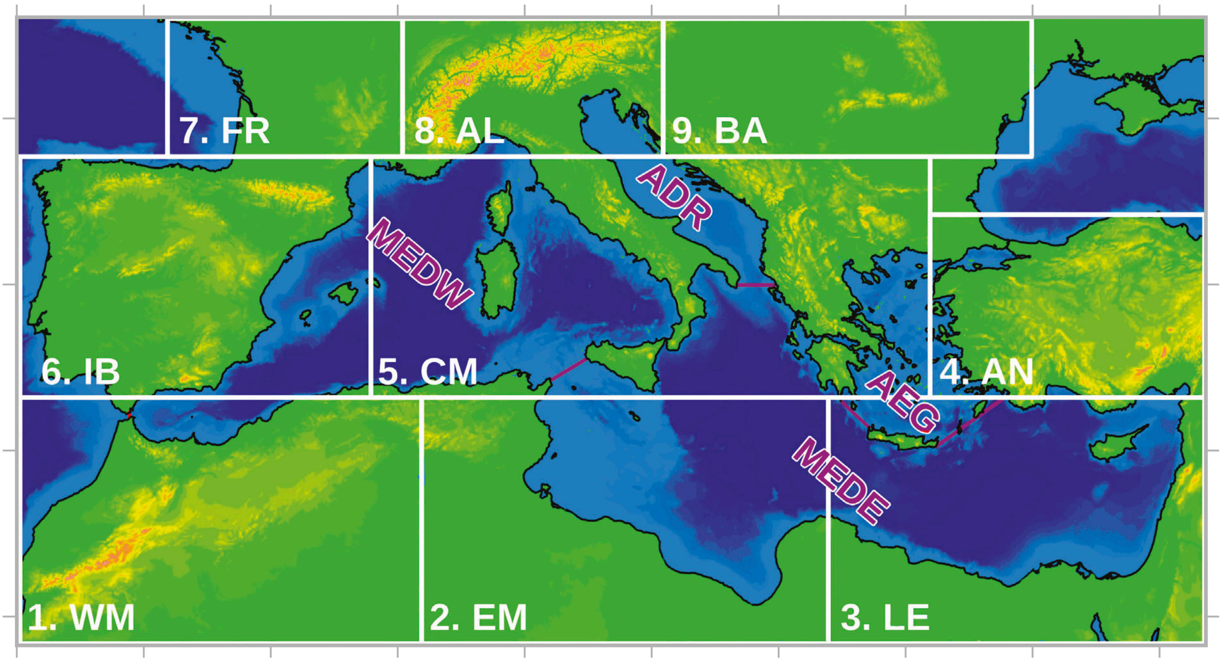

Figure 2.1 | Mediterranean coastline, topography over land and bathymetry over the sea plus the box definition. Relief data are derived from the ETOPO1 1 Arc-Minute Global Relief Model[5]. Sub-regions are defined as West Maghreb (WM), East Maghreb (EM), Levant (LE), Anatolia (AN), Central Mediterranean (CM), Iberia (IB), France (FR), Alps (AL) and Balkans (BA). The Mediterranean Sea is divided into 4 sub-basins, the Western Mediterranean Sea (MEDW), the Eastern Mediterranean Sea (MEDE), the Aegean Sea (AEG) and the Adriatic Sea (ADR).

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[5] http://www.ngdc.noaa.gov/mgg/global/global.html

period (around 1850 or 1900) as a reference but regional climate models and regional high-quality observations are not available for that period. This choice (2 full decades at the end of the 20th century) also targets to facilitate the repeatability of the MAR1 computations made in future Mediterranean studies or reports.

In addition to the reference period, we define also the "present-climate" period (1995-2014), which defines the current climate conditions. The reference period is fixed in different reports to be able to intercompare results of simulations across different model generations, whereas the present-climate will move from one report to another. For example, the IPCC-AR4 (IPCC 2007) defined 1981-2000 as present climate, whereas the IPCC-AR5 (IPCC 2013a) used 1986-2005. For the assessment of past changes, the longest period available (generally 1950-2019 or 1900-2019, if possible) in the observations is used in this report and units such as °C per decade are used in order to compare past trends computed over different past periods.

For the future, we keep 20-year time slices in order to sample the same level of internal variability as in the reference period. We divide the 21st century in 20-year time slices with a present-climate period (2000-2019), a near-future period (2020-2039), a mid-term period centered in 2050 (2040-2059) and a far-future period close to the end of the 21st century (2080-2099). The mid-21st century period is arguably of particular interest for many stakeholders, especially for mid-term adaptation. The end of the 21st century period is also of interest for stakeholders working on mitigation targets and involved in very long-term planning (e.g., for the design and planning of dams, forests, cities).

For the future climate change assessment, an important part of the uncertainty is related to the future evolution of socio-economic development. To be able to propose future climate projections considering various possible socio-economic trajectories and climate policy pathways, we follow the IPCC scenario approach. Where more recent studies are not available, the assessment also considers studies based on the older IPCC SRES approach (Nakićenović 2000). Although results based on multiple IPCC scenarios are reported in the MAR1, we mostly focus on two options which encompass the range of IPCC-AR5, CMIP5 and CORDEX simulations: the "business as usual" scenario (RCP8.5, for an explanation of the RCPs see *Box 2.2*) and the optimistic scenario closest to the UNFCCC Paris Agreement target (RCP2.6). These scenarios have been chosen also due to model projection availability constraints at the regional scale.

Detecting trends and attributing regional climate change to human influence is challenging due to natural climate variability and the strong spatio-temporal dependency of different climate variables. For projections, uncertainty estimates are provided where this is possible. For small model ensembles, the total range is also given. For larger ensemble, 90% confidence intervals are used as much as possible or else "whisker plots" describing the various statistics of the distribution (median, 25th and 75th percentile, 90% interval, minimum and maximum values).

2.2.1.1 Observations and reanalyses

More and more observation datasets have become available at regional scales, either from satellite or *in-situ* observations, or from reconstructions and reanalyzes. This new generation of observation-based products are (1) long and homogeneous enough to allow trend studies (ESA-CCI) (Ribes et al. 2019); (2) of sufficiently high spatial resolution to capture complex topography and land-sea mask (SAFRAN, EURO-4M), thereby allowing regional to local studies; and (3) of sufficiently high temporal resolution (daily or hourly, COMEPHORE) (Fumière et al. 2019), to allow the study of regionally-relevant extreme events. High-resolution gridded products have also become available for southern Mediterranean countries e.g., Cyprus (Camera et al. 2017) or Tunisia (Tramblay et al. 2019).

Finding the best fit-for-purpose observation dataset is becoming a new challenge, given the large number of available products, often characterized by substantial differences. Results of past trend studies and model evaluations are sensitive to the choice of the reference dataset (Flaounas et al. 2012; Prein and Gobiet 2017; Zittis 2018; Fumière et al. 2019; Kotlarski et al. 2019; Peña-Angulo et al. 2020). Long-term, accessible, gridded, well-calibrated and homogeneous in time and space *in-situ* data are nonetheless still lacking, especially for the ocean or the high-frequency variables over land. In addition, regional model-based reanalyzes are still rare.

Various observation datasets are used to assess the past evolution of the different components of the Mediterranean climate system. Atmospheric dynamics are mostly assessed against atmospheric reanalyzes (ERA-Interim, ERA20C, 20CR) (*Section 2.2.2)*. For aerosols, clouds and surface radiation, both satellite products and station data (BRSN, GEBA) are used to estimate past evolutions *(Section 2.2.3)*. The trend evaluation over land relies on high-resolution observation-based gridded products, i.e., CRU, E-OBS for temperature *(Section 2.2.4)* and CRU, E-OBS, U. Del, GPCC for precipitation *(Section 2.2.5)*. The other water cycle components are evaluated against reconstructed products blending *in-situ* observations, satellite and models of river networks (Ludwig et al. 2009; Pellet et al. 2019; Wang and Polcher 2019) *(Section 2.2.6)*, while satellite data are used for sea surface temperature (Marullo et al. 2010; Pisano et al. 2016; Pastor et al. 2018) *(Section 2.2.7)*, and *in-situ* data for the deep water characteristics (Houpert et al. 2016; Schroeder et al. 2017; Testor et al. 2018; von Schuckmann et al. 2018).

2.2.1.2 Modelling

Complex and realistic global and regional climate models (GCMs and RCMs), based on fundamental physics, chemistry and biology equations are currently the standard tools to simulate the future evolution of the regional climate system. Different types of climate models are available to study the Mediterranean climate (past and future), often organized in large coordinated multi-model initiatives under the World Climate Research Programme (WCRP) umbrella CORDEX (Giorgi et al. 2009) and CMIP5 (Taylor et al. 2012). Combining the various sources of information or extracting the most credible (actionable) information is a new challenge, sometimes called the "distillation" problem (Hewitson et al. 2014; Fernández et al. 2019).

The MAR1 climate assessment concerning future climate evolution is based on four climate model ensembles, chosen for their good representation of the Mediterranean climate and for their good coverage of the various sources of uncertainty in future climate projections:

- CMIP3 and CMIP5 GCM ensembles with resolution ranging approximately from 300 to 100 km: they are the largest GCM multi-model ensembles available so far. They cover at a relatively low resolution all the uncertainty sources and can provide data for all the components of the climate system (atmosphere, land, ocean, marine biogeochemistry and aerosols). Some of the participating models share components and this may result in a redundancy in the ensemble results (Knutti et al. 2017).
- The Euro-CORDEX RCM ensemble is a large high-resolution ensemble at 12 km resolution (Jacob et al. 2014), which has clearly improved the representation of climate variables compared to coarse resolution GCMs over land, e.g., for extreme precipitation (Fantini et al. 2018), regional winds (Obermann et al. 2018), mountain climate (Torma et al. 2015; Torma 2019), and over the sea, e.g., for regional winds (Herrmann et al. 2011) and extreme winds ("medicanes") (Gaertner et al. 2018). An example for the strong modification of the future climate change signal by high-resolution RCM compared to GCMs has been found for summer precipitation over the Alps (Giorgi et al. 2016). Although the EURO-CORDEX ensemble is a large high-resolution multi-model dataset, it does not cover the entire uncertainty space of the CMIP5 ensemble.
- The Med-CORDEX RCSM ensemble (Ruti et al. 2016) is a relatively small ensemble which does not cover the CMIP5 uncertainty range particularly well, but is the best data source available to study the future evolution of the Mediterranean Sea (Darmaraki et al. 2019b; Soto-Navarro et al. 2020), its ecosystems (Moullec et al. 2019) and atmosphere-ocean interactions. The models of this ensemble have high-resolution in both the atmosphere (resolution range: 25-50 km) and the ocean (resolution range: 6-30 km) component of the regional climate system (Somot et al. 2018).
- The CORDEX FPS-convection CPRCM ensemble (Coppola et al. 2020): this mini-ensemble provides the highest spatial resolution (2-3 km) for the greater Alpine region, reaching convection resolving scales. It yields, in particular, a strong improvement in the representation of extreme precipitation at sub-daily time scales (Kendon et al. 2014; Ban et al. 2015; Fosser et al. 2015; Berthou et al. 2018; Fumière et al. 2019). Convection resolving models are very promising tools to study the future evolution of extreme precipitation associated with thunderstorms, medicanes or mesoscale convective systems in the Mediterranean region (Lenderink et al. 2019) or urban-climate interactions.

A large variety of downscaling methods are available to study the Mediterranean climate (COST VALUE) (Maraun et al. 2019), including on-line tools on web processing servers (Cofiño et al. 2007). Among these methods, correcting climate change simulations using statistical tools (bias correction methods) allows to improve the present-climate statistics of climate simulations, with clear benefits for studying threshold-dependent extremes or for forcing impact models. All statistical methods require long-term observations (stations, gridded-products or satellite data calibrated for climate applications) for the learning phase and their application is therefore limited in regions where observations are lacking.

In the MAR1 report, CMIP ensembles are mostly used for the assessment of atmospheric dynamics, aerosol, cloud and radiation, water cycle, sea hydrology, sea level and acidification, whereas the Euro-CORDEX ensemble is used for the assessment of wind, clouds, temperature, precipitation and the cryosphere. The Med-CORDEX coupled regional models are used for sea hydrology and sea level, and the FPS-convection ensemble for the assessment of extreme precipitation.

Despite the continuous improvement of climate model ensembles by increased resolution and ensemble size, increased complexity and improved model physics, these still suffer from deficiencies and systematic errors. In particular their poor representation of some key regional phenomena may limit confidence for some aspects of the MAR1 assessment. This is especially true for coastal sea level, medicanes, tornadoes, hail phenomena, lightning, city climate, sub-daily precipitation, glaciers, clouds or cloud-aerosol interactions, human influence on land and water use.

2.2.2 General circulation and dynamics

2.2.2.1 General circulation

The proximity of the Mediterranean to the Atlantic and Indian Oceans and the surrounding massive land areas, with diverse climatic characteristics, places the area at the crossroads of many global climate patterns and processes of tropical and extra-tropical origin (Xoplaki et al. 2003a; Lionello et al. 2006; Lelieveld et al. 2012; Lionello et al. 2012a; Lionello 2012; Ulbrich et al. 2012). Its location on the eastern edge of the Atlantic Ocean means it is particularly affected by variability and change in the North Atlantic jet stream (or Polar Front Jet) in both winter and summer (Dünkeloh and Jacobeit 2003; Hurrell et al. 2003; Athanasiadis et al. 2010; Bladé et al. 2012) and by stationary blocking patterns (Tyrlis and Hoskins 2008). The Mediterranean Basin is also influenced by semi-permanent large-scale anticyclones (e.g., the Azores anticyclone in the west during summer and the cold Siberian anticyclone in the northeast during winter), while mobile anticyclones play also important role throughout the whole year (Hatzaki et al. 2014). During the summer, the climate of the Mediterranean is further influenced by circulation patterns set up by the Asian summer monsoon (Rodwell and Hoskins 1996) and local orography (Simpson et al. 2015).

Observed trends

The wintertime large-scale circulation has exhibited a long-term trend toward increased sea-level pressure and anticyclonic circulation over the Mediterranean *(Fig. 2.2a and b)* (Mariotti and Dell'Aquila 2012). Aside from this long-term trend, the historical record has also exhibited sizable multi-decadal variability. This is illustrated for the sea-level pressure anomalies in *Fig. 2.2e* and has also been discussed widely in the contexts of trends in the North Atlantic Oscillation (NAO) and associated Mediterranean drying that occurred over the latter half of the 20th century (Hurrell 1995) in which internal variability is thought to play an important role (Kelley et al. 2012). CMIP5 models suggest that the externally forced contribution to sea-level pressure trends since 1900 consist of a pattern that resembles that of the observed trends but with a magnitude that is considerably smaller *(Fig. 2.2c)*. It is likely that both external forcing and internal variability have contributed to the observed long-term trends (Hoerling et al. 2012). During summer, it is challenging to assess the observed long-term trends, as there is no strong agreement in the pattern of sea-level pressure change *(Fig. 2.2f and g)*. There are indications of a summertime decline in sea-level pressure over North Africa and the southern Mediterranean and, indeed, the CMIP5 models suggest that external forcings have contributed to a decline in sea-level pressure in this region over the 20th century *(Fig. 2.2h)*.

Future changes

Under rising greenhouse gas concentrations, climate models project that the Hadley Cell circulation will change, the tropics will expand and the mid-latitude westerlies and associated storm tracks will likely shift poleward *(medium/high confidence)* (Yin 2005; Lu et al. 2007b, 2007a; Chang et al. 2012; Barnes et al. 2013; Shaw et al. 2016; D'Agostino et al. 2017, 2020). This is expected to enhance subsidence and reduce storminess at the latitudes of the Mediterranean region, with a resulting reduction in precipitation *(medium confidence)*. While there is considerable inter-model spread in the magnitude of these projected changes and the forced signal can be small compared to internal variability (Woollings and Blackburn 2012; Barnes et al. 2013; Zappa et al. 2015; Quan et al. 2018; Grise et al. 2019), the Mediterranean could be influenced by additional local circulation anomalies, leading to pronounced hydroclimate changes (Seager et al. 2014; D'Agostino and Lionello 2020). Future projections suggest that the wintertime trend toward increased anticyclonic circulation

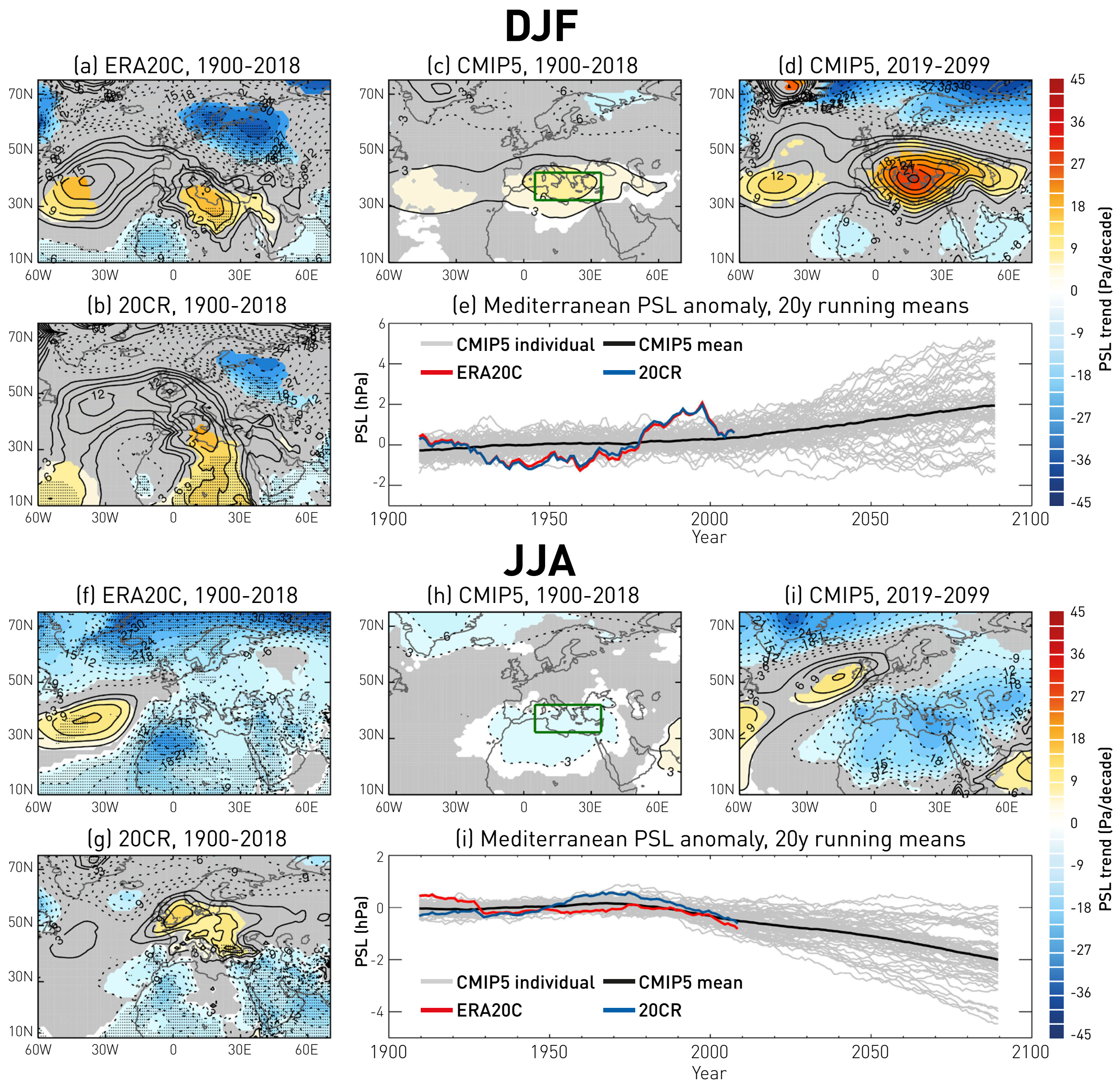


Figure 2.2 | Trends in sea level pressure (SLP). (a)-(e) show the DJF (December-January-February) season. (a) and (b) show 1900-2018 trends in SLP from ERA20C and 20CR reanalyses, respectively. Grey = not significantly different from zero at the 95% level. Significance is calculated by resampling, with replacement, the residuals of the linear trend, adding the resampled residuals to the linear trend and re-calculating the linear trend. This is repeated 1,000 times to obtain the probability (p-value) at each grid point that the trend is significantly different from zero. Spatial autocorrelation is accounted for using the False Discovery Rate method of Wilks (2016) with control value = 0.1. Stippling depicts grid points where the magnitude of the trend is larger than in any of the individual CMIP5 ensemble members. (c) shows the CMIP5 multi-model mean trend for 1900-2018. The ensemble mean for each model is calculated, then the linear trend is obtained before calculating the average trend across all models. Grey depict regions where less than 3/4 of the models agree on the sign of the change. (d) is as (c) but for future trends from 2019-2099. (e) shows time series of 20 year running mean SLP averaged over the Mediterranean (green box in c) for the two re-analyses, all individual ensemble members from all models and the CMIP5 multi-model mean. (f)-(j) are as (a)-(e) but for JJA (June-July-August).

over the Mediterranean will continue at an accelerated pace *(Fig. 2.2d)* (Giorgi and Coppola 2007). This is accompanied by a strengthening of the westerly winds and increased storminess over northern Europe, reduced westerlies over north Africa and decreasing storminess over the Mediterranean (Woollings and Blackburn 2012; Rojas et al. 2013; Zappa et al. 2013). Climate models predict a summertime poleward shift of the North Atlantic jet (Simpson et al. 2015) and a summertime decrease/wintertime increase in sea-level pressure centered over the Mediterranean *(Fig. 2.2i)* (Giorgi and Coppola 2007; Bladé et al. 2012), with the reduction in Mediterranean sea-level pressure continuing at an accelerated pace over the coming decades *(Fig. 2.2i)*, albeit with a large inter-model spread *(Fig. 2.2j)*. This was argued to be dominated by a heat-low response to drier soils in the Mediterranean region (Haarsma et al. 2009).

2.2.2.2 Teleconnection patterns

The influence of teleconnection patterns (linkages between weather changes occurring in widely separated regions of the globe) on Mediterranean climate has been extensively studied (Corte-Real et al. 1995; Hurrell and Van Loon 1997; Wibig 1999; Pozo-Vázquez et al. 2001; Quadrelli et al. 2001; Xoplaki et al. 2003a, 2003b, 2004; Hatzaki et al. 2009; Toreti et al. 2010; Ulbrich et al. 2012; Tyrlis and Lelieveld 2013; Rousi et al. 2015; Sen et al. 2019). Particularly during winter, the region is prone to the impacts of the westerly flow and the teleconnection patterns of North Atlantic Oscillation (NAO), Eastern Atlantic/Western Russia (EA/WR) and Scandinavian (SCAN) (Barnston and Livezey 1987).

The NAO is, for parts of the region, one of the most important modes of internal climate variability. It affects especially the storm-tracks and cyclogenesis over parts of the basin (Trigo et al. 2000, 2004; Reale and Lionello 2013) and mainly precipitation over the western-central Mediterranean in winter (Lamb and Peppler 1987; Rodríguez-Fonseca and de Castro 2002; Xoplaki et al. 2004). NAO is also found to have some influence on winter precipitation in parts of the eastern Mediterranean, however this influence is smaller (Dünkeloh and Jacobeit 2003; Xoplaki et al. 2004; Feliks et al. 2010; Felis and Rimbu 2010; Nissen et al. 2010). A lesser but distinct influence is detected between NAO and the Mediterranean surface air temperature (Hurrell 1995; Cullen and DeMenocal 2000; Ben-Gai et al. 2001; Pozo-Vázquez et al. 2001; Sáenz et al. 2001; Castro-Díez et al. 2002; Trigo et al. 2002b; Türkeș and Erlat 2003; Xoplaki et al. 2003b; Toreti et al. 2010).

Observed trends of NAO are not monotonic and are difficult to assess since decadal oscillations are too large to reach a conclusion with an acceptable level of confidence. Nevertheless, mostly negative trends prevail since the early 1990s following a positive trend starting in the 1960s (Ulbrich and Christoph 1999; Mariotti et al. 2002b; Türkeș and Erlat 2003; Trigo et al. 2004, 2006; Xoplaki et al. 2004; Pinto and Raible 2012; Saffioti et al. 2016; Iles and Hegerl 2017).

Climate projections mostly suggest a weak positive NAO trend in a warmer future climate *(low/medium confidence)*, accompanied by a small northeastward displacement of its centers-of-action by the end of the 21st century (Ulbrich and Christoph 1999; Gillett et al. 2003, 2013; Hu and Wu 2004; Stephenson et al. 2006; Bacer et al. 2016; Deser et al. 2017; Barcikowska et al. 2020). Some studies indicate no significant trends (Fyfe et al. 1999; Dorn et al. 2003; Rauthe et al. 2004; Fischer-Bruns et al. 2009), or even decreasing trends (Osborn et al. 1999).

Studies on the effect of El Niño Southern Oscillation (ENSO) phenomenon on Mediterranean precipitation have shown that links exist, particularly during autumn and spring in the western Mediterranean and during winter in the Eastern Mediterranean. However, results are not conclusive concerning their evolution and robustness. In fact, the ENSO signal is difficult to be isolated, because of the dominating mid-latitude dynamics, the sign of its correlation with total precipitation depends on season and it is not stationary (Rodó et al. 1997; Rodó 2001; Mariotti et al. 2002b, 2005; Knippertz et al. 2003; Hasanean 2004; Alpert et al. 2006; López-Parages and Rodríguez-Fonseca 2012; Kalimeris et al. 2017).

2.2.2.3 Extratropical cyclones and medicanes

The Mediterranean is one of the main cyclogenetic areas of the world (Petterssen 1956; Hoskins and Hodges 2002; Wernli and Schwierz 2006), with much of the high-impact weather (e.g., strong winds and heavy precipitation) associated with cyclonic structures. Cyclogenesis areas such as the north-western Mediterranean, North Africa, the north shore of the Levantine Basin, the seasonality (Alpert et al. 1990a, 1990b; Trigo et al. 1999, 2002a; Lionello et al. 2006, 2016; Campins et al. 2011), as well as the occurrence of explosive cyclogenesis (Kouroutzoglou et al. 2011; Reale et al. 2019) are well documented in the literature. Within Mediterranean cyclones, there is a sub-group of hybrid depressions of extratropical cyclogenesis, the so-called 'medicanes' (Mediterranean hurricanes) or tropical-like cyclones (Rasmussen and Zick 1987; Reale and Atlas 2001; Emanuel 2005). These are mesoscale maritime extratropical cyclones that can physically emulate tropical characteristics at a certain point of their life cycle (Emanuel 2005; Miglietta 2019). Such features can include a cloud-free area at the center (the "eye"), spiral bands with deep convection around it, intense surface winds and a warm-core and symmetric structure (Miglietta et al. 2015). These events can pose serious societal and ecological threat to the affected coastal regions (Nastos et al. 2018).

During the recent past there is an absence of strong trends in cyclone numbers affecting the Mediterranean (Lionello et al. 2016), however when trends are detected these are mostly negative *(low/medium confidence)* (Trigo et al. 2000; Maheras et al. 2001; Flocas et al. 2010; Nissen et al. 2010). Similarly, the number of explosive Mediterranean cyclones has likely decreased, but this reduction is not statistically significant (Kouroutzoglou et al. 2010). The statistical record of medicanes has limited reliability and sample size, given their maritime characteristics, small size and infrequent occurrence. Thus, it has not been possible to derive an objective climatology. Observational studies cannot be used to identify trends because the identification is commonly subjective (Miglietta et al. 2013; Tous and Romero 2013; Nastos et al. 2018). Dynamical downscaling methods have been used to build a medicane climatology, but only negligible trends were obtained (Cavicchia et al. 2014).

For the future, climate models project a reduction in the number of cyclones *(medium/high confidence)* especially in winter (Lionello et al. 2002; Geng and Sugi 2003; Bengtsson et al. 2006; Leckebusch et al. 2006; Lionello and Giorgi 2007; Pinto et al. 2007; Löptien et al. 2008; Ulbrich et al. 2009; Raible et al. 2010; Zappa et al. 2013; Nissen et al. 2014). There is some uncertainty, as the spread in the model responses appears to be quite large (Ulbrich et al. 2008, 2009; Harvey et al. 2012). With respect to cyclone intensity, climate projections are more controversial, as some models suggest a decrease in the frequency of the most intense systems (Pinto et al. 2007; Raible et al. 2010), while other models show more extreme events or increases in the intensity of extreme cyclones (Lionello et al. 2002; Gaertner et al. 2007). For medicanes, climate projections indicate a decreasing response in frequency but increasing intensity (Gaertner et al. 2007; Romero and Emanuel 2013, 2017; Cavicchia et al. 2014; Walsh et al. 2014; Tous et al. 2016; Romera et al. 2017; González-Alemán et al. 2019).

2.2.2.4 Regional winds

Surface wind speed and its changes on different temporal and spatial scales are governed by driving and drag forces, where all relevant contributions are difficult to estimate and disentangle (Wu et al. 2018a). Surface wind climate studies are less common than air-temperature and precipitation studies for example, and more work is needed to explain historical wind speed evolution and precisely estimate different sources of uncertainty in the future projections. This variable is now becoming more important, since parts of the region, both inland and offshore, have high potential for the production of wind energy (Balog et al. 2016; Onea et al. 2016) *(Chapter 3.3)*.

Observation-based studies of winds over the Mediterranean are rare, and depend on the availability of homogenized and long time series. In most regions, wind trends were found non-monotonic over the past decades and, concrete conclusions are difficult to be established (Pirazzoli and Tomasin 2003; Vautard et al. 2010; Azorin-Molina et al. 2014). An additional source of information are reanalysis datasets, but robust trends have been identified over only a few regions in the Mediterranean (Nissen et al. 2010; Donat et al. 2011; Bett et al. 2013). Climate model simulations over historical periods can also be used in assessing and understanding past trends (Knippertz et al. 2000).

Despite the uncertainties in future projections (Shepherd 2014; Belušić Vozila et al. 2019), there is a general agreement for a limited wind speed reduction over most of the Mediterranean, with the exception of the Aegean Sea and north eastern land areas *(Fig. 2.3, Section 2.2.8) (medium confidence)* (Somot et al. 2006; Mcinnes et al. 2011; Dobrynin et al. 2012; Planton et al. 2012; Belušić Vozila et al. 2019). Changes in the local winds (such as Bora, Mistral, Tramontane, Sirocco and Etesians) may have more complex responses involved, depending on the changes in their underlying feedbacks (Grisogono and Belušić 2009; Ulbrich et al. 2012). Regional projections over the Adriatic reveal strong sensitivity in the climate change signal of the local Bora and Sirocco winds (Belušić Vozila et al. 2019). In particular, the frequency of winter Bora events is projected to increase while the frequency of Sirocco events is expected to decrease. Overall, the mean wind speed during Bora and Sirocco events is expected to be reduced, with the exception of Bora in northern Adriatic. RCM projections of Mistral and Tramontane show small changes in the former and significant decrease in the frequencies of the latter (Obermann-Hellhund et al. 2018). Etesian winds over the Aegean Sea is one of the few exceptions since increases in the wind speed are expected for the future (Ezber 2018; Dafka et al. 2019). In general, RCM projections have the

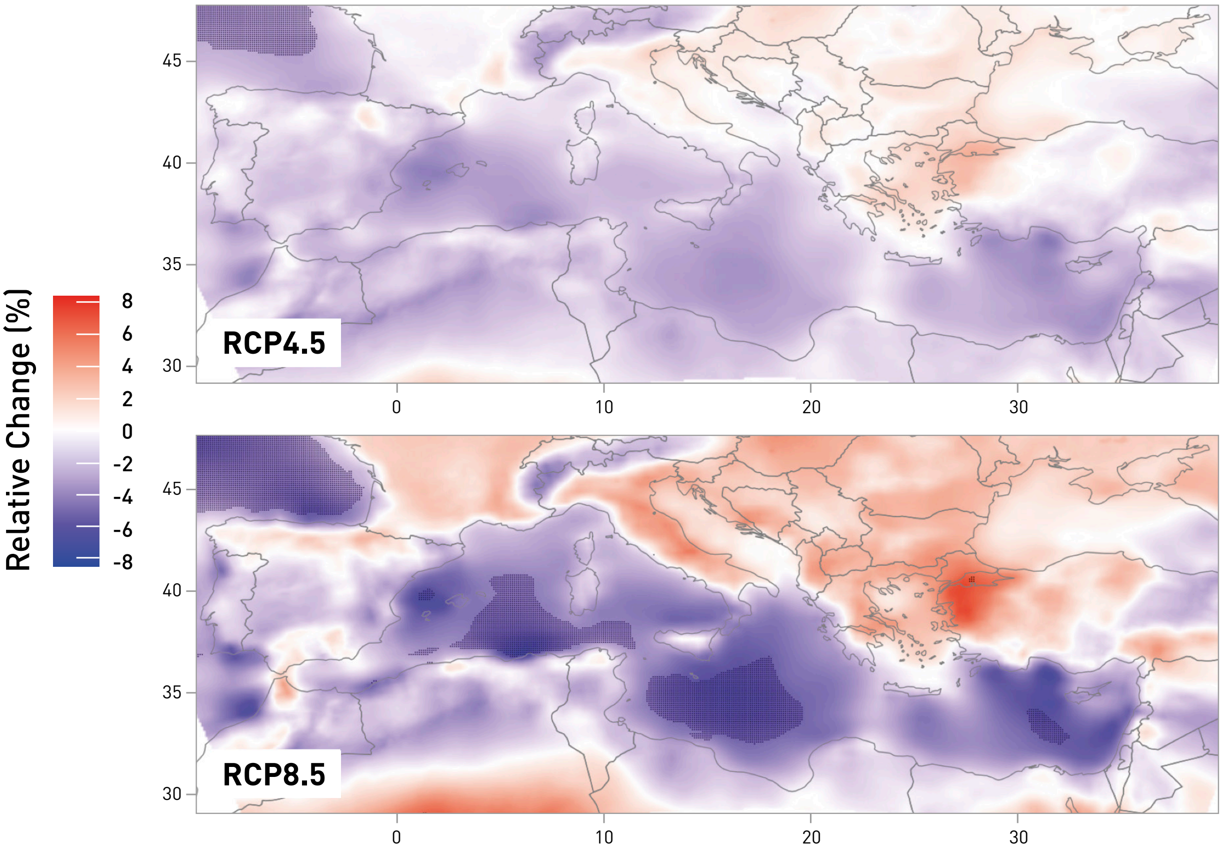


Figure 2.3 | Projected changes (%) in surface wind speed based on Med-CORDEX simulations (Ruti et al. 2016) for the end of the 21st century (2071-2100) relative to the period 1961-1990, for pathways RCP4.5 (top panel) and RCP8.5 (bottom panel). Seven RCMs were used for RCP4.5 and eight RCMs were used for RCP8.5. Dotted areas show differences that passed a 95% significance test.

tendency to simulate decrease of the wind energy density over the Mediterranean, with the exception of the Aegean Sea (Hueging et al. 2013; Tobin et al. 2015; Moemken et al. 2018).

Regional climate simulations indicate changes in wind speed over land regions as well *(Fig. 2.3)*. Most pronounced changes, consistent for both RCP4.5 and RCP8.5 pathways, are an increase of wind speeds over the Balkans and a decrease over the Alps.

2.2.3 Radiation, clouds and aerosols

The amount of solar radiation reaching the Earth's surface is a key determinant of the spatio-temporal variations of climate on our planet and is the ultimate energy source for all processes relevant for climate and life. The main factors explaining the variability of surface solar radiation over the Mediterranean region for different time scales (daily, seasonal, interannual, past and future trends) are clouds (Pyrina et al. 2015) and aerosols (Nabat et al. 2015a, 2015b). The daily variability in clouds and aerosols is strongly influenced by weather regimes (Rojas et al. 2013; Nabat et al. 2020) and climate oscillations such as the North Atlantic Oscillation, NAO (Chiacchio and Wild 2010).

Aerosols in the Mediterranean come from various and numerous sources (Lelieveld 2002), both natural, notably dust and sea-salt, and anthropogenic, notably sulfates, nitrates and black carbon *(Section 2.3)*. Their interactions with radiation and clouds are essential in understanding climate in this region.

2.2.3.1 Observed change in surface radiation

The long-term solar radiation records taken at widespread locations around the globe underwent substantial multidecadal variations, characterized by a reduction of surface solar radiation from the 1950s to the 1980s, known as "global dimming" and a partial recovery, thereafter, referred to as "brightening" (Wild 2009, 2012; Wild et al. 2017). This dimming/brightening pattern is also observed

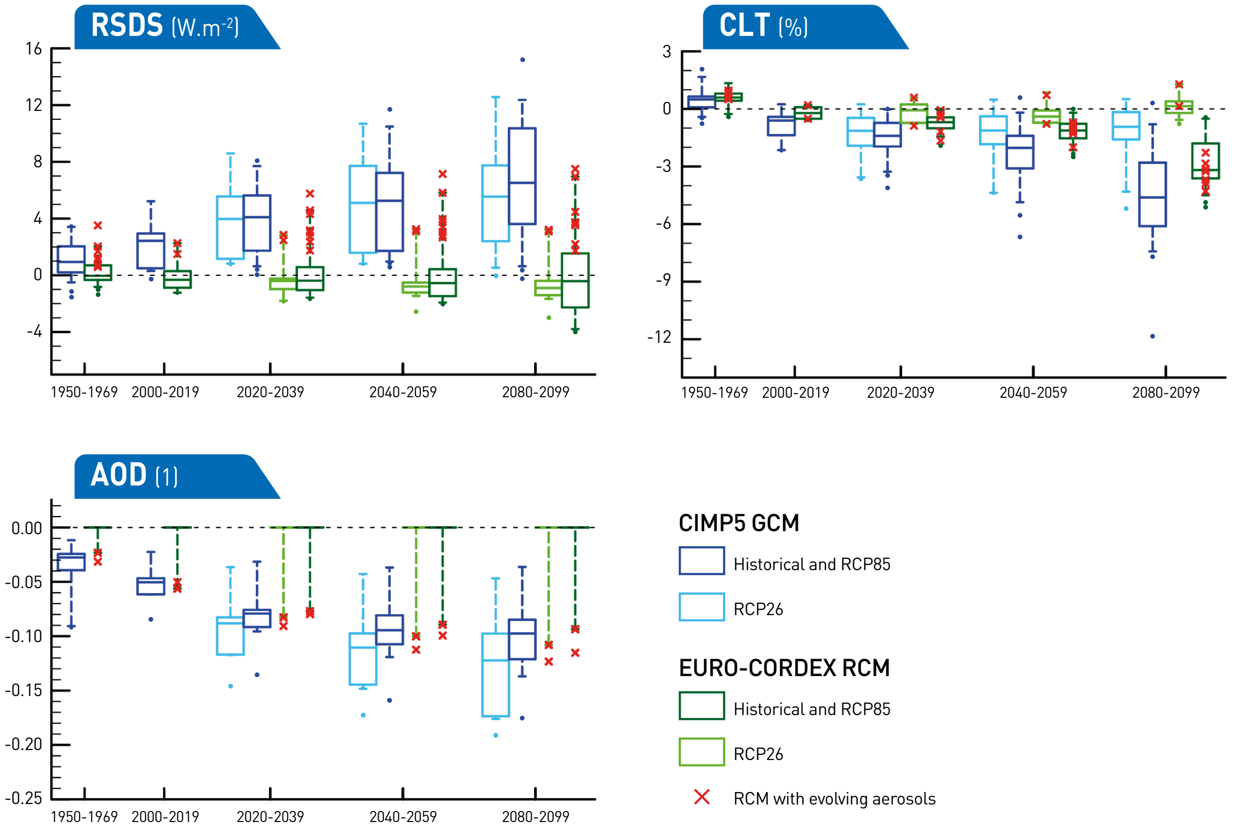


Figure 2.4 | Past and future evolution of Surface Downwelling Shortwave Radiation (RSDS in W m^{-2}), Total Cloud cover (CLT in %) and Aerosol Optical Depth (AOD) from 1950 to 2100 averaged over the Mediterranean area in CMIP5 Global Climate Models (GCM) and 12-km Euro-CORDEX Regional Climate Models (RCM) ensembles. Figures based on Bartok et al. (2017), redrawn and extended using published datasets.

in the Mediterranean area *(very high confidence)*, both in all-sky and clear-sky conditions, documented with many ground-based and satellite observations after careful data quality assessment and homogenization (Sánchez-Lorenzo et al. 2007, 2013, 2017; Zerefos et al. 2009; Kambezidis et al. 2016; Manara et al. 2016; Alexandri et al. 2017; Pfeifroth et al. 2018), as well as climate simulations (Folini and Wild 2011; Zubler et al. 2011; Nabat et al. 2014). The surface solar radiation trends averaged over the Mediterranean have been estimated in climate model simulations between -3.5 and -5.2 W m^{-2} per decade for the dimming period (1953-1968), against for the brightening period between +0.9 and +4.6 W m^{-2} per decade in 1989-2004 (Folini and Wild 2011) and 2.3 W m^{-2} per decade in 1980-2012 (Nabat et al. 2014). The surface solar radiation anomalies calculated by global climate models for the periods 1950-1969 and 2000-2019 against the reference period of 1980-1999 are positive, showing respectively the dimming and the brightening effects, since the reference period refers to the period where surface solar radiation was the lowest *(Fig. 2.4)*.

In parallel to the brightening period, a decrease in aerosol loads has been observed since 1980 both in ground-based stations (Li et al. 2014) and in satellite data (Floutsi et al. 2016). This decrease, corresponding to a trend in aerosol optical depth of -0.03 decade^{-1}, is mainly due to reductions in anthropogenic emissions, leading to a decrease in anthropogenic aerosol concentrations such as sulfate (Nabat et al. 2013). These aerosol trends have been shown to be the main explanation of the dimming-brightening phenomenon in the Mediterranean area *(high confidence)* through attribution model studies (Folini and Wild 2011; Zubler et al. 2011; Nabat et al. 2014), and with the direct aerosol effect responsible for about 80% of the simulated brightening. This phenomenon is qualitatively reproduced by most GCMs, but only by a few regional climate models, due to different treatments of aerosols in models *(Fig. 2.4)*. The evolution of natural aerosols is more uncertain over the same period.

Concerning clouds, a decrease in cloud cover of 0.63% per decade since the 1970s has also been detected from different observations datasets over the Mediterranean area (Sánchez-Lorenzo et al. 2017). This trend mainly concerns low and mid cloud layers (Kambezidis et al. 2016) *(medium confidence)*. The spread between models that capture these trends is high, because of their difficulties to capture cloud characteristics *(Fig. 2.4)*. Clouds may also have played a significant role in the past trend of surface solar radiation, at least locally *(low confidence)*. Stronger positive trends in surface solar radiation are detected in spring over western Mediterranean Basin, explained by a decrease in cloud optical depth for this season over this basin (Kambezidis et al. 2016), and despite an averaged positive trend of surface solar radiation observed over the eastern basin, more uncertainty exists due to the lack of observations of both clouds and aerosols (Alexandri et al. 2017).

2.2.3.2 Projected change in surface radiation

In future climate projections, anthropogenic aerosol loads over the Mediterranean are expected to keep on decreasing *(high confidence)* because of decreases in anthropogenic emissions in Europe (Shindell et al. 2013). The decrease is expected to be more pronounced in the near future with an aerosol optical depth anomaly between -0.12 and -0.03 (5-95% uncertainty range) for the 2040-2059 period with respect to the reference period 1980-1999 *(Fig. 2.4)*, and will slow down in the far future (between -0.18 and -0.04, 2080-2099 vs 1980-1999). The evolution of natural aerosols is more uncertain, due to current unknown future evolution of the desert dust *(Section 2.3.2)*.

Total cloud cover is also expected to decrease during the 21st century over the Mediterranean *(medium confidence)* (Boé and Terray 2014; Enriquez-Alonso et al. 2016; Bartók et al. 2017; Hentgen et al. 2019). This is consistent with the northward expansion of the Hadley cell (Sánchez-Lorenzo et al. 2017; D'Agostino et al. 2020) *(Section 2.2.2)* and with enhanced lower tropospheric drying (Hentgen et al. 2019). The expected anomaly in cloud cover for the mid-21st century ranges from -4.9 to -0.2% in the RCP8.5 (5-95% uncertainty range, *Fig. 2.4*), because of the difficulty of models to capture the spatial variability of the cloudiness evolution (Bartók et al. 2017).

As projected by GCMs, surface solar radiation is expected to continue increasing in the 21st century, especially in the near future *(medium confidence)*. The anomaly is between 0.6 and 7.7 W m^{-2} for the period 2020-2039 in the RCP8.5 (5-95% uncertainty range), in line with the decrease in anthropogenic aerosols (Boé et al. 2020; Gutiérrez et al. 2020) *(Fig. 2.4)*. However, this evolution is not shared by all RCMs (Bartók et al. 2017; Gutiérrez et al. 2020). Only regional climate models which consider aerosol dynamics simulate the increase in surface solar radiation as the global models (Boé et al. 2020; Gutiérrez et al. 2020). This increase in future surface solar radiation is reinforced by an expected decrease in cloud cover (Enriquez-Alonso et al. 2016), despite a compensational effect of increased absorption in clear sky conditions due to higher water vapor content in the atmosphere (Haywood et al. 2011) *(Fig. 2.4)*.

2.2.4 Temperature and related extremes

2.2.4.1 Observed temperature changes

Climate reconstructions, ground-based observations, reanalysis and remote-sensing datasets all corroborate the transition to warmer conditions during the 20th century and that warming has accelerated during the last decades *(high confidence)*. Basin-wide, annual mean temperatures are now 1.5°C above late 19th century levels *(Box 2.1, Fig. 2.33)*. Particularly after the 1980s, regional warming has accelerated and increases at a higher rate than the global average (Lelieveld et al. 2012; Lionello et al. 2012a; Zittis and Hadjinicolaou 2017; Cramer et al. 2018; Lionello and Scarascia 2018; Zittis et al. 2019). These studies present a strong consensus that the recent observed warming is robust throughout the region analysis, though magnitude and level of significance of the observed temperature trends in the Mediterranean varies depending (a) on the region, country or station under consideration, (b) on the type of data set investigated and (c) on the season and period of analysis.

Solar forcing and large volcanic eruptions are found to have a strong influence on the Mediterranean temperature variability over the last centuries (Trouet 2014). A combination of climate reconstructions, documentary sources and observed data suggests that looking at the long-term timescale (e.g., over the last 500 years), warm periods are not exceptional for the Mediterranean, which is characterized by a sequence of warming–cooling cycles (Luterbacher and Xoplaki 2003; Camuffo et al. 2010; Lelieveld et al. 2012). A study of summer temperature since Roman times shows that although the mean 20th century European (including the northern part of the Mediterranean Basin) was not significantly warmer than some

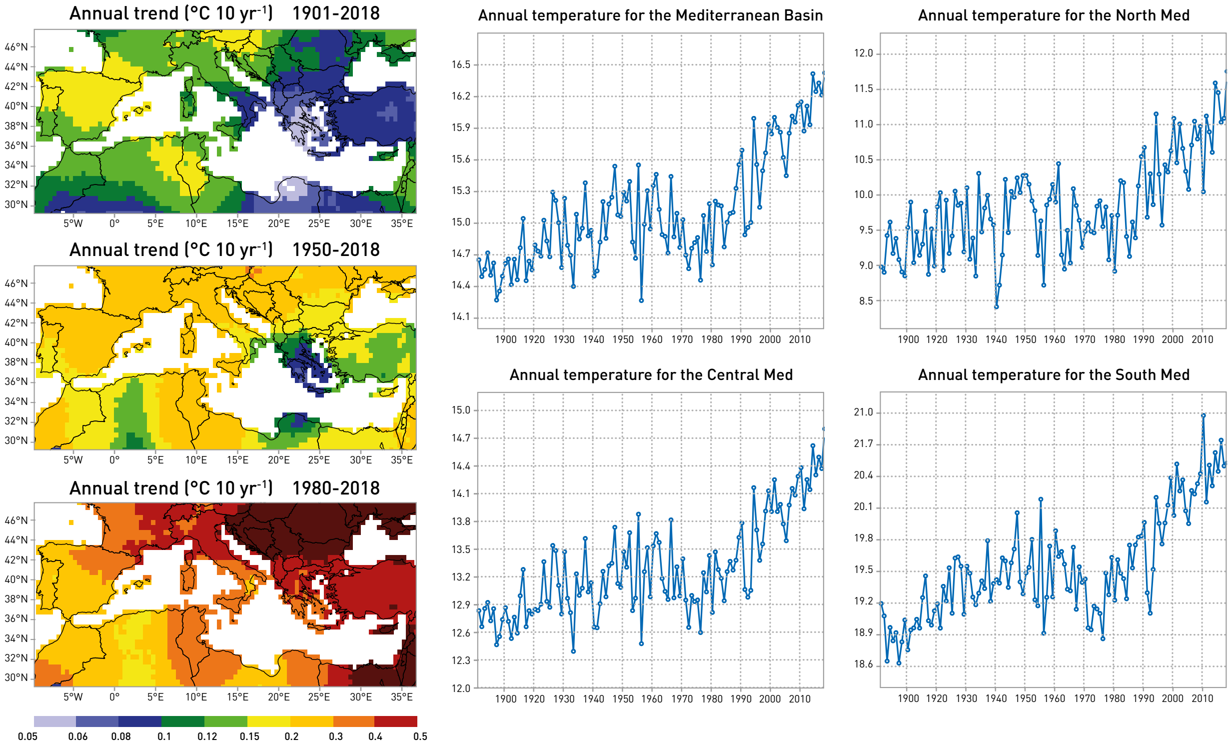


Figure 2.5 | Observed temperature trends (left panels) and time-series of temperature over land for the Mediterranean based on the Climatic Research Unit (CRU) (Harris et al. 2020) gridded observations. Time-series refer to the whole Mediterranean as defined in the left panels and for three Mediterranean sub-regions *(Fig. 2.1)*: North (FR, ALBA), Central (IB, CM, AN) and South Mediterranean (WM, EM, LE).

earlier centuries, there are no earlier 30-year periods found to be warmer than the most recent 3 decades (Luterbacher et al. 2016).

Recent climatic trends are clear, particularly after the 1980s. Over these last decades, according to different type of observations, significant positive trends of the order of 0.1-0.5°C per decade have been identified *(Fig. 2.5)* (Nasrallah and Balling 1993; Saaroni et al. 2003; Feidas et al. 2004; Brunetti et al. 2006; El Kenawy et al. 2009; Tanarhte et al. 2012; Lelieveld et al. 2012; Lionello 2012; Donat et al. 2014; Mariotti et al. 2015; Lionello and Scarascia 2018; Bilbao et al. 2019). In addition, for parts of the basin, there is some evidence that the diurnal temperature range has also changed (Price et al. 1999; Bilbao et al. 2019; Sun et al. 2019).

Besides mean values, hot and cold extremes have also become warmer, while in particular there is strong evidence and consensus that heat waves have become more frequent and severe. Various climatic indicators show significant increasing trends of extreme heat events characteristics (e.g., duration, frequency and intensity). The number of warm and tropical nights has also increased over most Mediterranean locations including Iberia, north Africa, Italy, Malta, Greece, Anatolia and the Levant (Kostopoulou and Jones 2007; Bartolini et al. 2008; Kuglitsch et al. 2010; El Kenawy et al. 2011; Galdies 2012; Donat et al. 2014; Filahi et al. 2015; Lelieveld et al. 2016; Ceccherini et al. 2017; Nashwan et al. 2018; Tolika 2019). Parts of the region were impacted by some of the most severe record-breaking weather events of the last decade, mainly related with summer heat extremes (Coumou and Rahmstorf 2012). Considering only winter, some studies that suggest a different behavior of hot and cold extremes between the eastern and western parts of the Mediterranean, with negative temperature trends in the former and positive trends in the latter (Hertig et al. 2010; Efthymiadis et al. 2011), but these studies do not include the most recent warm decades.

2.2.4.2 Future temperatures

According to future projections, the greater Mediterranean Basin is among the most responsive regions to global warming. Previous studies have identified the region as one of the most prominent climate change hot spots (Giorgi 2006; Lionello et al. 2006; Giorgi and Lionello 2008; Diffenbaugh and Giorgi 2012; Lionello 2012; Lionello and Scarascia

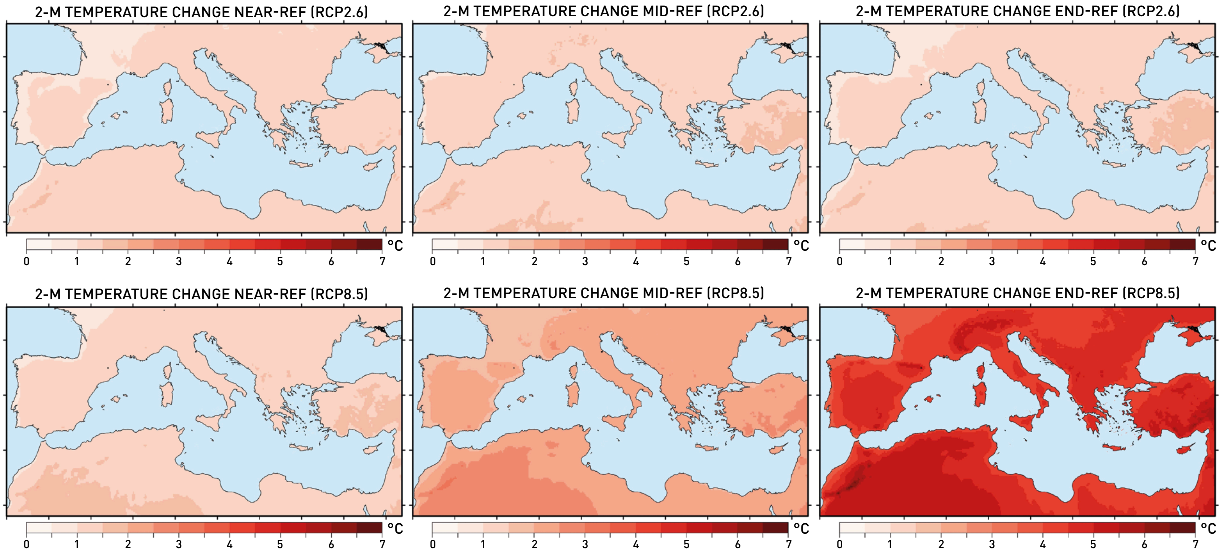


Figure 2.6 | Projected changes in annual temperature between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean of EURO-CORDEX 0.11° simulations for pathways RCP2.6 (top panels) and RCP8.5 (bottom panels).

2018). Multi-model ensembles of climate simulations indicate that widespread warming will almost certainly occur in the Mediterranean in the 21st century *(high confidence)*, though, climate models might overestimate actual values in warm and dry conditions (Boberg and Christensen 2012).

The warming level of warming strongly depends on the reference period definition, the future time horizon and the level of greenhouse gas forcing (Christensen et al. 2007; Giorgi and Lionello 2008; Collins et al. 2013; Dubrovský et al. 2014; Jacobeit et al. 2014; Mariotti et al. 2015; Ozturk et al. 2015; Lionello and Scarascia 2018; Zittis et al. 2019). A quantitative estimation based on state-of-the-art EURO-CORDEX regional simulations is presented in *Table 2.1* and *Fig. 2.6-2.7*. Over land regions, a robust and significant warming of the range of 0.9-5.6°C (with respect to the reference period 1980-1999) is suggested for the future. The robustness and significance of the climate signal is much higher for air temperature rather than other variables such as precipitation (Knutti and Sedláček 2012; Lelieveld et al. 2016). There are strong indications and a general consensus that regional warming will continue faster than the global average and will exceed the global mean value by 20% on an annual basin and 50% in summer *(high confidence)* (Vautard et al. 2014; Dosio and Fischer 2018; Lionello and Scarascia 2018; Nikulin et al. 2018). Daytime temperatures are expected to increase more than nighttime temperatures, indicating an increase of the amplitude of the diurnal temperature range (Lionello and Scarascia 2018).

Changes in the occurrence of extreme events closely follow changes in inter-annual variability. Therefore, such changes can be also considered as a proxy measure of seasonal extremes (Schär et al. 2004; Giorgi 2006). The intensity of extreme temperature is projected to increase more rapidly than the intensity of more moderate temperatures over the continental interior due such increases in temperature variability (Beniston et al. 2007).

Projected changes in extreme temperature indicators suggest that the frequency and severity of heat waves will increase *(high confidence)* (Diffenbaugh et al. 2007; Goubanova and Li 2007; Giorgi and Lionello 2008; Fischer and Schär 2010; Diffenbaugh and Giorgi 2012; Sillmann et al. 2013; Russo et al. 2014; Jacob et al. 2014; Kostopoulou et al. 2014; Zittis et al. 2016; Lelieveld et al. 2016; Ouzeau et al. 2016; Lionello and Scarascia 2020). According to projections for a business-as-usual scenario, summer daily maximum temperature is expected to increase up to 7°C by the end of the 21st century in comparison with the recent past (Sillmann et al. 2013; Lelieveld et al. 2016). Besides warmer daytime temperature maxima, parts of the Mediterranean will likely face an increase of more than 60% in the number of tropical nights. Increase of warm temperature extremes will be dramatic particularly in summer and with a 4°C global warming almost all nights will be warm and there will be no cold days (Sillmann et al. 2013; Dosio and Fischer 2018; Lionello and Scarascia 2020).

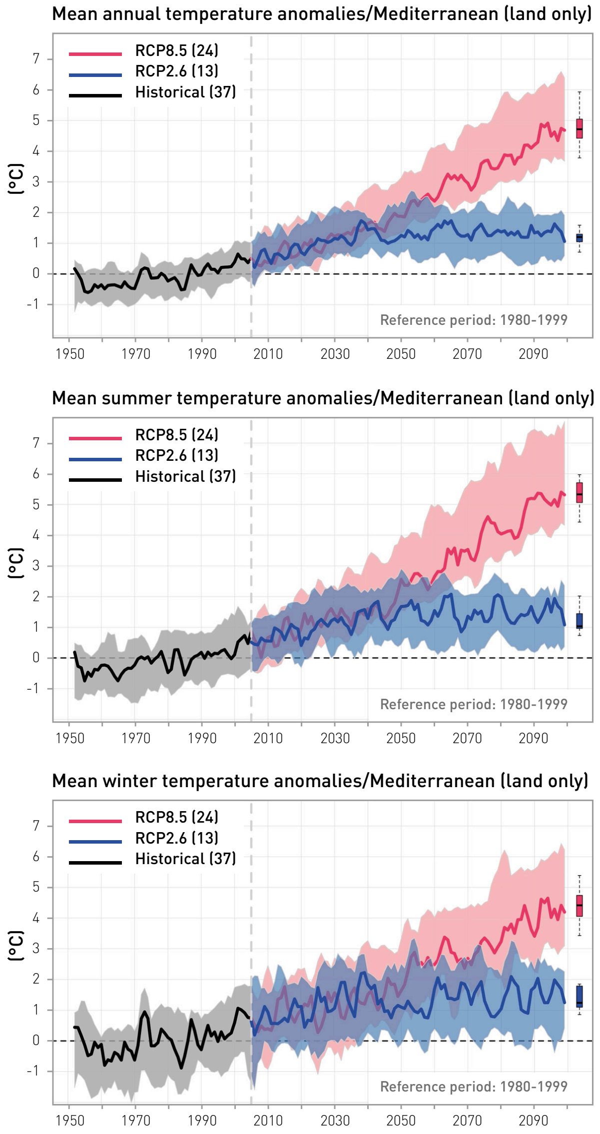


Figure 2.7 | Time-series of simulated mean annual (top panel), summer (middle panel) and winter (bottom panel) temperature averaged over the Mediterranean based on EURO-CORDEX 0.11° simulations for historical times (black curve) and future pathways RCP2.6 (blue curve) and RCP8.5 (red curve). Solid lines indicate the ensemble means and shaded areas the spread of the simulations. Box-plots represent the averages over the decade 2091-2100 in terms of model spread.

Warming is projected to be milder in winters and much stronger during summers. This is mainly attributed to land-atmosphere interactions and the transition to drier conditions (Seneviratne et al. 2006; Jaeger and Seneviratne 2011; Quesada et al. 2012; Zittis et al. 2014). Another important feedback, particularly for southern Mediterranean, is the coupling of longwave radiation between the desert soil surface and lower atmosphere which amplifies warming and intensifies the summertime heat low over the Sahara (Cook and Vizy 2015; Evan et al. 2015). The exceptional summertime warming over parts of the region is also likely associated with a thermal low, which is explained by the widening of the Persian trough that extends from South Asia to the eastern Mediterranean, and is projected to expand westward and combine with the intensifying thermal low over the Sahara (Lelieveld et al. 2016).

2.2.5 Precipitation, related extremes and the water cycle

2.2.5.1 Observed trends in precipitation

Observed precipitation trends during the full or portions of the 20th century up to present day, covering the full or portions of the Mediterranean Basin, are available in gridded format from various sources, such as CRU, UDEL, E-OBS, EURO4M. Annual, DJF (December-January-February) and JJA (June-July-August) precipitation trends from the CRU dataset for different time periods, 1950-2018 and 1980-2018 are shown in *Fig. 2.8*. *Fig. 2.9* shows the temporal evolution of land precipitation (1901-2018) averaged over the full Mediterranean area and its northern, central and southern portions (defined as the sum of the three northern, central and southern regions of *Fig. 2.8*, respectively).

The sign of the observed precipitation trend exhibits pronounced spatial variability and depends on the time period and season considered *(Fig. 2.8)*. For example, the period 1950-2018 shows a prevailing decreasing trend over most of the Mediterranean Basin of annual and winter precipitation, which is reversed over large portions of the basin if we only consider the period 1980-2018. This is because of the marked multidecadal variability of precipitation in the Mediterranean, which may actually mask trends induced by greenhouse gas emissions. The prominent role of multidecadal variability is also evident when precipitation is regionally averaged *(Fig. 2.9)*. In this case the most evident trend is a decrease of winter precipitation over the central and southern portions of the basin since the second half of the 20th century. Overall, because of the marked multidecadal variability of precipitation and the small magnitude of trends, the confidence in the detection of trends from greenhouse gas emissions for the historical past is low (Lelieveld et al. 2012; Lionello et al. 2012a; Peña-Angulo et al. 2020; Vicente-Serrano et al. 2020).

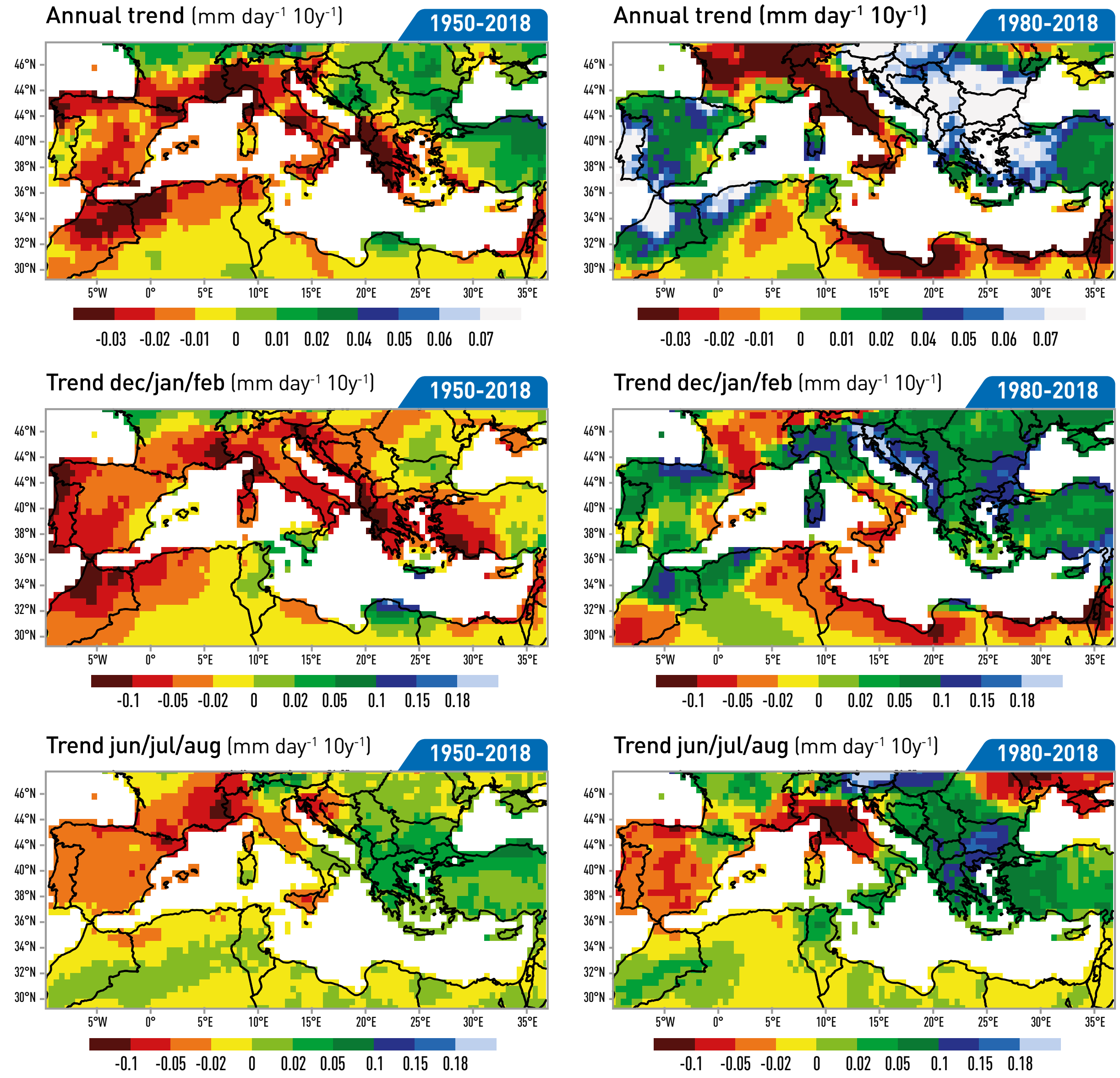


Figure 2.8 | Observed annual, DJF, JJA precipitation trends from the CRU dataset. Left and right panels consider the 1950-2018 and 1980-2018 periods, respectively.

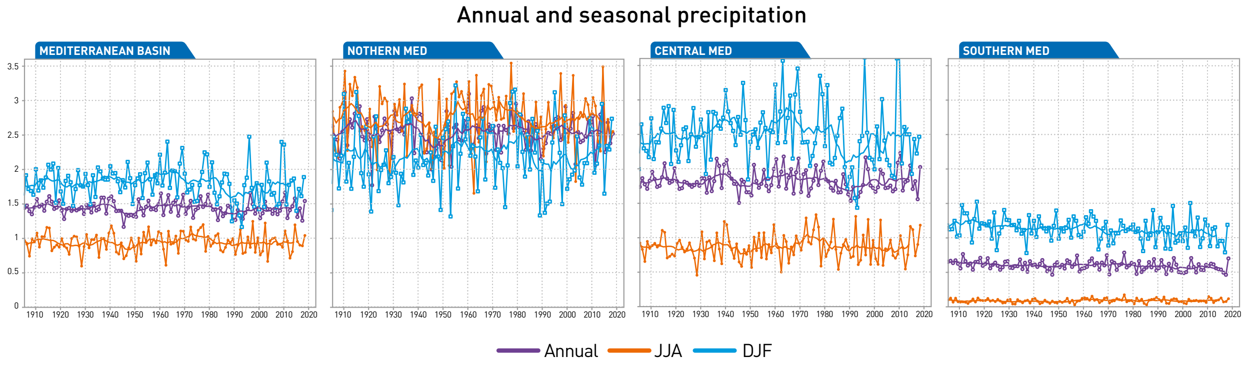


Figure 2.9 | Time series of annual, DJF, and JJA precipitation over land from the CRU dataset. Time-series refer to the whole Mediterranean as defined in the left panels and three Mediterranean sub-regions *(Fig. 2.1)*: North (FR, ALBA), Central (IB, CM, AN) and South Mediterranean (WM, EM, LE).

2.2.5.2 Future precipitation

Mean precipitation changes

21st century precipitation projections for the Mediterranean region have been produced based on GCM and RCM ensembles of experiments. Analyses of GCM projections over the Mediterranean region have been conducted for CMIP3 (Giorgi and Coppola 2007; Giorgi and Lionello 2008; Mariotti et al. 2008) and CMIP5 (Mariotti et al. 2015; Lionello and Scarascia 2018). Several generations of RCM-based projections for the EURO-Mediterranean region are also available from projects such as PRUDENCE (Déqué 2007), ENSEMBLES (Déqué et al. 2012) and EURO-CORDEX (Jacob et al. 2014). In addition, projections based on coupled regional atmosphere-ocean models have been conducted as part of the CIRCE (Gualdi et al. 2013) and MED-CORDEX (Ruti et al. 2016) projects.

A consistent dominant signal emerges from these projections, consisting of a predominant drying through the entire Mediterranean Basin in the warm seasons (April through September, with largest magnitude in JJA), drying in most central and southern areas along with wetting in the northernmost regions (e.g., the Alps) in the winter season *(medium confidence)*. This large-scale pattern of change is illustrated for the Euro-CORDEX dataset, at the annually averaged scale, in *Fig. 2.10* for the RCP2.6 and RCP8.5 scenarios and different future time slices. *Table 2.1* provides quantitative values of precipitation change for different scenarios and model ensembles over the Mediterranean region.

In general, the patterns of change intensify in magnitude from the near future to the far future time slices and from the low to high greenhouse gas emission scenarios, i.e., they intensify with the anthropogenic forcing and resulting global warming. As a result, for example, at the Mediterranean scale, the CMIP5 ensemble yields a decrease of annual precipitation over the Mediterranean area of about 4% per degree of global warming (Lionello and Scarascia 2018).

The magnitude and pattern of precipitation decrease vary widely across models. For example, the summer precipitation reduction in the CMIP3 and CMIP5 datasets for the high-end greenhouse gas emission scenarios (roughly equivalent to the RCP8.5) varied from less than 10% to over 40% across models (IPCC 2007; Giorgi and Lionello 2008; Lionello and Scarascia 2018). Although qualitatively consistent, different ensembles show different sensitivities over the Mediterranean. The CMIP5 GCM ensemble produced a less pronounced summer drying than the CMIP3 one, when expressed in terms of change per degree of global warming (IPCC 2013b). RCM-based projections, e.g., as part of Euro-CORDEX yield a lower drying that GCM-based ones, with reduced areas

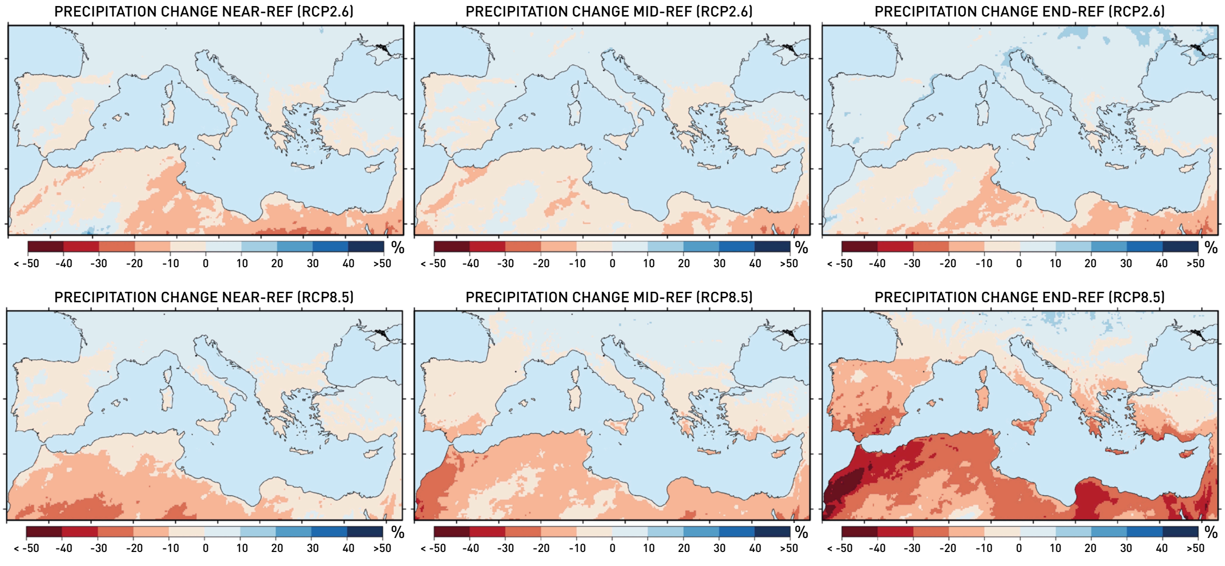
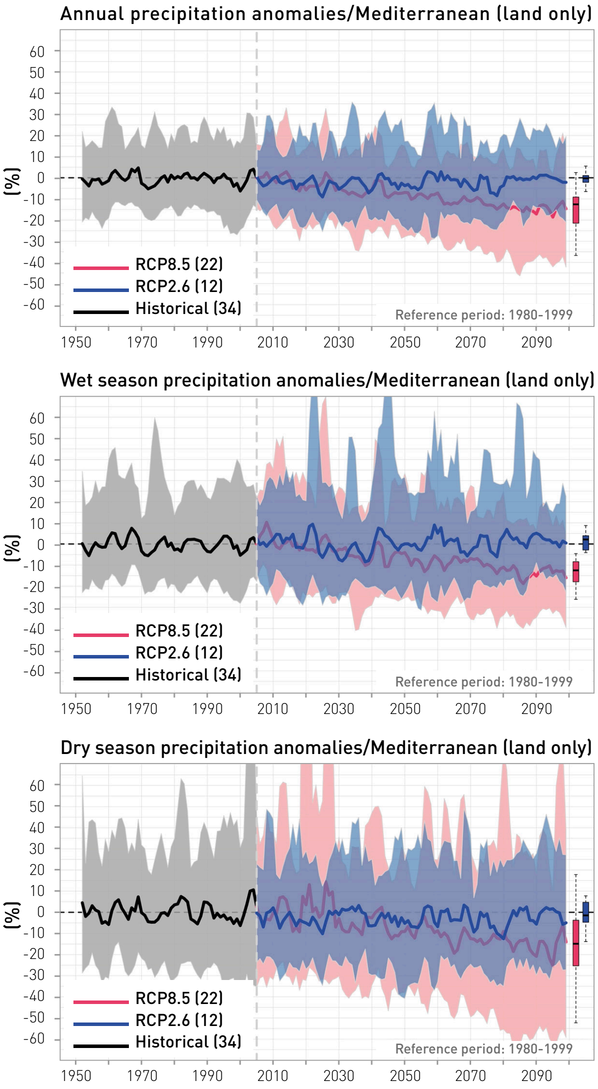


Figure 2.10 | Maps showing EURO-CORDEX-based change in annual, winter and summer precipitation change, for the RCP2.6 and RCP8.5 scenarios and the near-future, mid-term and far-future with respect to the reference period.

of precipitation decrease in the future compared to the GCMs. Considering a range of global warming of 0.9-5.6°C *(Section 2.2.4.2)* at the end of the 21st century (with respect to the reference period 1980-1999) and a decrease of 4% per degree of global warming, this gives a reduction between 4 and 22% for the Mediterranean annual precipitation (on land).

Fig. 2.11 shows the temporal evolution of Mediterranean scale precipitation (RCP2.6 and RCP8.5) from 1950 to 2100 in the EURO-CORDEX dataset, and presents both mean and inter-model range of data. The large inter-model spread includes some positive values and two scenarios start to separate, at least in an ensemble mean sense, only after the mid of the 21st century. Therefore, while it is possible to assess that precipitation will likely decrease over the Mediterranean Basin, at least under the higher end scenarios, it is difficult to assign robust quantitative values, especially at sub regional scale.

The uncertainty in projections is even larger as we move to the local scale because of the effects of local forcings, e.g., topography and coastlines. For example, focusing on the high elevations of the Alpine chain, Giorgi et al. (2016) found that the RCM projections at 12 km resolution exhibit an increase of summer precipitation in areas where the GCMs project a decrease. This is due to the occurrence of increased convection related to high elevation warming and heating. As another example, increases of cold season precipitation in the upwind side of mountain chains and decreases in the lee side have been found by the high-resolution simulations of Gao et al. (2006) in response to the topographically-forced precipitation shadowing effect. These results were confirmed by the analysis of the EURO-CORDEX ensemble projections (Kotlarski et al. 2019). In other words, high resolution RCM projections suggest that care needs to be taken when extending large scale patterns to the local scale, since local scale changes can be heavily affected by topography and coast lines.


Annual precipitation anomalies/Mediterranean (land only)

Wet season precipitation anomalies/Mediterranean (land only)

Dry season precipitation anomalies/Mediterranean (land only)

Figure 2.11 | Time-series of simulated mean annual (top panel), wet (middle panel) and dry (bottom panel) season over the Mediterranean land areas based on EURO-CORDEX 0.11° simulations for historical times (black curve) and future pathways RCP2.6 (blue curve) and RCP8.5 (red curve). Solid lines indicate the ensemble means and shaded areas the spread of the simulations. Box-plots represent the averages over the decade 2091-2100 in terms of model spread.

Variability and extremes

Several studies have assessed changes in interannual variability of precipitation over the Mediterranean region in GCM-based projections, mostly using as a measure of variability the coefficient of variation (i.e., the interannual standard deviation divided by the mean), which removes the strong dependence of precipitation standard deviation from the mean (Räisänen 2002; Giorgi and Bi 2005; Giorgi and Coppola 2009; Giorgi et al. 2019). They all found a prevailing increase in precipitation variability over the Mediterranean, especially over areas showing strong precipitation decreases, which thus appears to be a robust response in global climate projections. However, this result may not apply if the metrics used to measure variability is the standard deviation.

Giorgi et al. (2011, 2014) carried out an analysis of changes in different hydroclimatic indices from an ensemble of CMIP5 projections and, on an annual basis, consistently found an increase in mean daily precipitation intensity and 95th percentile of daily precipitation, a decrease in precipitation frequency and wet spell length and an increase in the number of dry days and dry spell length *(medium confidence)*. The hydroclimatic intensity index introduced by Giorgi et al. (2011), which is essentially the product of precipitation intensity and mean dry spell length, shows a consistent increase throughout the Mediterranean Basin. These conclusions based on GCM projections, were essentially confirmed by an analysis of high-resolution EURO-CORDEX projections by Jacob et al. (2014), except for a slight decrease of 95th percentile daily precipitation over some areas of the Iberian, Italian and Hellenic peninsulas and southern France in summer. A recent study (Lionello and Scarascia 2020), based on CMIP5, shows that global warming will further increase the existing difference in intensity of precipitation and hydrological extremes between North and South Mediterranean areas. Both the daily precipitation intensity the total precipitation during extreme events are already larger in the North than in the South Mediterranean areas, and differences will increase with global warming. The projected increase of dry spell length is larger in the south than in the North Mediterranean *(medium confidence)*.

In conclusion, *(high confidence)* both global and regional climate projections indicate a predominant shift towards a precipitation regime of higher interannual variability (when measure by the coefficient of variation), higher intensity of precipitation and greater extremes (especially in winter, spring and fall, but not in the southern areas), decreased precipitation frequency and longer dry spells (especially in summer). This hydroclimatic response to global warming is greater for the RCP8.5 than the RCP2.6 scenario and for the far future vs. the near future time slices *(high confidence)*.

2.2.5.3 Changes in evaporation, net water losses over sea and over land

Evaporation in the Mediterranean not only provides moisture locally, but also results in a net export of water to neighboring areas, primarily to the South and East (Mariotti et al. 2002a; Nieto et al. 2006). The Mediterranean Sea is the dominant regional evaporation source, and changes in Mediterranean Sea evaporation impact the sea's water, salt and heat budgets. Large-scale internal climate variability and greenhouse gas forced global change have been primary drivers of Mediterranean evaporation changes during the 20th century and into the 21st century, while local processes have acted to modulate those effects (Mariotti and Dell'Aquila 2012). Overall, the net surface water loss (evaporation minus precipitation over the sea) has increased over most of the Mediterranean surface, mainly due to a decrease of precipitation during the period 1960-1990 and a strong evaporation increase since the mid-seventies due to local warming (Mariotti 2010; Sevault et al. 2014; Mariotti et al. 2015; Skliris et al. 2018). The freshwater discharge due to the river runoff has also decreased (Ludwig et al. 2009). Projected regional warming trends point to continuing increases in Mediterranean Sea evaporation, land drying in southern areas during summer and a net regional water loss.

Observations-based estimates of Mediterranean Sea evaporation from the OAFlux Programme starting in 1958 point to decadal variations with a minimum around 1965-1975, and an overall positive trend of about 10% decade^{-1} (0.06 mm day^{-1} decade^{-1}) (Mariotti 2010). Since the mid-1970s, there is a substantial evaporation increase (0.1-0.2 mm day^{-1} decade^{-1}) with a tendency toward higher rates of increase during the 1990s. Much of the evaporation increase since the mid-1970s has been in early winter, especially in the Ligurian Sea, Adriatic Sea, and southeastern Mediterranean. The evaporation increase has resulted in a rate of increase in freshwater fluxes during 1979-2006 estimated in the range of 0.1-0.3 mm day^{-1} decade^{-1}. Increases in sea surface temperatures have primarily driven these evaporation changes via changes in the surface humidity gradient. Based on OAFlux data, the estimated Mediterranean mean rate of evaporation change in relation to the warming is about 0.7 mm day^{-1} K^{-1} (or 25% K^{-1}) over the period of 1958-2006. An increase in net Gibraltar water flux to compensate for the overall increase in fresh water loss has been derived (Fenoglio-Marc et al. 2013).

For the land surrounding the Mediterranean Sea, past evapotranspiration changes are regionally and seasonally dependent and largely follow precipitation trends, since soil moisture availability is a primary limiting factor. Increasing soil-moisture limitations seem to have driven recent global evapotranspiration decline and increased drought tendencies over the Mediterranean region (Sheffield and Wood 2008; Vicente-Serrano et al. 2014; Samaniego et al. 2018). Evapotranspiration estimates from French National Centre for Meteorological Research (CNRM) (Douville et al. 2013) display a tendency for evapotranspiration to increase during winter since the 1970. For the summer there is a progressive decrease (Mariotti et al. 2015).

The future evolution of the Mediterranean Sea physical characteristics is strongly related to the evolution of the air-sea and land-sea exchanges of water and heat. For the Mediterranean Sea, the net surface water loss by the sea is constituted by the combination of the evaporation over the sea, the precipitation over the sea, the river runoff and the Bosphorus Strait net transport. Increase in the net surface water loss by the sea is expected in the future due to a decrease in precipitation and in river runoff and an increase in evaporation (Mariotti et al. 2008, 2015; Sánchez-Gomez et al. 2009; Elguindi et al. 2011; Dubois et al. 2012; Planton et al. 2012; Adloff et al. 2015). Relative to the 20th century, this increase ranges from +8 to +35% for the mid-21st century (2020-2049) and from +20 to +60% at the end of the 21st century (2070-2099) in the medium-range A1B socio-economic scenarios (Planton et al. 2012).

To a first order, CMIP5 projections are largely similar to those based on CMIP3 (Mariotti et al. 2008) and consistent with those based on regional model downscaling (Sánchez-Gomez et al. 2009; Dell'Aquila et al. 2018). By 2071-2098, the Mediterranean Sea evaporation is projected to increase during all seasons and especially in winter (projected annual-mean increase is 0.25 ±0.08 mm day^{-1}) (Mariotti et al. 2015). Note that future change in the Nile freshwater inflow remains unknown due to the impossibility so far to accurately model the influence of regional water- and land-use anthropogenic activities on its past and future evolution (Somot et al. 2006; Dubois et al. 2012).

Over land, evapotranspiration projections present mixed changes, with a precipitation-driven increase in winter over Northern areas, and a decrease in summer over many land areas, especially over Spain, western Northern Africa and Turkey. Evapotranspiration increase will be also driven by increase of atmospheric evaporative demand (Vicente-Serrano et al. 2015). These evapotranspiration changes have been linked to a projected northward expansion of the Mediterranean land type (Alessandri et al. 2015) and regional surface vegetation changes (Anav and Mariotti 2011).

Changes in precipitation and evaporation over the Mediterranean Basin will lead to changes in drought occurrence. Drought can be of different types, such as meteorological, hydrological and agricultural drought, which can often be difficult to separate. Here we focus on meteorological drought, essentially measured by indices of monthly, seasonal up to annual precipitation deficits, such as the precipitation index (PI) or the standardized precipitation index (SPI). The Mediterranean Basin, is impacted by frequent drought episodes due to the strong inter-annual variability of rainfall in this region, and a trend towards drier conditions and increased meteorological drought occurrence after the 1970s over the Mediterranean Basin was found based on analyses of observations (Vicente-Serrano et al. 2011; Hoerling et al. 2012; Spinoni et al. 2015; Caloiero et al. 2018). Due to the pronounced interannual and decadal variability of Mediterranean precipitation, the robustness of this result needs to be confirmed, and may differ for different areas of the Mediterranean.

Concerning projections, since most model simulations indicate a trend towards drier conditions over the Mediterranean, especially in the warm season and over the southern areas, it is expected that the frequency and intensity of meteorological drought will increase under warmer climates. This has been confirmed *(high confidence)* by extensive analyses of precipitation projections with both global and regional climate models (Giorgi and Lionello 2008; Mariotti et al. 2008; Dai 2013; Dubrovský et al. 2014; Spinoni et al. 2015, 2018; Stagge et al. 2015; Quintana-Seguí et al. 2016; Naumann et al. 2018; Lionello and Scarascia 2020).

2.2.6 The cryosphere

2.2.6.1 Observed trends in the cryosphere

After the peak of the "little ice age" (~1,400-1,860 AD, Ivy-Ochs et al. 2009) increasing summer and mean annual air temperature led to a dramatic reduction in the area and volume of glaciers across high mountains of the Mediterranean (Hughes 2018). Short glacier readvances were observed in the 1890s, 1920s, 1970s and 1980s (Zemp et al. 2008). Deglaciation rate generally accelerated in recent decades (Rabatel et al. 2013), although the patterns of glacier retreat were complicated by the sensitivities of glaciers to different climatic regimes (Hughes 2018). As glacier retreats to cirque headwalls, it becomes more dominated by local topoclimatic controls, especially avalanching snow. Nevertheless, a complete loss of glaciers in some low-latitude mountain ranges has already occurred (Rabatel et al. 2013), accompanied by a shorter duration of seasonal snow cover (Brown and Mote 2009). Several small cirque glaciers existing in the southern Dinaric Alps, Balkan Peninsula, Turkey, Pyrenees, Sierra Nevada and the Apennines disappeared across the 20th century and in the last decades (Hughes 2018). In the Alps, glaciers covered 4,470 km^2 in 1850, 2,909 km^2 in the 1970s and 2,270 km^2 in 2000, meaning a 50% loss from 1850 to 2000 (Zemp et al. 2008). Few very small glaciers still exist in mountains of Montenegro and Albania. Elsewhere, perennial ice and snow patches still survive and attest to how close some Mediterranean mountains are to supporting small glaciers even where the equilibrium line altitude (ELA) is located above the highest peaks (Hughes 2018). ELA raised by about 170 m in the western Alps over the period 1984-2010 (Rabatel et al. 2013) while in the southeastern Alps change in the ELA was in the order of about +250 m between the 1980s and 2010 (Colucci and Žebre 2016).

Temperature increase led to a shift of periglacial processes to higher elevations as well as degradation of mountain permafrost in high mountain environments (Oliva et al. 2018). In the western and central Mediterranean, permanently frozen ground is now rarely found below 2,500 m. Alpine permafrost belt is detected above 2,630 m in northern aspects and 2,800 m in southern ones and in the Pyrenees, above 2,400 m in the Southern Alps, above ~2,350 m on Rila Mountain and ~2,700 m on Mount Olympus and above 2,800-3,400 m in northeastern Turkey and central Anatolia (Oliva et al. 2018). No permafrost belt is found in the highest mountains in southern Europe (Sierra Nevada) and northern Africa (Atlas) where permanent frozen conditions are only found in the form of isolated patches at the highest elevations at 3,000-3,100 m (Oliva et al. 2016) and 3,800 m (Vieira et al. 2017), respectively. Certain climate conditions (i.e., reduced snow cover) can favour the presence of permafrost patches at relatively low elevations in the Central Apennines or by lithological conditions (i.e., volcanic sediments, karst lithology), as detected in the highest active European volcano (Mt. Etna) at elevations above 2,900 m (Maggi et al. 2018) or in limestone dominated mountains across the Mediterranean (Colucci and Guglielmin 2019).

2.2.6.2 Future conditions in the cryosphere

Mountain glaciers in the Mediterranean region are projected to continue losing mass in the 21st century until complete disappearance of most mountain glaciers by the end of the century *(very high confidence)*. A recent multi-model projection exercise (GlacierMIP, Hock et al. 2019) indicates that relative volume losses by 2100 (average of model runs ±1 standard deviation) are of the order of 69 ±19% for RCP2.6 and 93 ±10% for RCP8.5. This indicates that, even under scenarios with strong reduction in greenhouse gas emissions, only glaciers at the highest elevation will persist at the end of the 21st century. For mid-century, changes depend far less on the climate scenario, with reductions of the order of 50 ±20% for RCP2.6 and 60 ±20% for RCP8.5.

Projected changes of the mountain snow cover are studied based on climate model experiments, either directly from GCM or RCM output, or following downscaling and the use of snowpack models. Future changes in snow conditions are mostly driven by changes in meteorological drivers. The projections generally do not specifically account for future changes in the deposition rate of light absorbing particles on snow and associated changes in snow albedo. At lower elevation, under the current multi-annual mean rain/snow transition elevation, the water mass of the snow cover is projected to decline by 25% likely range: (10-40%, between the recent past period (1986-2005) and the near future (2031-2050), regardless of the climate scenario). By the end of the 21st century (2081-2100), reductions of up to 80% (likely range 50-90%) are expected under RCP8.5, 50% (likely range from 30-70%) under RCP4.5 and 30% (likely range 10-40%) under RCP2.6 (Beniston et al. 2018; Hanzer et al. 2018; Verfaillie et al. 2018). At higher elevations, projected reductions are smaller *(high confidence)*, as temperature increases at higher elevations affect the ablation component of snow mass evolution (in particular, melt and sublimation), rather than the onset and accumulation component. The strong interannual variability of snow conditions is projected to remain a key feature of this cryospheric component throughout the 21st century *(high confidence)*.

In the Mediterranean domain, permafrost is only located in the mountains, often patchy and confined to areas of rugged topography, including cliffs. In contrast to glacier and snow cover, climate projections of the ground thermal regime have not been performed in a comprehensive manner, using a cascade of climate models and impact models. Evidence stems from small-scale studies, but all studies points towards increased permafrost thaw in mountain environments, following surface air temperature changes (Marmy et al. 2016; Beniston et al. 2018). Future changes in mountain permafrost have major implication for natural hazards (slope instabilities).

2.2.7 Ocean hydrology

The Mediterranean Sea can be considered as a laboratory of the global ocean (Lacombe 1990; Béthoux et al. 1999) as it shows many key and interesting oceanic physical processes, such the open-sea deep convection occurring in some areas (Gulf of Lion, South Adriatic, and the Cretan Sea) leading to the formation of cold and salty deep-water masses (Tsimplis et al. 2006; Schroeder et al. 2012). The dominance of evaporation in the Mediterranean Sea and intermediate water formation (in the Rhodes Gyre) leads to an anti-estuarine thermohaline circulation with a surface layer with the Atlantic Water (AW, comparatively fresh and warm) and a layer with the Levantine Intermediate Water (LIW, very salty and comparatively cold) entering and exiting across the Gibraltar Strait, simultaneously.

In addition, the Mediterranean Sea is surrounded by various and complex topography channeling regional winds (Mistral, Tramontane, Bora, Meltem, Sirocco, Etesians) that define local circulations. The presence of complex coastlines, islands, narrow and shallow straits require adapted observation strategies and high-resolution modeling tools. Further, the Mediterranean Sea is also known to impact the Atlantic Ocean through the Mediter-

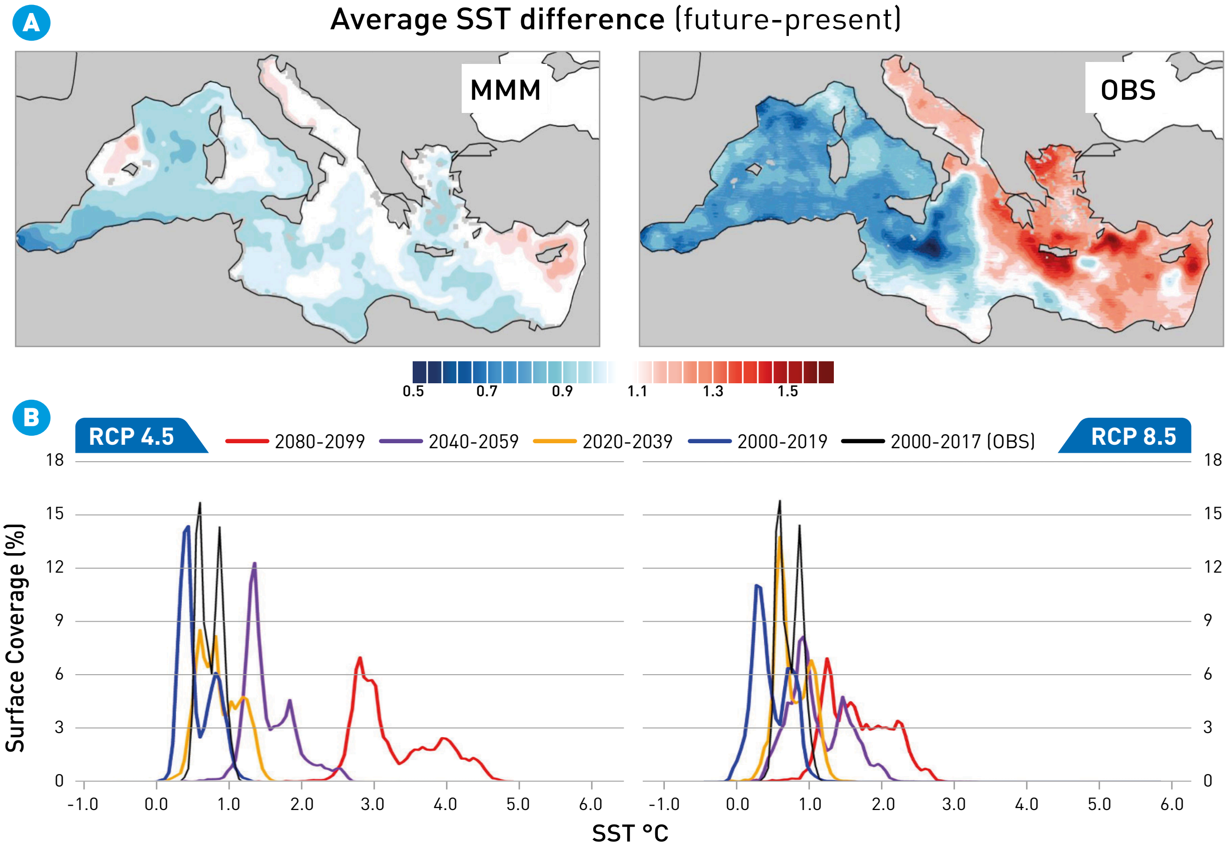


Figure 2.12 | A) Local amplification factor of the Mediterranean sea surface warming using 1980-1999 as reference period. Local sea surface warming values are divided by the basin-averaged warming value. Reddish (resp. blueish) colors mean that the area is warming more (resp. less) that the basin-average. The top panel is the ensemble mean of five Med-CORDEX coupled regional climate system models, further averaging warming rates of four 20-year long time periods (2000-2019, 2020-2039, 2040-2059, 2080-2099) and 2 scenarios (RCP4.5, RCP8.5). The bottom is based on the CMEMS observations (2000-2017). **B) Fraction of the Mediterranean Sea surface (in %) experiencing a given sea surface temperature change value (in °C),** compared to the reference period (1980-1999) for various periods (2000-2019 in blue, 2020-2039 in orange, 2040-2059 in purple, 2080-2099 in red) and for the scenarios RCP4.5 and RCP8.5 using the envelope of the results of 5 Med-CORDEX coupled regional climate system models. The change in the CMEMS observations is added for the period 2000-2017 (in black). Information is first aggregated at the yearly scale.

ranean Outflow Waters that flow into the Atlantic at about 1,000 m depth and are considered as a source of salt and heat for the Atlantic Ocean (Artale et al. 2006).

2.2.7.1 Observed change in marine waters

There is increasing evidence that Mediterranean water masses are becoming warmer and deep water masses saltier. This assertion is supported both by direct measurements (Béthoux and Gentili 1999; Rixen et al. 2005; Vargas-Yáñez et al. 2010, 2017) and by numerical simulations (Beuvier et al. 2010; Harzallah et al. 2018; Somot et al. 2018).

Since the 1980s upper layer temperature has increased (Rivetti et al. 2017; Vargas-Yáñez et al. 2017) as well as sea surface temperature (Marullo et al. 2010; Pastor et al. 2018), with acceleration since the 1990s (Macías et al. 2013). Since the beginning of the 1980s, the sea surface warming rate ranges between +0.29 and +0.44°C decade^{-1} on average over the whole Mediterranean Sea, depending on the studied period and on the reference data sets (Nabat et al. 2014; CEAM 2019; Darmaraki et al. 2019a). In the period 2000-2017 with respect to 1980-1999, all Mediterranean Sea areas show a positive yearly-mean sea surface temperature anomaly of at least +0.2°C. The sea surface warming has not been uniform, but mostly bimodal *(Fig. 2.12b)* with stronger trends in the eastern basin (Adriatic, Aegean, Levantine and North-East Ionian Seas, *Fig. 2.12a*), where some areas warmed by +1.2°C. Very local places in the Levantine Basin have warmed 50% more rapidly than the Mediterranean Sea average whereas a spot in the Ionian Sea has warmed 50% less than the basin average *(Fig. 2.12a)*. Note that the climate models currently underestimate the observed sea surface warming (blue and black lines in *Fig. 2.12b*) (Nabat et al. 2014; Sevault et al. 2014; Dell'Aquila et al. 2018).

In the Mediterranean Sea, periods of abnormally warm sea surface, also called "marine heat waves" have become more frequent, more intense, spatially more extended and more severe over the last decades (Oliver et al. 2018; Darmaraki et al. 2019a). To illustrate this trend, the most severe marine heat waves detected since 1982 are 2003, 2012, 2015, and 2017 (Bensoussan et al. 2019). In addition, 14 marine heat waves occurred during the 2008-2017 10-year period whereas only 2 occurred during the 1982-1991 period (Darmaraki et al. 2019a). Contrary to sea surface temperature, a corresponding sea surface salinity evolution has not been reported (Rixen et al. 2005; Sevault et al. 2014), except for specific locations (Ozer et al. 2017; Vargas-Yáñez et al. 2017).

Long-term trends in the Mediterranean Sea intermediate and deep hydrology have been detected, though they are affected by marked variability on decadal time scales, the Eastern Mediterranean Transient (EMT, Roether et al. 2007), Western Mediterranean Transition (WMT, Schroeder et al. 2016) and BiOS (Gačić et al. 2010) being probably the most known manifestations of this.

Since the mid 1990s the temperature and the salinity of the Levantine Intermediate Water (LIW) have increased by 0.53°C (*Fig. 2.13,* "Sicily Channel" panel) and 0.13 psu, i.e., with rates of 0.024°C yr^{-1} and 0.006 psu yr^{-1}, respectively (Schroeder et al. 2017). Such trends are at least one order of magnitude greater than those reported for the global ocean intermediate layer (Schroeder et al. 2017). The western basin deep waters are shown to have gradually increased their temperature and salinity since the 1950s (Rohling and Bryden 1992; Béthoux et al. 1998; Rixen et al. 2005; Marty and Chiavérini 2010), with an acceleration after the mid 1980s and an even stronger rate since 2005 due to an abrupt WMT (Marty and Chiavérini 2010; Borghini et al. 2014; Schroeder et al. 2016). Deep-water trends of 0.04°C ±0.001°C decade^{-1} and 0.015±0.003 psu decade^{-1} (since 1961) have been reported by comparing time series of deep CTD (conductivity-temperature-depth) casts (Borghini et al. 2014) (*Fig. 2.13*, bottom panel).

Changes in the Mediterranean water mass characteristics have a signature also in the water outflowing from the Mediterranean Sea through the Strait of Gibraltar (Millot et al. 2006; Naranjo et al. 2017). Mooring observations collected since 2004 (*Fig. 2.13*, "Gibraltar Strait" panel) show a positive trend in temperature and salinity of 7.7x10^{-3} °C yr^{-1} and 0.63x10^{-3} psu yr^{-1}, respectively (von Schuckmann et al. 2018). Since 2012 a noticeable increase of these trends is interpreted as the signal of the WMT (Naranjo et al. 2017). In addition, no significant changes in the strait transports (net exchange: Fenoglio-Marc et al. 2013; Boutov et al. 2014; Soto-Navarro et al. 2015) and surface circulation (Pascual et al. 2014) have been detected.

No significant trends in frequency of dense water formation events have been detected (Beuvier et al. 2010; Houpert et al. 2016; Somot et al. 2018; Dunić et al. 2019), although a strong interannual variability is reported for each of the dense water formation sites, the northwestern Mediterranean (Marty and Chiavérini 2010; Houpert et al. 2016; Somot et al. 2018; Waldman et al. 2018), the Adriatic Sea (Dunić et al. 2019), and the Aegean Sea (Roether et al. 2007; Beuvier et al. 2010).

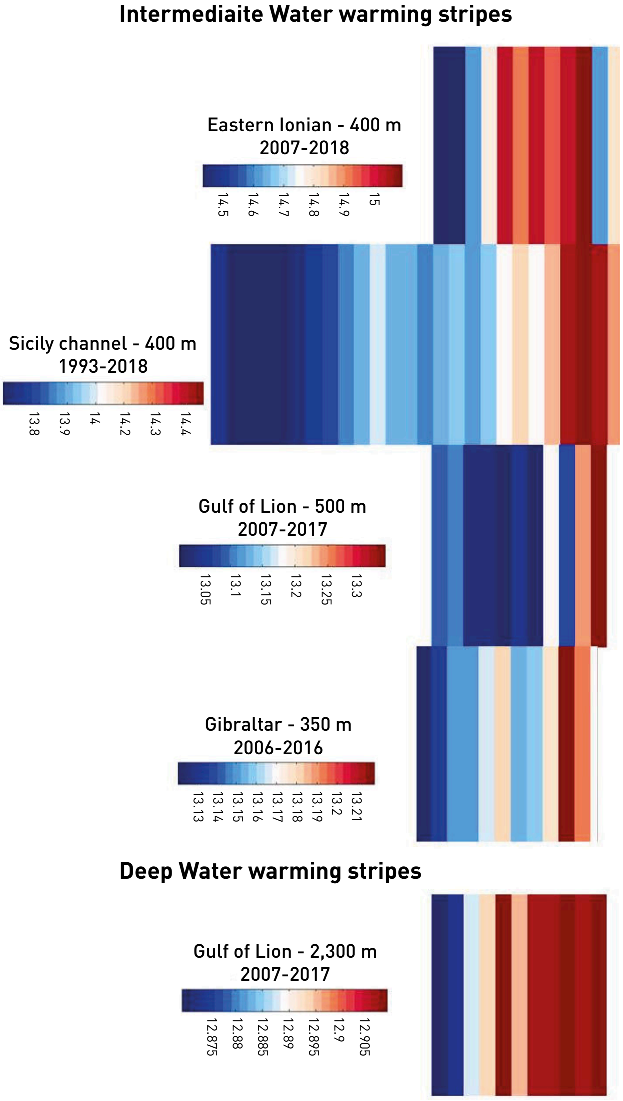


Figure 2.13 | Warming stripes in the Intermediate Water (from east to west) and the Deep Water (in the Gulf of Lion). Each stripe refers to a single year and covered periods differ depending on variable. Values have been computed using yearly potential temperature averages in different locations where long-term mooring data are available at different depths. Data from the eastern Ionian come from the HCMR Pylos deep Observatory (Velaoras et al. 2013), and have been downloaded from CMEMS. Data from the Sicily Channel come from the CNR-ISMAR mooring (Schroeder et al. 2017) and can be downloaded from CMEMS. Data from the Gulf of Lion (500 m and 2,300 m) come from the LION Observatory of the MOOSE Network (Houpert et al. 2016) and can be downloaded from SEANOE (Testor et al. 2019). Data from the Gibraltar Strait come from the IEO (Spanish Oceanographic Institute) mooring (von Schuckmann et al. 2018) and can be downloaded from the Copernicus Marine Environment Monitoring Service (CMEMS). Note that colour scales are different for each panel.

2.2.7.2 Future change in marine waters

Air-sea and land-sea exchanges

The future evolution of the Mediterranean Sea physical characteristics is strongly related to the evolution of the air-sea and land-sea exchanges of water and heat. For the Mediterranean Sea, the net surface water loss by the sea is constituted by the combination of the evaporation over the sea, the precipitation over the sea, the river runoff and the Bosphorus Strait net transport. The net surface heat loss by the sea consists of the shortwave radiation, the longwave radiation, the latent heat and the sensible heat fluxes (these variables are assessed in more detail in *Sections 2.2.3, 2.2.4* and *2.2.5*, as well as in *Section 3.1.3.2*).

In addition to the changes in radiation, the future evolution of the Mediterranean Sea physical characteristics is strongly related to the evolution of the other air-sea heat fluxes. Under present-climate conditions, the net heat loss by the Mediterranean Sea surface (namely the sum of shortwave radiation, longwave radiation, latent heat and sensible heat fluxes) is positive meaning that sea is losing heat by its surface over a long period of time. In the future, the net heat loss by the sea surface is expected to decrease (Somot et al. 2006, 2008; Dubois et al. 2012; Gualdi et al. 2013; Adloff et al. 2015; Soto-Navarro et al. 2020), because the increase in shortwave, net longwave and sensible heat fluxes will dominate the increase in latent heat loss (Dubois et al. 2012). With respect to the end of the 20th century and based on coupled regional climate models, the decrease in the net heat loss could reach between -1.8 and -5.5 W m^{-2} by 2050 following the medium-range A1B scenario (Dubois et al. 2012) and between -2.1 and -6.4 W m^{-2} (resp. -1.0 and -3.7 W m^{-2}) at the end of the 21st century following high-range RCP8.5 (resp. medium-range RCP4.5) scenarios (Soto-Navarro et al. 2020). This implies that the atmosphere could even start to warm the Mediterranean Sea from the mid-21st century instead of cooling it in the present-day climate according to some models *(medium confidence).* Changes in the Mediterranean Sea surface heat budget depend to a great extent on the socio-economic scenario chosen: the higher the greenhouse gas emissions, the greater the response of the budget.

To summarize, an increase in the net surface water loss by the sea is expected in the future due to a decrease in precipitation and in river runoff and an increase in evaporation (*Sections 2.2.5* and *3.1.1*). In addition, a decrease in the net surface heat loss by the sea is expected in the future (*Sections 2.2.3* and *2.2.5*) because the increase in shortwave, net longwave and sensible heat will dominate the increase in latent heat loss. In particular, this means that, from the middle of the 21st century, some models predict that the atmosphere could, in average, warm the Mediterranean Sea instead of cooling it in the present-day climate.

Future changes in the wind strength over the sea will likely remain low even at the end of the 21st century in pessimistic scenarios *(Section 2.2.2)*.

Sea surface temperature

In future climate change scenarios based on both GCMs and RCMs including the Mediterranean Sea representation, a significant warming of the Mediterranean Sea surface temperature is projected *(very high confidence)* (Somot et al. 2006; Planton et al. 2012; Shaltout and Omstedt 2014; Adloff et al. 2015; Mariotti et al. 2015; Alexander et al. 2018; Darmaraki et al. 2019b). The warming rate depends at the first order on both the temporal horizon and the greenhouse gas emission scenario *(very high confidence)* (Adloff et al. 2015; Mariotti et al. 2015; Darmaraki et al. 2019b). The sea warming will generally remain below that of the air over surrounding land *(high confidence)* due to ocean thermal inertia, probably leading to an increase in land-sea temperature contrast (Somot et al. 2008). With respect to the end of the 20th century, the annual-mean and basin-mean sea surface temperature is expected to increase by 0.6-1.3°C before the mid-21st century and by 2.7-3.8°C (resp. 1.1-2.1°C) at the end of the 21st century period under the pessimistic RCP8.5 (resp. medium RCP4.5) scenario (Darmaraki et al. 2019b). The upper values of those warming ranges are possibly underestimated as higher warming are obtained in CMIP5 GCMs (Mariotti et al. 2015; Darmaraki et al. 2019b).

Future warming will be roughly homogeneous in space *(medium confidence)* with the Balearic Sea, the North Ionian Sea, the Northeast Levantine Sea and the Adriatic Sea identified as potential hotspots of maximum warming *(low confidence) (Fig. 2.12a)* (Adloff et al. 2015; Darmaraki et al. 2019b; Soto-Navarro et al. 2020). This hotspot pattern however does not match well with the observed warming pattern *(Fig. 2.12a)*, illustrating that climate change related evolution is likely still hidden by natural variability. Spatially, the future warming of the sea surface is bimodal as it has been in the past *(Fig. 2.12b)*. For the near-future (2020-2039) with respect to the end of the 20th century, local annual-mean sea surface temperature change is everywhere positive and can reach locally +1.6°C at maximum whatever the scenarios whereas at the end of the 21st century, the local annual-mean warming spreads from 2 to 5°C for scenario RCP8.5 (resp. from 0.5-3.0°C for RCP4.5).

Warming is not projected to be constant all year round. Stronger warming is expected in summer and weaker warming in winter *(medium confidence)*, resulting in substantial increase in warm extremes and a decrease in cold extremes (Alexander et al. 2018). As an illustration, under RCP8.5, maximum monthly-mean sea surface temperature anomalies could reach +3°C over 2040-2059 and more than +5°C over 2080-2099 (median of the CMIP5 models) averaged over the Mediterranean Sea (Alexander et al. 2018). In addition, from the period 2040-2069, the 30-year mean sea surface temperature will always be warmer than the warmest year during the period 1976-2005 *(medium confidence)*. This will already be the case in about 50% of the years for the 2010-2039 period (Alexander et al. 2018).

Marine heat waves will very likely increase in spatial coverage, become longer, more intense and more severe than today *(medium confidence)*. The intensity of this evolution strongly depends on the temporal horizon and on the socio-economic scenario (Frölicher et al. 2018; Darmaraki et al. 2019b). By 2021–2050, it is expected that marine heat wave frequency increases by a factor 1.5, duration by 2.4–2.7, mean intensity by 1.5 and severity by 5-7 with values largely independent from the socio-economic scenarios (Darmaraki et al. 2019b). By 2100, models project at least one long-lasting marine heat wave occurring every year under RCP8.5 up to 3 months longer, and about 4 times more intense and 42 times more severe than today's events. Their occurrence is expected between June and October, affecting at peak, the entire Mediterranean Basin (Darmaraki et al. 2019b). Under a RCP8.5 scenario, the 2003 marine heatwaves may become a normal event for the period 2021-2050 and a weak event at the end of the 21st century *(medium confidence)* (Darmaraki et al. 2019b).

The warm extreme sea surface temperature changes at the end of the 21st century is likely due to a combination of three factors: a mean sea surface warming, an amplification of the seasonal cycle and an increase in the interannual and day-to-day variability (Alexander et al. 2018; Darmaraki et al. 2019b).

Sea surface salinity

The future evolution of sea surface salinity of the Mediterranean Sea remains largely uncertain as its sign of change (Adloff et al. 2015; Soto-Navarro et al. 2020). Any change will likely be spatially and temporally inhomogeneous *(medium confidence)* due to the primary role of the river and near-Atlantic freshwater inputs (Adloff et al. 2015; Soto-Navarro et al. 2020). For the end of the 21st century, basin-scale surface salinity anomalies range from -0.18 to +0.16 psu (resp. -0.25 to 0.25 psu) for the pessimistic RCP8.5 (resp. RCP4.5) scenario (Soto-Navarro et al. 2020). However, a surface salinity increase in the eastern Mediterranean Basin is more likely than not whereas the western basin may see an increase or a decrease in its surface salinity (Adloff et al. 2015; Soto-Navarro et al. 2020).

Surface circulation and exchanges across straits

Change in sea surface circulation has not been deeply assessed yet in the literature (Adloff et al. 2015; Macías et al. 2018), despite their strong capacity to locally modulate the future sea surface temperature and salinity anomalies. In particular, it is likely that the surface circulation changes affect the local sea surface warming hotspots listed above. Noticeable surface circulation changes have been reported for the end of the 21st century in the Balearic Sea and in the North Ionian Sea independently from the scenario choice (Adloff et al. 2015).

At the strait of Gibraltar, the net heat transport towards the Mediterranean Sea will likely increase due to near-Atlantic warming as well as the net mass transport due to increased sea surface water deficit (Somot et al. 2006; Marcos and Tsimplis 2008; Carillo et al. 2012; Adloff et al. 2015; Soto-Navarro et al. 2020). The future evolution of the net salt transport at the strait is unclear, because it depends on the salinity change in the near-Atlantic Ocean surface layer entering the Mediterranean Sea (Marcos and Tsimplis 2008; Adloff et al. 2015; Soto-Navarro et al. 2020). This means that it is currently unclear if the salt transport from the Atlantic will increase or decrease in the future leading to large uncertainty for the salinity change in the Mediterranean Sea.

Deep water characteristics

Due to the contrasting effects of increase in sea surface temperature and salinity, the future evolution of the sea surface density is uncertain. Generally, scenarios with strong greenhouse gas concentration increase project a decrease in surface density associated to an increase in vertical stratification of the water column. Increase in density (thus a decrease in stratification) is still possible in scenarios with low level of warming (Adloff et al. 2015). Due to its active thermohaline circulation, the surface climate change signal may be propagated efficiently towards the deeper layers of the Mediterranean Sea (Somot et al. 2006; Carillo et al. 2012) and lead to larger deep warming rates than in other oceans in the world.

The warming and saltening rates of the deep layers is very uncertain as it depends on various factors such as the surface signal, the intensity of the present and future Mediterranean thermohaline circulation (MTHC). This means in particular that the socioeconomic scenario is not the main source of uncertainty in future changes of the deep layers (Adloff et al. 2015). At the end of the 21st century, water masses deeper than 600 m may warm between +0.03 and +1.38°C, and their salinity may increase or decrease with a large uncertainty range, depending on the model (-0.05; +0.51) psu (Adloff et al. 2015; Soto-Navarro et al. 2020).

All published studies agree on a long-term weakening of the open-sea deep convection, the winter deep water formation and the related branch of the thermohaline circulation in the western Mediterranean Sea in high emission scenarios (Thorpe and Bigg 2000; Somot et al. 2006; Adloff et al. 2015; Soto-Navarro et al. 2020). However, natural variability may lead to increase in deep water formation with respect to today's situation during short periods in the future (Macías et al. 2018). For the end of the 21st century and the A2 scenario, decrease of the maximum mixed layer depth reached in the northwestern Mediterranean Sea reach between -17% and -82% depending on the model choice (Somot et al. 2006; Adloff et al. 2015). The picture in the eastern Mediterranean Sea is more contrasted with weakening in some simulations but enhanced convection and thermohaline circulation in others (Somot et al. 2006; Adloff et al. 2015; Soto-Navarro et al. 2020). Some simulations (but not all) project that EMT-like situation may become the new normal situation for the eastern basin (Adloff et al. 2015).

2.2.8 Sea level, storm surges and wave heights

A particular characteristic of the Mediterranean Sea in terms of sea level variability is that it is a semi-enclosed domain linked to the global ocean through the Strait of Gibraltar. This implies that changes in the nearby Atlantic are quickly transferred into the Mediterranean as a basin-wide barotropic signal. At the same time, basin-wide sea level anomalies caused by local forcing (e.g., thermal expansion, evaporation) tend to be transferred to the global ocean in a way that the Mediterranean is in balance with the nearby Atlantic. As a consequence, the Mediterranean basin-wide variations, especially at low frequencies, closely follow the variations in the nearby Atlantic (Calafat et al. 2012; Adloff et al. 2018). The exception to this is the part of the variability related to changes in the atmospheric mechanical forcing (i.e., wind and atmospheric pressure), which can produce Mediterranean-Atlantic differences of few cm even at multidecadal time scales (Menemenlis et al. 2007; Jordà et al. 2012).

The Mediterranean Sea is a microtidal region, with tidal range mostly below 15 cm and relatively low sea levels with 50-year return values below 60 cm over most of the basin (Marcos et al. 2009). These values are small compared to other European Seas. The two exceptions are the North Adriatic and the Gulf of Gabes, where storm surge levels are estimated to be several times per year above 50 cm, with 5-year return values around 90 cm and 70 cm, respectively (Conte and Lionello 2013).
The wave climate in the region is milder than in the Atlantic with smaller mean wave heights (1-1.5 m) and shorter periods (5-6 s) and presents an important spatial variability due to the complex orography and coastline surrounding the basin (Menéndez et al., 2014). Its variability is connected to NAO and the Indian Monsoon index (Lionello and Sanna 2005) and other northern hemisphere teleconnection indices, particularly the East Atlantic Pattern (Lionello and Galati 2008). Annual maxima along the coastlines are largest (above 5 meters) at the northwestern coast of Africa, but high values well above 4 meters occur in several parts (Lionello et al. 2017).

2.2.8.1 Observed change in sea-level

During the 20th century, coastal tide gauges around the Mediterranean have recorded a rise in the mean sea level. Once tide gauge data have been corrected for the vertical land motion, the sea level trend is very consistent among sites being ~1.4 mm yr^{-1} (Wöppelmann and Marcos 2012). This trend is superimposed on interannual and decadal variability that can temporarily mask the sea level rise. The clearest example is the period 1960-1980 during which Mediterranean sea level showed a decreasing trend because a higher than usual atmospheric pressure (Tsimplis et al. 2005). After that period, the atmospheric pressure returned to the typical values and sea level continued to follow the global evolution. For the more recent period, in which sea level has been monitored by satellite altimetry (1993-2018), Mediterranean sea level trend has increased up to 2.8 ±0.1 mm yr^{-1}, consistent with global sea level trend (3.1 ±0.4 mm yr^{-1}) (Cazenave and WCRP Global Sea Level Budget Group 2018). The rise at global scale is mainly the result of a combination of water thermal expansion and land-based ice melting. During the 20th century both factors contributed equally, although during the last decades, glacier melt is dominating (Cazenave and WCRP Global Sea Level Budget Group 2018).

Analyses of tide gauge data have revealed an increase in the magnitude and duration of the extreme sea level events in the region during the last decades, caused by the rise in the relative mean sea level (for the northern Adriatic Sea: Lionello et al. 2012b; Marcos et al. 2015). In general, wave observational records are too short for assessing multidecadal trends, with the exception of the Northern Adriatic Sea, where one among the worldwide longest instrumental time series (1979 to present) shows an increase in the number of storms, but a decrease of the extreme wave heights (Pomaro et al. 2017).

2.2.8.2 Future sea-levels

The modeling of Mediterranean mean sea level future variations is not straightforward. With their coarse spatial resolution, present-day global climate models (GCMs) are not able to reproduce the regional processes in the basin, although, they are better suited to represent the connection to the global ocean (Calafat et al. 2012). Conversely, regional climate models (RCMs) can capture part of the regional variability but are usually not designed to reproduce the connection with the global ocean, and thus missing a key part of the variability (Adloff et al. 2018). Therefore, sea level rise projections solely based on RCMs have missed that component and only should be considered for the regional patterns, which can cause local spatial deviations from the basin average by up to +10 cm (Carillo et al. 2012; Adloff et al. 2015, 2018). In conclusion, accounting for all components shows that the Mediterranean sea level rise will be close to the northeastern Atlantic, where future sea level will be similar (difference lower than 5%) to the global mean sea level because regional differences produced by changes in the circulation and mass redistribution almost compensate each other (Slangen et al. 2017). This leads to estimate that the basin mean sea level will likely be 37-90 cm higher than at the end of the 20th century, with a small probability to be above 110 cm. Main contributions to basin-average sea level changes are coming from terrestrial ice melting and the northeastern Atlantic dynamics (Jordà et al. 2020, *Fig. 2.14*). A different computation based on the sea level projections in the SROCC (Oppenheimer et al. 2019) and accounting for the uncertainty calculation method of the AR5 (Church et al. 2013), confirms that the likely range of the Mediterranean Sea level will be approximately in the range from 20 to 110 cm higher (depending on scenario) at the end of the 21st century than at the end of the 20th century (Le Cozannet et al. 2019; Thiéblemont et al. 2019).

RCMs and GCMs do not model extreme sea level events and specific 2D simulations forced by high frequency atmospheric forcing are needed. Published studies point towards a reduction on the average number of positive surges throughout the 21st century (Marcos et al. 2011; Conte and Lionello 2013; Lionello et al. 2017). Overall, the results indicate small progressive reduction in comparison with their present-day magnitude as a function of time and of the emission scenario, reaching a value in the range from -5% and -10% at the end of the 21st century in the RCP8.5 scenario (Lionello et al. 2017). In any case future sea level rise will become the dominant factor and it will lead to an increase frequency and intensity level of coastal floods (Lionello et al. 2017; Vousdoukas et al. 2017).

Regarding future changes in waves, they will be determined by changes in the wind field over the Mediterranean Sea *(Section 2.2.2)*. Published studies point towards a generalized reduction of the mean significant wave height field over a large fraction of the Mediterranean Sea, especially in winter (Lionello et al. 2008, 2017; Perez et al. 2015). Similarly, the wave extremes are expected to decrease in number and intensity, although there is no consensus whether very large extreme events, associated with very strong winds, would also decrease (Gaertner et al. 2007; Romera et al. 2017; Romero and Emanuel 2017).

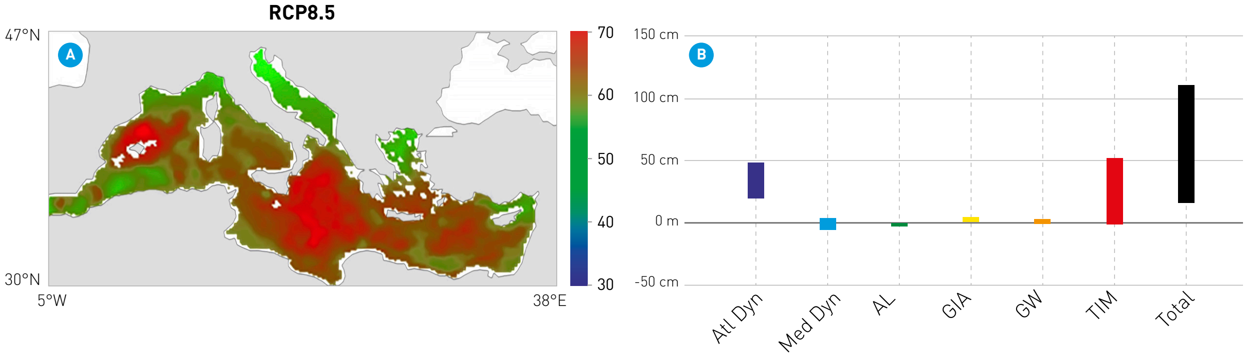


Figure 2.14 | Projected Mediterranean sea level rise averaged in (2080-2099) with respect to present climate (1980-1999) under scenario RCP8.5. Results based on CMIP5 and Med-CORDEX outputs for the dynamical components and Slangen et al. (2017) for other components. (a) Sum of all contributors (b) Range of projected values for the different contributors: NE Atlantic dynamics (Atl Dyn), Mediterranean dynamics (Med Dyn), Atmospheric Loading (AL), Glacial Isostatic Adjustment (GIA), Ground Water (GW) and Terrestrial Ice Melting (TIM) and Total.

2.2.9 Acidification of the Mediterranean Sea

Human activities are responsible for an increase in atmospheric CO_2 since the beginning of the industrial era. The input of anthropogenic carbon in the Mediterranean is caused by the flux at the air-sea interface, but also results for the Mediterranean Sea, from exchange with the Atlantic Ocean across the Strait of Gibraltar. Approximately 30% of anthropogenic carbon is absorbed by the oceans (Sabine et al. 2004) and leads to decrease of pH in ocean water masses. The Mediterranean Sea is able to absorb relatively more anthropogenic CO_2 per unit area than the

	RECENT CHANGE			PROJECTED CHANGES RCP2.6									PROJECTED CHANGES RCP8.5								
				20-YEAR PERIODS									20-YEAR PERIODS								
	2000-2019			NEAR-FUTURE (2020-2039)			MID-CENTURY (2040-2059)			END OF THE 21ST CENTURY (2080-2099)			NEAR-FUTURE (2020-2039)			MID-CENTURY (2040-2059)			END OF THE 21ST CENTURY (2080-2099)		
CHANGE IN SURFACE TEMPERATURE (°C, MEAN VALUE, LAND-ONLY)																					
	BASED ON CRU			BASED ON EURO-CORDEX 12 KM ENSEMBLE																	
	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA	ANN	DJF	JJA
MED	0.8	0.41	1	1.1	1.1	1.2	1.3	1.2	1.5	1.3	1.4	1.3	1.3	1.3	1.5	2.2	2	2.5	4.6	4.2	5.3
WEST MAGHREB	0.5	0.1	0.8	1.3	1.1	1.3	1.4	1.1	1.6	1.3	1.3	1.4	1.4	1.2	1.6	2.4	2.1	2.7	5	4.2	4.6
EAST MAGHREB	0.6	0.3	0.6	1.2	1	1.2	1.4	1.1	1.6	1.4	1.3	1.4	1.4	1.2	1.6	2.3	2	2.6	4.6	4	5.3
LEVANT	0.9	0.7	1	1.2	1	1.2	1.3	1.3	1.4	1.3	1.3	1.3	1.3	1.3	1.4	2.1	1.9	2.4	4.3	3.9	4.8
ANATOLIA	0.9	0.4	1.2	1.2	1.2	1.3	1.4	1.4	1.6	1.5	1.6	1.5	1.4	1.4	1.6	2.3	2.1	2.6	4.6	4.3	5.3
CENTRAL MED	0.8	0.3	1	1.1	1	1.3	1.3	1.2	1.4	1.2	1.4	1.2	1.3	1.3	1.5	2.1	1.9	2.5	4.3	3.9	5.1
IBERIA	0.5	0.2	0.8	1	0.9	1.2	1.1	0.9	1.3	1	1	1.1	1.1	1	1.3	2	1.7	2.4	4.3	3.6	5.3
FRANCE	0.7	0.4	0.7	0.9	0.9	1	1.1	0.9	1.1	0.9	1.1	0.8	1	1	1.1	1.8	1.7	2	3.9	3.6	4.7
ALPS	0.8	0.5	1	1.1	1.1	1.1	1.3	1.2	1.3	1.1	1.4	1	1.2	1.3	1.3	2.1	2.1	2.2	4.5	4.5	5
BALKANS	1.1	0.8	1.4	1.1	1.1	1.1	1.3	1.4	1.3	1.2	1.7	1	1.3	1.4	1.4	2.1	2.3	2.2	4.4	4.6	4.8
CHANGE IN PRECIPITATION (%, MEAN VALUE, LAND-ONLY)																					
	BASED ON CRU			BASED ON EURO-CORDEX 12 KM ENSEMBLE																	
	ANN	WET	DRY	ANN	WET	DRY	ANN	WET	DRY	ANN	WET	DRY	ANN	WET	DRY	ANN	WET	DRY	ANN	WET	DRY
MED	1.3	2.5	-0.4	0.8	2.3	-1	1	2.3	-0.6*	3.9	6	1.1*	0	1.5	-2.1*	-1.9	0	-4.5	-6.8	-2	-13.3
WEST MAGHREB	2.7	1.3	6.2	-6.7	-7.8	-5.2	-6.2	-5.7	-6.9	-1.7*	0.8	-4.9	-11.2	-9.4	-13.7	-16.8	-20.3	-11.8	-31.2	-33	-28.7
EAST MAGHREB	-7.6	-11.1	5.9	-10.1	-11	-8.7	-5.4	-3.4*	-8.4	-7.8	-8.2	-7.2	-9.7	-8.6	-11.4*	-11.8	-11.7	-11.9	-23.6	-24.1	-22.7
LEVANT	-1.6	-3.5	12.2	-5.8	-5.1	-8.4	-5.8	-4.7	-10.1	-5.8	-4.3	-12	-4.6	-5.1	-2.4*	-10.7	-10	-13.5	-23.5	-23.6	-23.1
ANATOLIA	5.7	3.7	10	0.5*	3.1*	-4.1	-0.1*	2*	-3.9*	2.6	5.3	-2.4	0.2*	2.2	-4.1	-2.4	-0.2	-6.5	-8.7	-4.4	-16.4
CENTRAL MED	2.8	1.3	6.3	0.1*	1.8	-2.4	0.8*	2.1*	-1.2*	3.8	6.3	-0.8	-0.5*	1.5*	-4*	-3.3	-0.7	-7.6	-9.7	-4.7	-18.1
IBERIA	4.9	10	-4.1	-0.1	2.3*	-3.6	0.3*	2.6	-3.2*	5	10.1	-2.8*	-1.5*	0.5*	-4.9*	-6	-2.2	-12.4	-15.1	-7.5	-27.7
FRANCE	-1.8	0.7	-4.4	2.5	4.3	0.3*	2.4	4.2	0.2*	4.1	5.2	2.8	1.6	3.1	-0.3*	0.1	4.4	-5.2	-2.5*	6.7	-13.9
ALPS	-0.5	2.2	-2.8	3.5	6.3	0.7*	4.6	6	3.2	6.2	7.1	5.3	2.9	5	0.9*	3.1	6.6	-0.4*	1.5	9.2	-6.3*
BALKANS	2.5	6.7	-0.4	5.3	8.8	2.4	4.5	6	3.3	8.3	11.8	5.4	3.9	6.6	1.5	4.7	8.1	1.6*	4.9	14.4	-3.7*
CHANGE IN SURFACE SOLAR RADIATION (W/M^2, 90% INTERVAL BASED ON CMIP5 SIMULATIONS, LAND+SEA)																					
	ANN			ANN			ANN			ANN			ANN			ANN			ANN		
MED	0.3 ; 5.2			0.8 ; 8.6			0.8 ; 10.7			0.5 ; 12.6			0.6 ; 7.7			1.0 ; 10.5			0.6 ; 12.4		
CHANGE IN CLOUD COVER (%, 90% INTERVAL BASED ON CMIP5 SIMULATIONS, LAND+SEA)																					
MED	-2.1 ; 0.2			-3.6 ; 0.2			-4.4 ; 0.5			-4.3 ; 0.5			-3.3 ; 0.0			-4.9 ; -0.2			-7.4 ; -0.8		
CHANGE IN AOD (-, 90% INTERVAL BASED ON CMIP5 SIMULATIONS, LAND+SEA)																					
MED	-0.06 ; -0.02			-0.12 ; -0.04			-0.15 ; -0.04			-0.18 ; -0.05			-0.10 ; -0.03			-0.12 ; -0.04			-0.14 ; -0.04		
CHANGE IN SURFACE TEMPERATURE (°C)																					
	CMEMS (2000-2017)			TOTAL RANGE BASED ON MED-CORDEX RCSM																	
MEDSEA	0.74 (+0.23 ; +0.87)			X			X			X			0.59 ; 1.18			1.30 ; 2.07			2.86 ; 4.10		
CHANGE IN SEA LEVEL (CM, BASED ON BLENDED MULTIPLE DATABASE, SEE THE TEXT, CM, VERY LIKELY RANGE)																					
MEDSEA										(+42, +82)									(+70, +110)		

Table 2.1 | Climate change as a function of time period and Representative Concentration Pathway for the land sub-regions in *Fig. 2.1* and the whole Mediterranean Sea area. All changes are with respect to the (1980-1999) reference period. For temperature and precipitation, recent changes are based on the Climate Research Unit CRU-TS, future changes are based on the EURO-CORDEX regional model simulations. When values are annotated with "*" less than 2/3 of the models agree on the sign of projected changes. For surface solar radiation, cloud cover and aerosol optical depth values are based on CMIP5 global simulations. For sea surface temperature, recent changes are based on CMEMS observations (2000-2017), future changes on the Med-CORDEX regional simulations. For sea level rise, future changes are based on blended multiple databases *(see text).*

global ocean for two reasons. It is more alkaline, thus giving it greater chemical capacity to take up anthropogenic CO_2, and deep waters are ventilated on shorter timescales (Schneider et al. 2010), thus allowing rapid penetration of CO_2 in its interior.

2.2.9.1 Observed change in acidity

Concerning the past trends of anthropogenic carbon absorption by the Mediterranean Sea, the presence of natural CO_2 prevents to determine it from direct measurements in the water column. Estimations of anthropogenic CO_2 from data-based approaches are limited and with large uncertainties that provides concentrations that disagree by more than a factor of two in the Mediterranean Sea (Schneider et al. 2010; Touratier and Goyet 2011). These large differences further result in even opposing estimates for the net CO_2 transport across the Strait of Gibraltar.

In this context, the modeling approach using high-resolution regional model provided some insights on the information resulting from the data based-estimates and quantification of processes responsible of anthropogenic CO_2 storage and acidification of the Mediterranean Sea (Palmiéri et al. 2015). 25% of total anthropogenic carbon inventory in the Mediterranean Sea is due to net exchange at the Strait of Gibraltar, while the remaining 75% is from the air-sea flux. It confirms that the 10% higher mean total alkalinity of the Mediterranean Sea is responsible for a 10% increase in anthropogenic carbon inventory. The higher alkalinity acts to neutralize acidification and simulated average surface pH change is thus similar for the Mediterranean Sea and the global ocean (-0.08 units), with deep waters exhibiting a larger anthropogenic change in pH than typical global ocean deep waters because ventilation times are faster (between -0.005 and -0.06 units) (Palmiéri et al. 2015).

2.2.9.2 Future change in acidity

The published literature concerning specifically the future acidification of the Mediterranean Sea is quite limited leading to low confidence in the assessment. Based on thermodynamic equations of the CO_2/carbonate system chemical equilibrium in seawater, Goyet et al. (2016) calculated the variation of pH (ΔpH) as a function of theoretical anthropogenic CO_2 concentrations. Under the most optimistic SRES scenario, the results indicate that in 2100, pH may decrease down to 0.245 in the western basin and down to 0.242 in the eastern basin (compared to the pre-industrial pH). Whereas for the most pessimistic SRES results for 2100 project a pH decrease down to 0.462 and 0.457, for the western and for the eastern basins, respectively (Goyet et al. 2016). However, these estimates do not consider that the warming of seawater will decrease exchanges across ocean-atmosphere interface and penetration of anthropogenic Jungcarbon, thus they tend to overestimate future acidification.

2.3 Pollution

2.3.1 Introduction

The 2030 Agenda for Sustainable Development pledges to "ensure that all human beings can enjoy prosperous and fulfilling lives and that economic, social and technological progress occurs in harmony with nature" (UN 2015). Pollution puts at risk the possibility of achieving these outcomes and hence health and well-being. Pollution touches all parts of the planet. It is affecting our health through the food we eat, the water we drink and the air we breathe. Approximately 19 million premature deaths are estimated to occur annually as a result of the way we use natural resources and impact the environment to support global production and consumption. By definition, "pollutant" shall mean any substance that is introduced into the environment that has undesired effects, or adversely affects the usefulness of a natural resource (air, soil, water and ecosystems). Pollutants can take many forms: (i) physical, substances that are not necessarily involved in chemical or biological reactions, e.g., dust; (ii) chemical, substances that are involved in chemical reactions, e.g., pesticides; and (iii) biological, e.g., bacteria.

2.3.2 Physical pollutants

Particulate matter (PM) levels have been monitored during the past decades, mainly because of their effects on health and climate. Aerosols into the atmosphere arise from a variety of anthropogenic activities (transport, industry, biomass burning, etc.) as well as natural sources (volcanic eruptions, sea salt, soil dust suspension, natural forest fires, etc.) (Seinfeld and Pandis 2006). Both sources result in direct emission of PM (primary PM) and emission of gaseous aerosol precursors (leading to secondary PM). A number of epidemiological studies have examined the impact of PM on human health, expressed as increased mortality and morbidity varying according to the physical (size, shape, etc.) and chemical (composition) characteristics of PM (Van Dingenen et al. 2004).

The PM impact on climate is primarily a cooling effect due to increased scattering to space as the atmospheric aerosol burden increases. The overall cooling by aerosols might be equivalent to a radiative forcing of up to 2.5 W m^{-2}, counterbalancing global warming by greenhouse gases (Gillett et al. 2013; Knutson et al. 2013). More important than this direct effect may be the indirect effect that aerosols have on climate, acting as cloud condensation nuclei (CCN) (Levin et al. 2003; Gerasopoulos et al. 2006). Moreover, the particles have a large effect in reducing visibility as well as play a significant role in the deterioration of monuments and buildings (Gerasopoulos et al. 2006). Several studies conducted over the Mediterranean Basin revealed a distinct spatial inhomogeneity (Gerasopoulos et al. 2006), with PM levels increasing from north to south and west to east of the basin (Querol et al. 2009), and distinct sources. PM analysis through the years allowed the identification and classification of PM episodes as follows: (i) local urban PM pollution events (mostly in the cold season), (ii) regional PM pollution episodes (warm season) and (iii) dust outbreaks (Rodríguez et al. 2003).

2.3.2.1 Particulate matter (PM) levels and sources

Several factors favor the occurrence of high PM concentrations in the Mediterranean Basin. First, the abrupt topography, coupled with the characteristic synoptic scale patterns, results in low mean wind speeds that hinder the air mass renovations and favor the accumulation of PM in the surrounds of emission regions – leading to the so-called Atlantic/Northern clean air advections events (Rodríguez et al. 2007). Second, the low precipitation in the Mediterranean Basin favors the long residence time of PM in the atmosphere, leading to higher background PM levels (Rodríguez et al. 2007; Querol et al. 2009). The joint influence of low precipitation rates and traffic-forced resuspension of road (which is strongly enhanced by the dust accumulation in streets and roads), construction and demolition dust promoted the local urban episodes in the Mediterranean Basin (Rodríguez et al. 2007; Talbi et al. 2018). This factor, combined with the high percentage of water coverage of the area, especially in the East region of the basin, has a great contribution of the sea-salt aerosols to the PM levels and composition (Im 2013).

PM observations from monitoring networks, in the period 2007-2009, were analyzed in order to characterize particulate pollution and its health effects across Mediterranean countries (Karanasiou et al. 2014). It was concluded that the average concentrations for PM across the Mediterranean Basin are within the range of annual means typical of European sites and according to the monitoring site characteristics (traffic and urban background sites) (Querol et al. 2004; Putaud et al. 2010). The regional patterns mentioned in previous studies were highlighted, with higher PM concentrations in Italian and Greek cities, and lower levels in the Western Mediterranean (Barcelona, Marseille, Madrid, Huelva). PM10 levels at the traffic sites showed a quite similar variation. In Turin, as in the other cities of the Po valley (Bologna, Milan, Parma, Modena and Reggio Emilia), the combination of stagnant air conditions with high emissions and high population density is the main cause of very strong pollution episodes (Cyrys et al. 2012). Similarly, the air pollution problems in Athens and Thessaloniki are the result of the high population density and the accumulation of air pollutants over the city, due to topography (basin surrounded by mountains), narrow and deep street canyons and adverse meteorological conditions (Karanasiou et al. 2009; Kassomenos et al. 2011). Thermal inversions, followed by accumulation of air pollutants in the lower layers of the atmosphere are also very common in different locations like Athens (Karanasiou et al. 2014) or Beirut (Saliba et al. 2006), increasing the evening concentrations of ambient PM10.

In most countries of the southern Mediterranean, air pollution is not sufficiently monitored (Naidja et al. 2018). Emission inventories are less precise than that available in the northern Mediterranean since they are generally based on surveys and questionnaires. Because of that, local scientific articles were relatively scarce and hard to find. However, most of the available studies show that PM concentrations in this Mediterranean region are much higher than the limit values given in WHO guidelines (Naidja et al. 2018). Emissions from road traffic, resuspension of road dust, especially on unpaved roads, and natural contributions have been found to be an important source of fine particles and play a key role on the observed levels and exceedances (Mahmoud et al. 2008; Abderrahim et al. 2016; Naidja et al. 2018). Cairo (Egypt) is an example of a city where road traffic emissions are hugely important in PM10 concentration, and, ac-cording to WHO is ranked in the 33rd position on the list of the most polluted cities by PM10 (Mahmoud et al. 2008; Lowenthal et al. 2014; Naidja et al. 2018).

Since it is expected that the majority of the Mediterranean population will continue to live in cities, especially in the eastern and southern part of the basin, with a tendency to growth, higher anthropogenic pressure in a context of climate change will occur (Rafael et al. 2015; Naidja et al. 2018). Most PM exceedances were registered in regional background sites (Escudero et al. 2007), with more than 70% of them being attributed to dust outbreaks (Escudero et al. 2007; Mitsakou et al. 2008). Compared with the central and northern Europe, the occurrence of higher PM concentrations associated with dust outbreaks is higher in the Mediterranean Basin (Rodríguez et al. 2007), and are more frequent and more intense in the central and eastern than those in the western Mediterranean Basin. These episodes have been studied on an 11-yr period (2001–2011) (Pey et al. 2013). Dust outbreaks are very frequent in the southern Mediterranean, where they occur more than 30% of the days, while in northern Mediterranean this value is below 20%. The central Mediterranean appears as a transitional area, with a decreasing south to north gradient of dust outbreaks, with slightly higher frequency of dust episodes in its south, when compared to west and east sides of the basin, for similar latitudinal positions (Pey et al. 2013).

Regarding intensity characteristics and seasonality patterns, significantly high contributions are common in autumn-spring in the eastern Mediterranean, with occurrence of many severe episodes (daily dust averages over 100 µg m^{-3} in PM10) throughout the year. However, in the western Mediterranean a clear summer prevalence is noticed, with low occurrence of severe episodes; and no seasonal trend is detected in the central region, with moderate-intensity episodes (Pey et al. 2013). The contribution of dust outbreaks to PM concentrations reveals a downward trend in the period between 2006 and 2011, a period in which there was also a decrease of the NAO index for the summer period. Therefore, it can be concluded that a sharp change in the atmospheric circulation have affected the number of dust episodes and, consequently, the annual dust inflows to PM10 *(Fig. 2.15)* observed in the Mediterranean Basin (Pey et al. 2013).

The low PM2.5/PM10 ratio (approximately 0.25) in the eastern Mediterranean region also indicates that the particle size distribution has a large contribution of coarse particles which are either affected by a background level of naturally occurring dust (dust outbreaks from the Saharan Desert and sea salt particles from the Mediterranean Sea itself) or that the region is characterized by high levels of primary coarse PM emissions (Koçak et al. 2007b, 2007a). Even though the PM2.5/PM10 ratio showed seasonal variations, the values remained lower than 0.5 in most cases (Koçak et al. 2007a; Asaf et al. 2008), a value that is least two times lower than those of the western Mediterranean (Saliba and Massoud 2010).

2.3.2.2 Particulate matter (PM) chemical profiles

Regarding the chemical composition of PM, different species can be found such as carbonaceous compounds, inorganic ions and metals (Galindo et al. 2018). Although they are present at extremely low levels, some components such as trace metals are relevant in air quality studies because of

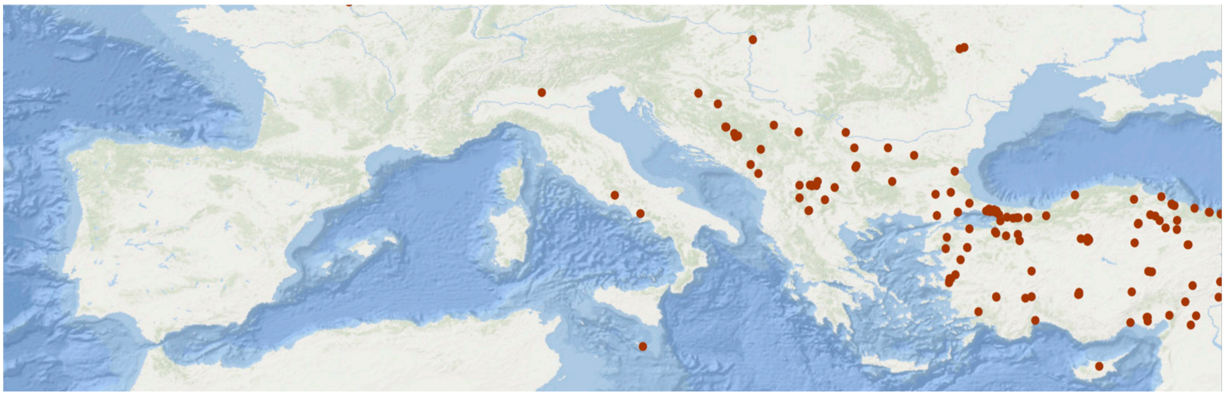


Figure 2.15 | PM10 concentration above the annual limit value of 40 µg·m^{-3} (based on EU Directive 2008/50/CE).

their toxicity and environmental persistence (Roig et al. 2013). Recent clinical and toxicological studies demonstrate the link between exposure to airborne metal through inhalation and pulmonary and cardiovascular effects, genotoxic and carcinogenic outcomes and increased daily mortality (Gottipolu et al. 2008; Lippmann and Chen 2009; Tchounwou et al. 2012).

Cooling metal concentrations are considered as good tracers of specific pollution sources, both natural and anthropogenic (Arhami et al. 2017; Diapouli et al. 2017). The main natural sources include wind-blown dust and sea-spray (Chen et al. 2008; Engelbrecht and Jayanty 2013) including elements such as calcium, aluminum, iron, potassium, sodium and magnesium. Desert dust contribute to PM composition and have a high influence on climate in the North as well as in the South of the Mediterranean (Kchih et al. 2015; Kaskaoutis et al. 2019). Specific meteorological circulations and natural sources like the Mediterranean Sea and the proximity of Sahara create specific patterns of aerosol concentrations that could influence not only the particulate concentrations through Europe but also the global climate due to the transport of dust from the Sahara (Ganor et al. 2010).

Regarding anthropogenic activities, exhaust and non-exhaust vehicle emissions, coal combustion and a variety of industrial processes, like metal works and smelters, are the major sources of heavy metals such as zinc, copper, nickel or chromium (Thorpe and Harrison 2008; Pant and Harrison 2013). In the last decades, emissions of some heavy metals in Mediterranean Basin have dropped significantly, in particular from industrial facilities due to improvement of abatement techniques (Dayan et al. 2017). In the case of lead, a drastic reduction in ambient concentrations has been observed since the introduction of unleaded gasoline (Cho et al. 2011; Salvador et al. 2012). The influence of traffic and dust outbreak intrusions on PM levels and metal content have been studied (Galindo et al. 2018), showing that the PM coarse fraction was affected more by variations in traffic intensity than the submicron fraction: the highest decreases during the weekends due to the reduction in traffic induced resuspension. That dust outbreaks had a greater impact on the levels of other metals such as titanium and lead, significantly affecting their seasonal variability. High concentrations of vanadium and nickel compared with the values found at larger urban areas were observed. This could be attributed to a significant contribution from soils, dust outbreaks (Galindo et al. 2018) and even ship emissions (Monteiro et al. 2018a; Russo et al. 2018).

Another issue related to PM composition is its radionuclide content. Radionuclides in the atmosphere rapidly attach on submicron-sized aerosols, and their variability in ground-level air is driven by the behavior of aerosols (Povinec et al. 2012; Hirose and Povinec 2015). Atmospheric radionuclides are deposited from the air onto the land and sea surface by wet and dry deposition. In this way, the terrestrial and marine environments are labeled by natural and anthropogenic radionuclides that can be used as tracers of environmental processes (Pham et al. 2017). Radionuclide content can pose a health hazard following an accident involving nuclear material (Baeza et al. 2016). However, the occurrence of anthropogenic radionuclides in aerosols is also due to erosion and resuspension processes, as well as the emission and transport of particulate matter due to biomass burning as consequence of wild fires (Strode et al. 2012; Evangeliou et al. 2014), and dust transport due to dust outbreaks (Hernández et al. 2005). Due to these processes, the anthropogenic radionuclide concentration in near surface atmosphere is variable. Naturally occurring radionuclides are also present in airborne particles as they are also present in soil particles able to be eroded, re-suspended or transported by the processes previously described, and also due to the radon exhalation from soil, which is especially significant to lead-210 and polonium-210 (Baeza et al. 2016).

2.3.2.3 Plastics (macro/micro/nano)

We live in the plastic age, since synthetic polymers are present in most aspects of human life both in developing and industrialized countries. The worldwide production for plastics increased annually by 10% since the 1950s, reaching 300 Mt in 2015 (Geyer et al. 2017). As of 2015 approx. 6,300 Mt of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment (Geyer et al. 2017). Synthetic thermoplastics constitute the most abundant and still growing component of anthropogenic debris entering the Earth's oceans (Ivar do Sul and Costa 2014). Up to 80%, or sometimes more, of the waste that accumulates on land, shorelines, the ocean surface or seabed is plastic (Barnes et al. 2009). The smallest form of plastic litter is called micro-plastic (<5 mm) and can represent up to 335,000 items km^{-2} or 5 kg km^{-2} in marine waters, and up to 25 kg km^{-2} in coastal sediments (Koutsodendris et al. 2008; Ryan et al. 2009). Plastic debris, their dissolved derivatives, as well as, the adsorbed organic pollutants (Hirai et al. 2011) pose a direct risk to human and marine ecosystem health (Galloway 2015; Koelmans et al. 2017). As a rule, widely used plastics do not rapidly degrade naturally when released into the environment, it can take 50 or more years for plastic to fully decompose (Müller et al. 2001).

In the Mediterranean Sea, the average density of plastic (1 item per 4 m²), as well as its frequency of occurrence (100% of the sites sampled), are comparable to the accumulation zones described for the five subtropical ocean gyres (Cincinelli et al. 2019), increasing the impact for marine biota with hotspots for the risk of plastic ingestion across multiple taxa especially in the coastal zone (Compa et al. 2019). Plastic debris in the Mediterranean surface waters *(Fig. 2.16)* was dominated by millimeter-sized fragments, but showed a higher proportion of large plastic objects than that present in oceanic gyres, reflecting the closer connection with pollution sources (Cózar et al. 2015). Multi-annual simulations of advected surface passive debris depict the Tyrrhenian Sea, the northwestern Mediterranean sub-basin and the Gulf of Sirte as possible retention areas (Mansui et al. 2015). No permanent structure able to retain floating items in the long-term were found, as the basin circulation variability brings sufficient anomalies to alter the distribution (Mansui et al. 2015).

Beyond the concern with "traditional" PM effects, an emergent research issue worldwide has been focused in the occurrence of microplastics in the atmospheric compartment (MP; plastic particles with a longest dimension < 5 mm). MP may undergo photo-oxidative degradation in the environment, along with wind shear and/or abrasion against other ambient particulates, eventually fragmenting into fine particles (Gasperi et al. 2018). The risk of inhaling fibrous MP following widespread contamination within different environmental compartments deserves special attention owing to both the scale of their worldwide production and their potential to fragment into smaller, more bioavailable fibers. Human exposure to MP could also occur through ingestion, for example fibrous MP can settle on the floor; children, owing to crawling and frequent hand-to-mouth contact, ingest daily settled dust (Gasperi et al. 2018). Two studies have demonstrated the presence of MP in the atmosphere (Dris et al. 2016, 2017), thereby suggesting potential human exposure (none of these studies has been conducted in the Mediterranean Basin).

2.3.3 Chemical pollutants

2.3.3.1 Nutrients

Nutrients (mainly nitrogen, N, and phosphorous, P) constitute an important factor controlling marine

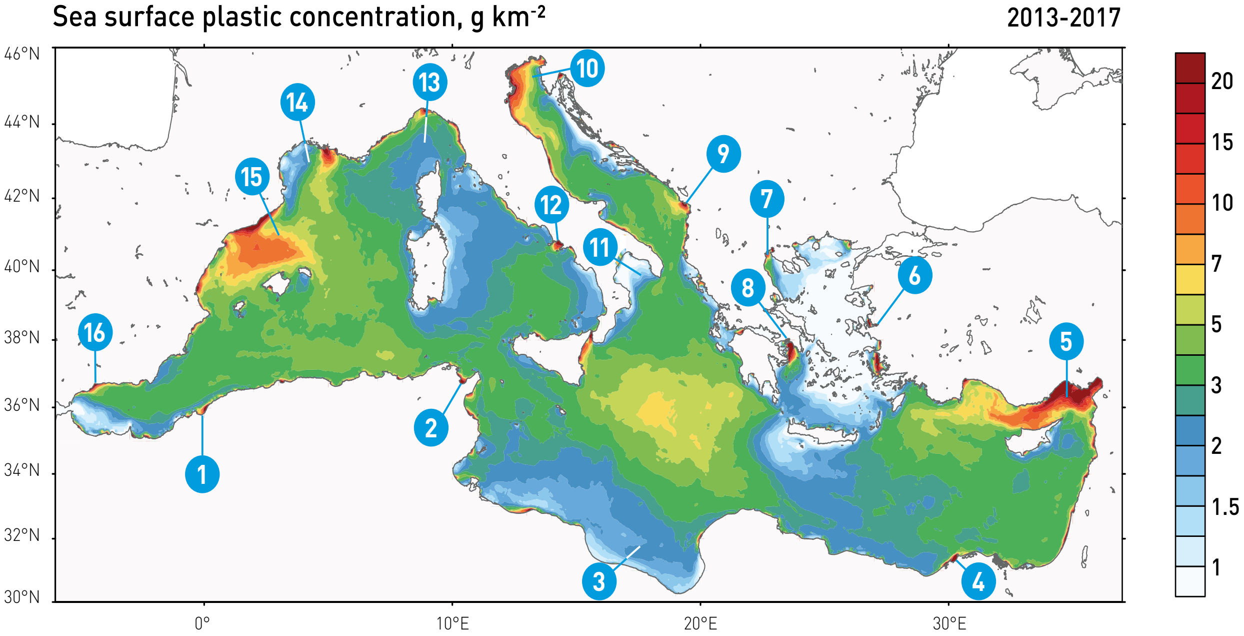


Figure 2.16 | Averaged 2013–2017 map of plastic debris concentration (g km^{-2}) at the sea surface. Some geographical names used in the text are given: the (1) Gulf of Arzew, (2) Gulf of Tunis, (3) Gulf of Sidra, (4) Abu Qir Bay, (5) Cilician Sea, (6) Izmir, the (7) Thermaic Gulf, (8) Saronic Gulf, (9) Buna-Bojana, (10) NW Adriatic, (11) Taranto Gulf, (12) Gulf of Naples, (13) Gulf of Genoa, (14) Gulf of Lion, (15) Catalan Sea, and (16) Malaga Bay (Liubartseva et al. 2018).

primary producers, as they control phytoplankton growth, biomass and species composition (Sakka Hlaili et al. 2006). According to the nutrient concentrations, marine waters are characterized as oligotrophic (low nutrient concentrations), mesotrophic (nutrient enriched water), or eutrophic (nutrient rich water). The Mediterranean Sea is characterized by oligotrophic off-shore waters, with decreasing levels of nutrients eastwards from Gibraltar to the Levantine Sea (Ignatiades et al. 2009; Tanhua et al. 2013). The Eastern Mediterranean Sea is the most oligotrophic region, with very low nitrate concentrations (< 0.5 µm) and phosphorous (< 0.2 µM) (Pujo-Pay et al. 2011). Pronounced phosphorous limitation, with N/P ratio > 30, is observed for the south of Levantine Sea and Ionian Sea (Kress et al. 2003; Pujo-Pay et al. 2011).

However, Mediterranean coastal areas, which are highly populated, are experiencing increasing N and P loading from anthropogenic activities, such as urban effluents, industrial discharges, agricultural runoffs, aquaculture activities and riverine inputs from a drainage area of 1.5×10^6 km^2 (UNEP/MAP 2017). The overall inputs of N and P in these areas are about 1.5-4.5 and 0.1-0.4 Mt yr^{-1}, respectively. The main sources of N in Mediterranean are urban wastewater treatment (45%) and livestock farming (24%). Fertilizer use can also bring nitrogen and inputs can exceed 10^6 kg yr^{-1} *(Fig. 2.17)*. Aquaculture contributed also to the emission on N (10%). For P, the main emitters are manufacture of fertilizers (40%), farming of animals (39%) and urban wastewater treatment (13%) (UNEP/MAP 2012b).

Some coastal regions are known as hotspots of nutrient inputs. In the North of Mediterranean Sea, the Lagoon of Venice and the Gulf of Lion sustained high nitrate levels, 18 µM and 9 µM, respectively (Acri et al. 2004; Severin et al. 2014). Nitrate rich waters characterize also the Eastern Adriatic Sea (4 µM) (Skejic et al. 2017) and the Western Tyrrhenian Sea (6.5 µM) (Astraldi et al. 2002). In the southern Mediterranean, The Gulf of Gabès is a main region known for P enrichment (1–11.2 µM,), since Tunisia is an important producer country of P fertilizers. Nitrate (6-6.5 µM) and ammonia (~4 µM) showed also pronounced levels in this Gulf (Drira et al. 2016). High nitrate concentrations were often measured in other Tunisian coastal systems, such as the Lagoon of Bizerte (NO_3^-: 1-6.3, NH_4^+: 20–30 µM) (Sahraoui et al. 2012) and the North Lake of Tunis (NO_3^-: 7.5–198 µM) (Armi et al. 2011). In the Algerian-Provençal Basin and the Gibraltar Strait, enrichment of water with nitrate has been reported (9.5-10 µM) (Béthoux et al. 1998; Gómez et al. 2000).

Nutrient enrichment of Mediterranean Sea may result in a high increase in phytoplankton growth and biomass, leading to the eutrophication. The impacts of eutrophication include hypoxia or anoxia and may provoke harmful algal blooms, some of them toxic. Harmful algal blooms (HABs) cause human illness and mortality and have socio-economic impacts related to toxicity of harvested fish and shellfish, loss of aesthetic value of coastal ecosystems, and reduced water quality impacting tourism *(Section 2.3.4)*.

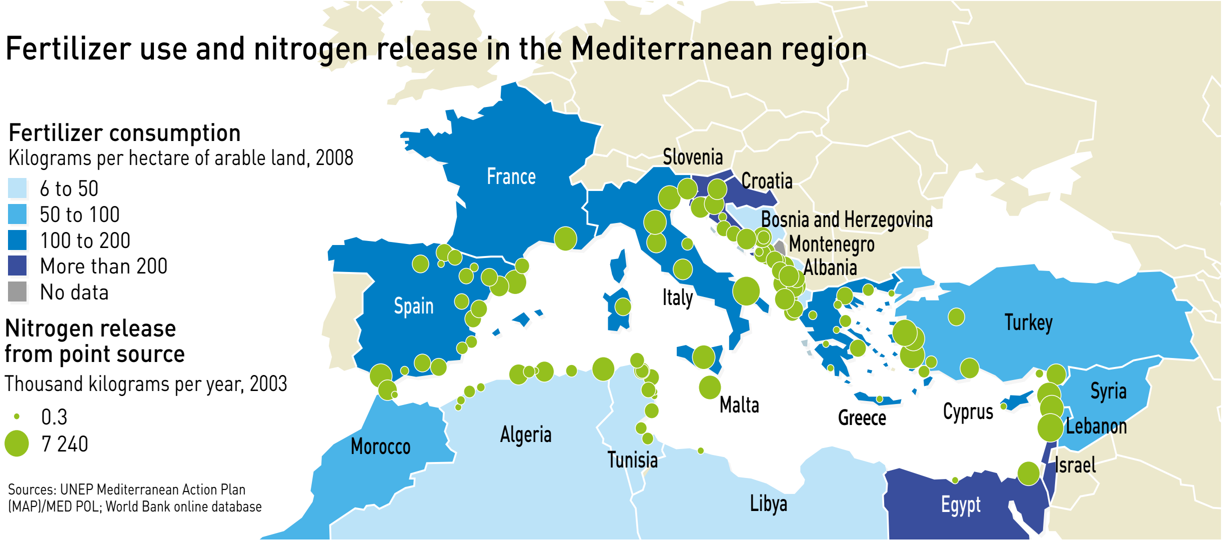


Figure 2.17 | Fertilizer use and nitrogen release in Mediterranean Sea (UNEP-GRID Arendal 2013).

2.3.3.2 *Gaseous pollutants: nitrogen dioxide, sulphur dioxide, ozone*

The Mediterranean Basin is one of the regions in the world where high concentrations of gaseous air pollutants (nitrogen dioxide – NO_2, sulphur dioxide – SO_2, and ozone – O_3) have been reported frequently (Dayan et al. 2017). The elevated concentrations observed are attributed to the combination of diverse emission sources affecting the Mediterranean Basin including industry, traffic and shipping emissions (Karanasiou et al. 2014). The Mediterranean climate is characterized by arid conditions as well as many hours of sunshine and specific atmospheric recirculation patterns that significantly enhance air pollution levels (Karanasiou et al. 2014; Querol et al. 2018).

Commonly, NO_2 concentrations in North Mediterranean countries are higher than those observed in northern Europe (Cyrys et al. 2012). This fact was attributed to the transport sector, and to the higher conversion of nitric oxide (NO) to NO_2 caused by high temperatures and O_3 concentrations (Schembari et al. 2012; Karanasiou et al. 2014). The spatial pattern of N deposition varies across the Mediterranean Basin *(Fig. 2.18)*. In Iberia, dry deposition is an important component of the total atmospheric N input to natural habitats (García-Gómez et al. 2018; Oliveira et al. 2020).

Ships are among the major emitters of air pollutants such as SO_2 and NO_x, their contribution to the emissions from the transport sector (Schembari et al. 2012) and to the air pollution in the Mediterranean Basin (Monteiro et al. 2018b; Russo et al. 2018) is growing. Several studies have also shown that NO_2 exceedances (yearly and hourly) in cities of the Mediterranean Basin are caused by road traffic emissions (Borrego et al. 2012; Belhout et al. 2018) *(Fig. 2.19)*.

The large variety of Volatile Organic Compounds (VOCs), NO_x emissions and the climate conditions of Mediterranean Basin influences O_3 formation and destruction (Sahu and Saxena 2015; Sahu et al. 2016). These factors result in higher O_3 concentrations and frequent tropospheric O_3 episodes recorded across the Mediterranean Basin, with different frequencies in the East and West (Sicard et al. 2013).

The western Mediterranean Basin is characterized by frequent sea breezes, driven by sea-land thermal contrast. These sea-land breezes play an important role for the O_3 concentrations since they transport air masses, including O_3 precursor gases, from urban agglomerations located in coastal areas, towards inland suburban and rural areas (Millán et al. 2000).

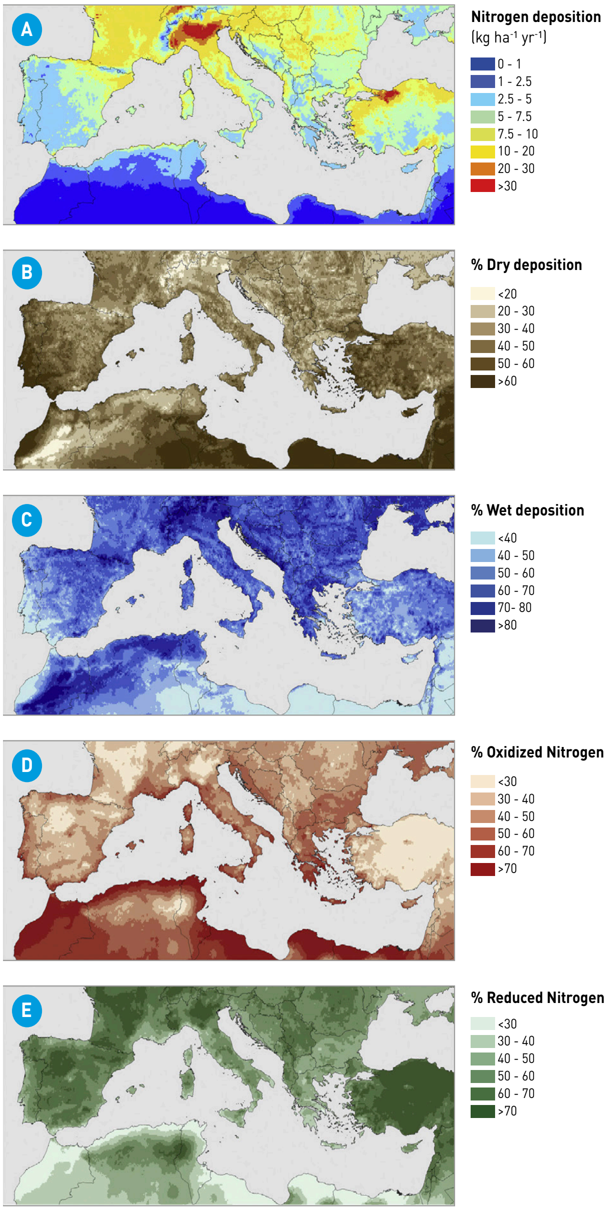


Figure 2.18 | Modelled nitrogen deposition for the Mediterranean region based on the European Monitoring and Evaluation Programme (EMEP) model at 0.1x0.1° longitude-latitude resolution (EMEP MSC-W chemical transport model version rv4.7)[6]. Modelled N deposition is based on 2013 emissions data. (A) Total N deposition (oxidized+reduced; dry+wet), (B) percentage of dry deposition, (C) percentage of wet deposition, (D) percentage of oxidized deposition and (e) percentage of reduced deposition (Ochoa-Hueso et al. 2017).

High O_3 episodes in this region are linked to the combination of one or several of these mechanisms: (i) local/regional photochemical production and surface transport from coastal to inland regions;

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[6] www.emep.int

Figure 2.19 | Nitrogen dioxide (NO_2) concentrations above the annual limit value of 40 µg·m^{-3} (based on EU Directive 2008/50/CE).

(ii) O_3 transport from higher-altitude atmospheric layers, due to air mass re-circulation in the previous days; and (iii) long-range transport of O_3 and its precursor gases (Querol et al. 2018). In the eastern Mediterranean Basin, the O_3 episodes depends on the relative strength of the high-pressure system covering the eastern Mediterranean and Balkan area: (i) strong pressure gradient with northerly winds, creating good ventilation in the Athens Basin (Kallos et al. 2014); (ii) weak pressure gradient with local/regional O_3 events prevail; and (iii) stratospheric O_3 contributions to increase surface O_3 concentrations during specific meteorological scenarios (Zanis et al. 2014; Kalabokas et al. 2015). Tropospheric O_3 concentrations observed in the summer over this region *(Fig. 2.20)* are among the highest over the Northern Hemisphere (Dayan et al. 2017).

2.3.3.3 Trace metallic elements

Metal trace elements (MTE, or heavy metals in the old designation) whose main ones are cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn) and mercury (Hg) are common elements in the earth's crust (Navarro-Pedreño et al. 2008). They are also generated by human activities (Hassanien and Abdel-Latif 2008; Tovar-Sánchez et al. 2016; Merhaby et al. 2018). Urban and industrial wastewaters, atmospheric deposition and run-off from metal contaminated sites constitute the major sources of toxic metals (UNEP/MAP 2012a).

High MTE levels have been found in various soils (vegetated soils, dikes, waste rock and slag) at mining sites in Morocco. These mining activities in addition to agricultural and pastoral practices constitute a way of entry of the MTEs into the food chain and thus increase the risk of contamination of the population. Several plant species are adapted to these high levels of MTE and thus represent an important potential for the development of mining site rehabilitation strategies (Smouni et al. 2010). In agricultural soils of the Argolida Basin (Peloponnese, Greece), the MTE concentrations are high, following a decreasing order: Fe > Mn > Ni > Zn ~ Cr > Cu > Co ~ Pb > As > Cd (Kelepertzis 2014).

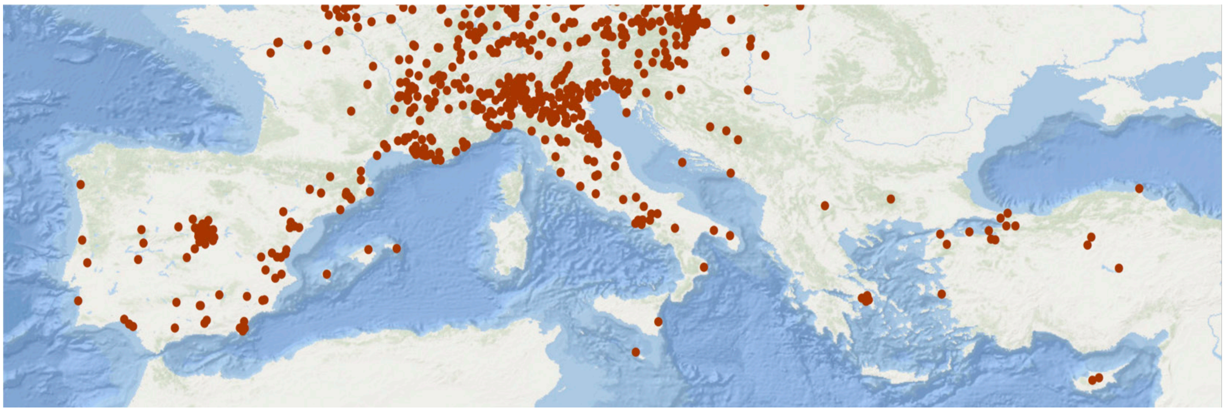

Figure 2.20 | Number of days (more than 25) above ozone (O_3) limit value of 120 µg·m^{-3} (based on EU Directive 2008/50/CE).

	Al	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Ti	Zn
Min	36,866	75.2	42.4	26,313	0.04	552	47.9	44.7	2,343	86.8
Max	72,020	102.8	52.3	36,098	0.41	2,826	60.7	74.8	3,876	129.0
Mean	58,564	85.9	47.4	31,566	0.12	893	53.3	57.8	3,065	102.3

Table 2.2 | Metal concentrations ($\mu g\ g^{-1}$ dry weight) in marine sediment of Taranto Gulf (Ionian Sea, southern Italy) (Buccolieri et al. 2006).

In marine ecosystems, the hotspots of lead, mercury and cadmium were essentially located on the north-central and southeastern shores of the Mediterranean Basin *(Fig. 2.21)* (UNEP/MAP 2012b). Polluted surface samples on the Barcelona city continental shelf taken in 1987 reached enrichment factors of up to 490 for Hg, about 40 for Pb and Cd, and about 17 for Zn, Cr and Cu. In 2008, the data showed a decline with enrichment factors between 20 and 30 for Hg and Cd and between 5 and 12 for Zn, Cr, Pb and Cu (Palanques et al. 2017). In the Taranto Gulf (Ionian Sea, Southern Italy) *(Table 2.2),* MTE distribution is principally influenced by industrial and urban wastes. River discharges and prevailing anticlockwise marine currents are further factors influencing metal accumulation in sediments (Buccolieri et al. 2006). In surface sediments in Lebanon (eastern Mediterranean Sea), trace metals (Cd, Pb, Zn, and Cr) contamination at Beirut Port was classified as "the most highly polluted" and as "moderately polluted" at Tripoli Port (Merhaby et al. 2018).

Freshwater ecosystems are also affected by MTE pollution. In the Ichkeul Lake Basin (northeastern Tunisia) MTE showed concentrations in the sediment samples following the order: Fe > Mn > Zn > Pb > Ni > Cr > Cu > Cd (Touaylia et al. 2016). The concentrations of Fe, Cd, Ni and Cr in the bottom sediments of the Lower Litani River Basin (Lebanon) were higher in the dry season (Nehme et al. 2014). In river sediments from a semi-arid Mediterranean Basin (Algeria), MTEs were grouped by their level of contamination: high (Pb, Cd, Zn, Cu) and low (Al, Fe, Cr, Co, Ni). Sources of this contamination were essentially industrial, agricultural and domestic waste, as well as very specific ones (gasoline station) and diffuse pollution from atmospheric deposition (gasoline, ores, aerosols) (Benabdelkader et al. 2018).

MTE are known for their toxicity, persistence, and bioaccumulation in human and animal tissues, and biomagnify (concentrate at successively higher levels in tissues) in food chains (UNEP/MAP 2012b). In the northwestern Mediterranean Sea, the concentrations of 21 trace elements showed great variability in three species; fish (sea bass, *Dicentrarchus labrax*), mussels (*Mytilus galloprovincialis*) and oysters (*Crassostrea gigas*). The essential elements (Cu, Mn and Zn) were highest in oysters, but Fe, Cr, Ni, Se, Co and Mo levels were highest in mussels. Fish had the lowest concentrations for all trace elements, which were at least one order of magnitude lower than in

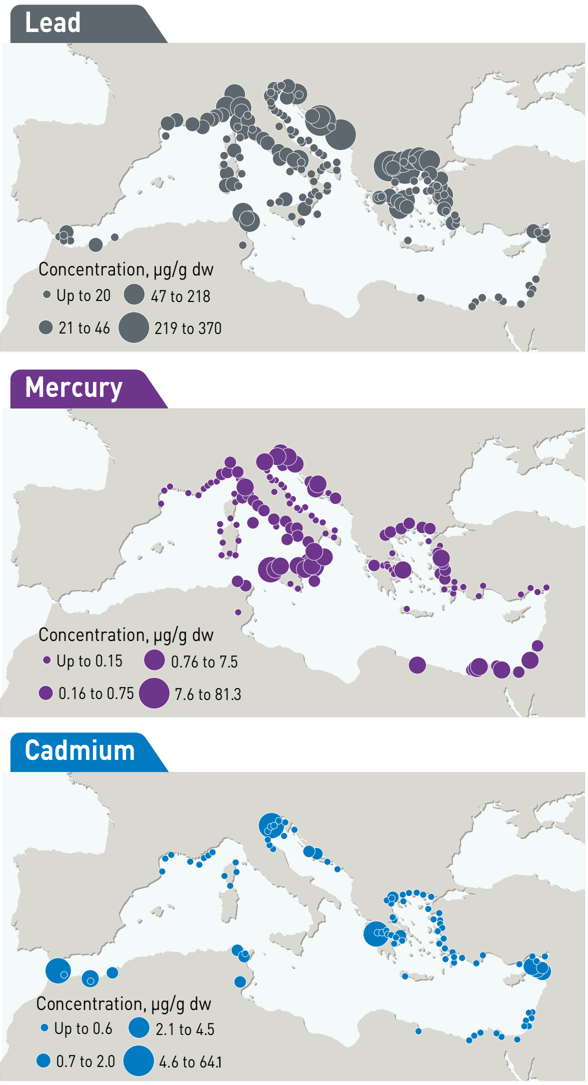

Figure 2.21 | Mean concentrations of principal trace metals in coastal sediments of the Mediterranean Basin (UNEP/MAP 2012b).

bivalves. The maximum values set by European regulations for Hg, Cd and Pb were never exceeded (Squadrone et al. 2016). The levels of As, Hg and Pb measured in some commercially key species from Sicilian coasts suggest relatively reduced pollution levels for fish resources in this part of the Mediterranean region (Traina et al. 2019).

2.3.3.4 Organic pollutants

Polycyclic Aromatic Hydrocarbons (PAHs)

The contamination of the marine environment by polycyclic aromatic hydrocarbons (PAHs) has received considerable attention since the early 1980s after occurrence of tragic marine oil spills like the Amoco Cadiz oil spill (March 1979, Brest, France; 223x10^3 t crude oil). PAHs consist of two or more fused benzene rings. PAH distribution is controlled by multiple and inter-dependent parameters. Some of these parameters are linked to intrinsic physicochemical properties of these compounds, mainly hydrophobicity which controls their partition between dissolved and particulate phases. Others are related to the hydrological and biogeochemical characteristics of the environment including water agitation and turbidity, sediment granulometry and particulate or dissolved organic matter content. They are issued from unburned petroleum or oil-derived products (petrogenic PAHs) or from the incomplete combustion of fossil fuels and biomass (pyrogenic PAHs). Petrogenic PAHs are characterized by lighter compounds (phenanthrene, naphthalene, fluorene) and their alkylated derivatives (methyl, dimethyl etc.) and have high affinity for the dissolved phase. Pyrogenic PAHs are characterized by unsubstituted higher molecular weight compounds that exhibit more affinity for suspended particles. Distribution of petrogenic-like and pyrogenic-like compounds help identification of PAH sources in the marine environment. Eight PAHs belong to the list of priority substances: Anthracene, Benzo (a) Pyrene, Benzo (b) Fluoranthene, Benzo (ghi) Perylene, Benzo (k) Fluoranthene, Indeno (123cd) Pyrene, Fluoranthene and Naphthalene. The top 5 are listed as priority hazardous substances due to their potential toxic, mutagenic and carcinogenic effects on organisms and human health (Hussein et al. 2016).

The diagnosis of the Mediterranean with regard to these substances is governed by international and national environmental agencies (i.e., the US Environmental Protection Agency (US-EPA), the European Environmental Commission, the United Nations Environment Program (UNEP), The National Observatory of the Environment and Sustainable Development, ONEDD (Algeria), National Environmental Protection Agency, ANPE (Tunisia), Egyptian Environmental Affairs Agency, EEAA (Egypt) that recommend the monitoring of 16-19 PAHs with special emphasis on PAHs micropollutants in marine matrices.

The overall data set suggests that both petrogenic and pyrogenic PAHs contribute to the PAH pool in Mediterranean coastal waters. Pyrogenic inputs increase in urbanized areas due to large atmospheric inputs and deposition in winter (Guigue et al. 2014; Barhoumi et al. 2018). Total PAH inputs from the Rhône river represent 50 t yr^{-1} whereas inputs from sewage treatment plant are much lower (<1 t yr^{-1}) (Witkowski et al. 2017). Due to their hydrophobicity, PAHs are considered to be preferentially associated with particles in coastal marine waters and sediments (Adhikari et al. 2015). Dissolved PAHs concentrations in the water column may be 4-fold higher than in suspended particles (Guigue et al. 2011). Dissolved PAH concentrations are in the range 0.158-3.655 ng L^{-1} ($\sum$18 PAHs) (Berrojalbiz et al. 2011) in Mediterranean open sea waters whereas higher concentrations characterize coastal urbanized areas, up to 560 ng L^{-1} ($\sum$32 PAHs) in Marseille-Gulf of Fos (France) (Guigue et al. 2011), 12–267 ng L^{-1} ($\sum$17 PAHs) in Venice lagoon (Italy) (Manodori et al. 2006), 13–120 ng L^{-1} ($\sum$7 PAHs) in Alexandria coastal waters (Egypt) (El Nemr and Abd-Allah 2003). In coastal sediments, concentrations range from 10-200 ng g^{-1} d.w. (dry weight) (Asia et al. 2009) in Marseille Bay, France (Gogou et al. 2000), Cretan Sea, Greece (Zaghden et al. 2005), Sfax, Tunisia (Cannarsa et al. 2014), Liguria, Italy (Merhaby et al. 2015), Tripoli harbor, Lebanon (Emara et al. 2008) and Eastern harbor, Egypt (Emara et al. 2008).

PAH concentration gradients are pronounced along coast-open sea transects. PAH concentrations rapidly decrease from the vicinity of rivers, estuaries and small effluents towards coastal and offshore waters. The contamination of estuaries of large rivers and that of harbors in the vicinity of big industrial and urban centers indicates a poor quality environment where a potential risk to the local population may occur (Barhoumi et al. 2018). Otherwise in most Mediterranean coastal waters, data reflect contamination levels from slightly polluted to polluted. Industrial areas near the cities of Sfax and Gabès (Tunisia) were reported moderate-to-highly impacted by hydrocarbons compared to other Mediterranean coastal environments (Fourati et al. 2018b, 2018a). They remain globally higher than those reported in the northern Gulf of Mexico and much lower than those recorded in Chinese coastal environments (Zhou and Maskaoui 2003; Fourati et al. 2018b).

In some cases, PAH concentrations are influenced by physical circulation processes that can lead to deposits of contaminants an order of magnitude higher offshore that those near the source of pollutants. Episodic processes of pollutants redistribution may also significantly affect the pollution status of marine areas. For example, the physical accumulation of PAH at air/sea interface (x 200-1,000) during microlayer formation in absence of wind (Wurl and Obbard 2004), followed by PAH scattering during microlayer disruption by wind blow recovery, can locally enhance PAHs concentrations and impact the biota. Similarly, PAH sediment remobilization during resuspension events may greatly modify their potential harmful effects on marine biota (Guigue et al. 2017). In Toulon bay (France), the resuspension of highly contaminated surface sediments (concentration of Σ34 PAHs = 38.2×10^3 ng g^{-1}) led to a 10-fold increase of dissolved Σ34 PAH concentrations in the water above. The remobilization in seawater was higher for 4-6 ring PAHs, especially benzo(g,h,i) perylene, whose concentration exceeded the authorized limit values of the European Water Framework Directive (Guigue et al. 2017). It is important to monitor pollutants not only at active industrial facility sites but also in disused industrial areas close to the sea border where remnant pollution can produce chronic adverse effects on marine biota.

Species feeding on particles and phytoplankton may bioaccumulate and/or bioamplify PAH concentrations in their body tissues. Measuring accumulation of PAHs in mussel bivalves from the *Mytilus edulis* complex has become a European Commission control strategy of marine waters quality in the Mediterranean (Olenycz et al. 2015; Sire and Amouroux 2016). Different metabolites may be measured in fish and shells and considered as markers of exposure to PAH. Research on the relationships with emergent contaminants is at its beginning and cocktail effects have not been much studied yet. Microplastics have a high potential to adsorb these hydrophobic contaminants and to transfer them throughout the food web to the deep ocean for longer sequestration time.

Pesticides

Pesticide Active Ingredients (PAI) can be considered as a contaminant as well as a pollutant, in the compartments where they are detected. Mainly originated by agricultural activities, water pollution by PAI is a concern for continental water resources (rivers, lakes and aquifers) and coastal and marine environment of the Mediterranean Sea. Studies carried out in southern Europe showed the high leaching of herbicides in Mediterranean weather conditions (Louchart et al. 2001), allowing the contamination of groundwater resources. In the other side, by runoff process, surface waters would be contaminated by PAI and their metabolites or degradation products. A large number of pesticide active ingredients (PAI) (over 1,300) are presently used or were used until non-approval or non-renewal in Europe (European Food Safety Authority 2011) and even modern screening methods limit the number of PAI analyzed in one sample (< 450) (Rousis et al. 2017). In water bodies, the maximum allowable concentrations are 2 µg L^{-1} for each PAI and 5 µg L^{-1} for all quantified PAIs. For drinkable water these limits are 0.1 µg L^{-1} and 0.5 µg L^{-1} respectively.

Concentrations of these molecules in water bodies (surface and underground waters) were qualified and quantified in nearly all the countries around the Mediterranean Sea. But a recent review at world scale (Stehle and Schulz 2015) stated the difference of availability of referenced data sets for insecticide concentrations in water: notably in the North and the North-East Africa poor information was available.

In European countries, particularly in France (Dubois et al. 2010; Lopez et al. 2015), Italy (Onorati et al. 2006; Meffe and de Bustamante 2014), Spain (Balaguer et al. 2018) and Greece (Lekkas et al. 2004; Konstantinou et al. 2006) implementation of the EU Water Framework Directive (WFD) produced large public data sets for pesticide concentrations in surface waters and aquifers by state administrations. According to the statistical office of the European Union, Spain and Italy are the countries with most use of pesticide. As a result, in those countries, pesticides are one of the most frequently detected classes of micro-pollutants in water[7]. It is not possible to give in this report an exhaustive account of all PAI mentioned in the literature as encountered in Mediterranean waters. Thus, we decided to focus on the most frequently detected PAI and give some examples of maximum concentrations measured.

In water bodies most frequently mentioned PAI-insecticides already in use are chlorpyrifos (18.8 µg L^{-1}) (Ccanccapa et al. 2015), dimethoate (0.640 µg L^{-1}) (Campo et al. 2013), malathion (0.048 µg L^{-1}) (Yurtkuran and Saygı 2013), imidacloprid (0.350+/-0.433 µg L^{-1}) (Herrero-Hernández et al. 2013) and diazinon (14.5 µg L^{-1}) (Youssef et al. 2015). Prohibited PAI-insecticides mentioned are DDT (dichlorodiphenyltrichloroethane) and its metabolites (0.40 to 3.22 µg L^{-1}) (Dahshan et al. 2016), HCB (hexa-

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[7] https://www.eea.europa.eu/airs/2018/environment-and-health/pesticides-sales

chlorobenzene) (1.1 µg L^{-1}) (Youssef et al. 2015) and endosulfan (0.247 µg L^{-1}) (El Bakouri et al. 2008).

The most frequently mentioned PAI-herbicides in use are simazin (3.18 µg L^{-1}) (Konstantinou et al. 2006), terbuthylazin (0.0219 µg L^{-1}) (Ricart et al. 2010), linuron (13.13 µg L^{-1}), 2,4-D (20 µg L^{-1}) and glyphosate with its metabolite AMPA (167 µg L^{-1}) (Meffe and de Bustamante 2014). Most prohibited PAI-herbicides mentioned in studies are atrazine-desethyl (0.158 µg L^{-1}) (Campo et al. 2013), metolachlor (1.120 µg L^{-1}) (Konstantinou et al. 2006), DEA (diethyl-atrazine) (1.98 µg L^{-1}) (Hildebrandt et al. 2008), diuron (0.0169 µg L^{-1}) (Robles-Molina et al. 2014), DIA (deisopropyl-atrazine) (8 µg L^{-1}) (Shomar et al. 2006), alachlor (0.213 µg L^{-1}) (Stamatis et al. 2013), isoproturon (7 µg L^{-1}) (Ricart et al. 2010) and molinate (0.026 µg L^{-1}) (Gómez-Gutiérrez et al. 2006).

Concentrations of PAI-fungicides are less mentioned than other PAI. Metalaxyl (0.49 µg L^{-1}) (Hildebrandt et al. 2008) and carbendazim (1.81 µg L^{-1}) (Licciardello et al. 2011) have been reported.

For the future, in most southern Mediterranean countries, prohibitions of particular PAIs for agricultural uses are applied within a few years delay from European Commission decisions. Many countries developed programs to reduce pesticide use that have uncertain effects like in France (Guichard et al. 2017). New proposed PAI are characterized by shorter standard half-lives and lower dose requirements, nevertheless there is no assurance that these "new" PAI once used widely in many different contexts will have virtuous environmental spreading behaviors.

Climate changes may have conversational effects on PAI water contamination. Firstly, some authors predict an increase use of pesticides to compensate increases of abundance and seasonal activity of bioaggressors (Boxall et al. 2009), although temperature enhancement has been declared to decrease PAI efficiency by conditional resistance of bioaggressors towards herbicides, insecticides and fungicides (Matzrafi 2019). Under these conditions, doses applied should be increased to guarantee the same protection with unseen consequences in environment spreading. Daily temperature fluctuation may increase PAI toxicity like for chlorpyrifos (Verheyen and Stoks 2019), but temperature enhancement should boost degradation of most known PAI probably shortening their half-life.

Change in precipitation patterns with increased occurrence of extreme precipitation events should also modify agricultural patterns. For instance, rainfed barley Mediterranean production yields would decrease (Verheyen and Stoks 2019) fueling some changes in the crop systems. Implementation of more intensive systems (Malek and Verburg 2018) can imply an increase of treatments. Increasing weight of extreme events would increase erosion (Raclot et al. 2018) and then promote displacement from land to sea for the PAIs easily adsorbed on soil particles like clay and organic matter.

2.3.3.5 Emerging contaminants

In the Mediterranean Basin, 63% of coastal settlements with more than 2,000 inhabitants operate a wastewater treatment plant, while 37% do not. Secondary treatment is mostly used (67%) in Mediterranean treatment plants, while 18% of the plants have only primary treatment (Chatha et al. 2017). As a consequence of this technical, social and environmental issue, different types of chemical substances are released into the environment (Gros et al. 2010; Ratola et al. 2012; Moreno-González et al. 2015; Paluselli et al. 2018b, 2018a). Among these substances, emerging contaminants (ECs) are a category that has received special attention over the last 25 years. ECs are defined as "contaminants of emerging concern that are naturally occurring, manufactured or man-made chemicals or materials which have now been discovered or are suspected present in various environmental compartments and whose toxicity or persistence are likely to significantly alter the metabolism of a living being" (Sauvé and Desrosiers 2014).

There are different classifications of these contaminants due to their usage or origin and effects. For example, (1) antibiotics, (2) antimicrobials, (3) detergent metabolites, (4) disinfectants, (5) disinfection byproducts, (6) estrogenic compounds, (7) fire or flame retardants, (8) fragrances, (9) insect repellants, (10) PAHs (polyaromatic hydrocarbons), (11) personal care products, and (12) pesticides or insecticides (13) pharmaceuticals, (14) plasticizers, (15) reproductive hormones, (16) solvents, (17) steroids and (18) surfactants (Singh and Kumar 2017).

ECs that are very soluble in water (tetracycline, sulfamethoxazole, carbamazepine, and erythromycin, etc.) receive more attention than others because of their impact on the environment (Klaper and Welch 2011). Potential ECs sources and pathways of ground and surface water pollution are shown in *Fig. 2.22*. Typically, the route of these compounds towards a water body begins with the excretion of the metabolites and parent compounds and their disposal to the wastewater treatment plants (Barrios-Estrada et al. 2018).

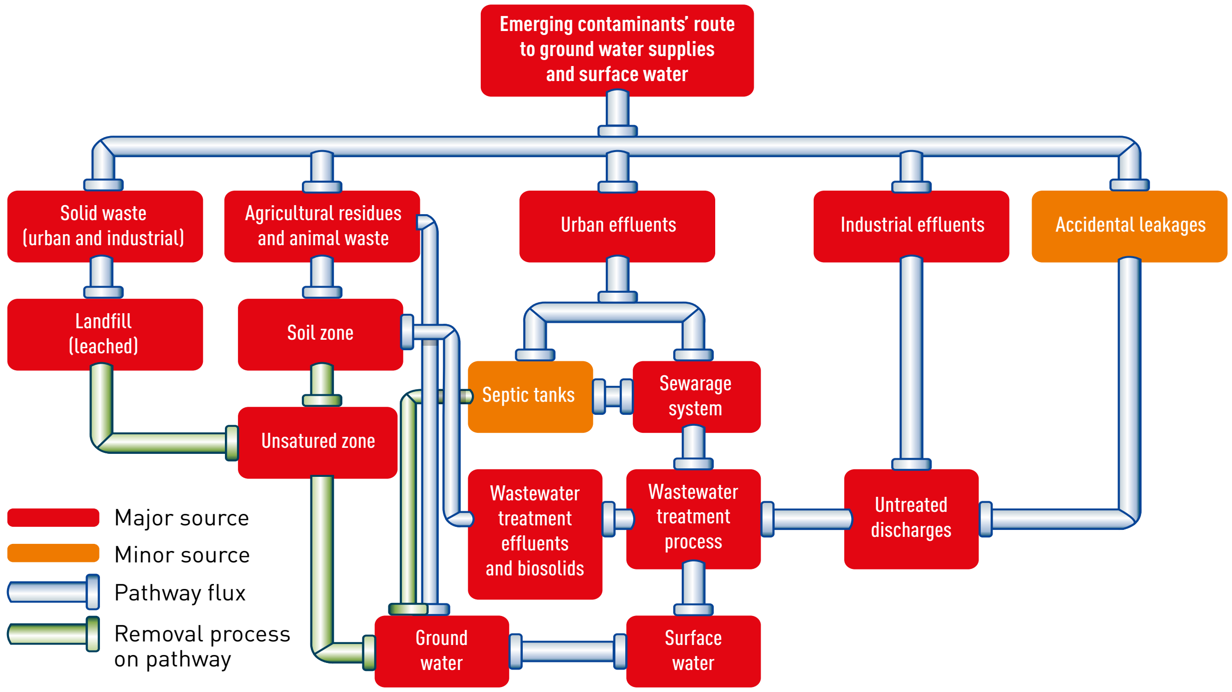


Figure 2.22 | Potential sources and pathways for grounds and surface water pollution (Barrios-Estrada et al. 2018).

The endocrine disruptors (EDs) are a subdivision of ECs with chemicals that interfere with the body's endocrine system and produce adverse developmental, reproductive, neurological, and immune effects in humans, abnormal growth patterns and neurodevelopmental delays in children (Moreno-González et al. 2015). The majority of the EDs come from products used to fight undesirable wildlife and agricultural threats (Moreno-González et al. 2015), for example, pesticides, fungicides and rodenticides, synthetic products used in plastic industry (bisphenols or phthalates) and a variety of buildings materials, isolation materials (polychlorinated biphenyl and metals). A list of common sources of EDs is shown in *Fig. 2.23.*

The presence of ECs in Mediterranean Basin is well documented. Phthalic Acid Esters (PAEs), including dimethyl phthalate (DMP), diethyl phthalate (DEP), di-isobutyl phthalate (DiBP), di-n-butyl phthalate (DnBP), benzylbutyl phthalate (BzBP) and diethylhexyl phthalate (DEHP), with total concentrations ranging from 130 to 1,330 ng L^{-1} were found in Marseille Bay (northwestern Mediterranean Sea) (Paluselli et al. 2018b). High concentrations of PAEs were also observed in deep waters offshore (310.2 ng L^{-1}) as well as in the Rhône River (615.1 ng L^{-1}) (Paluselli et al. 2018a).

A total of 20 pharmaceuticals in sea water and 14 in sediments were found at concentrations from low ng L^{-1} up to 168 ng L^{-1} (azithromycin) in sea water and from low ng g^{-1} up to 50.3 ng g^{-1} (xylazine) in sediments of Mar Menor lagoon located in the South East of Spain (Moreno-González et al. 2015). Pharmaceutically active compounds (PhACs) were detected in the Evrotas River (Southern Greece) waters. The diuretics and the analgesics/anti-inflammatory class were the most abundant, followed by antihypertensives, psychiatric drugs, ß-blocking agents and antibiotics and the concentration levels ranged from 0.31 ng L^{-1} up to 51 ng L^{-1} (Mandaric et al. 2019). Antibiotics were detected in more than 90% of the water samples collected from a Mediterranean river (Llobregat, Spain) and the concentration levels ranging from 0.3 ng L^{-1} (flumequine) to 907.6 ng L^{-1} (sulfamethoxazole) (Proia et al. 2013). Triclosan (an antimicrobial) was reported to be a contaminant of the Llobregat and Ebro rivers (Spain) and the concentrations in some samples were higher than 150 ng L^{-1}. These concentrations should be considered significant considering the toxicity of these compounds and their expected ability to be a precursor of other highly toxic compounds such as dioxins (Kantiani et al. 2008). Azithromycin (antibiotic) was measured at 16,633 ng L^{-1} in a tributary of El Albujòn (Spain) (Moreno-González et al. 2015) and acetaminophen was detected at 3,000 ng L^{-1} off Thessaloniki, Greece (Nödler et al. 2014). Some drug classes, such as analgesics, antibiotics and betablockers, were still quantified at levels between 0.3 (metoprolol) and hundreds of ng L^{-1} (azithromycin) in seawater. In

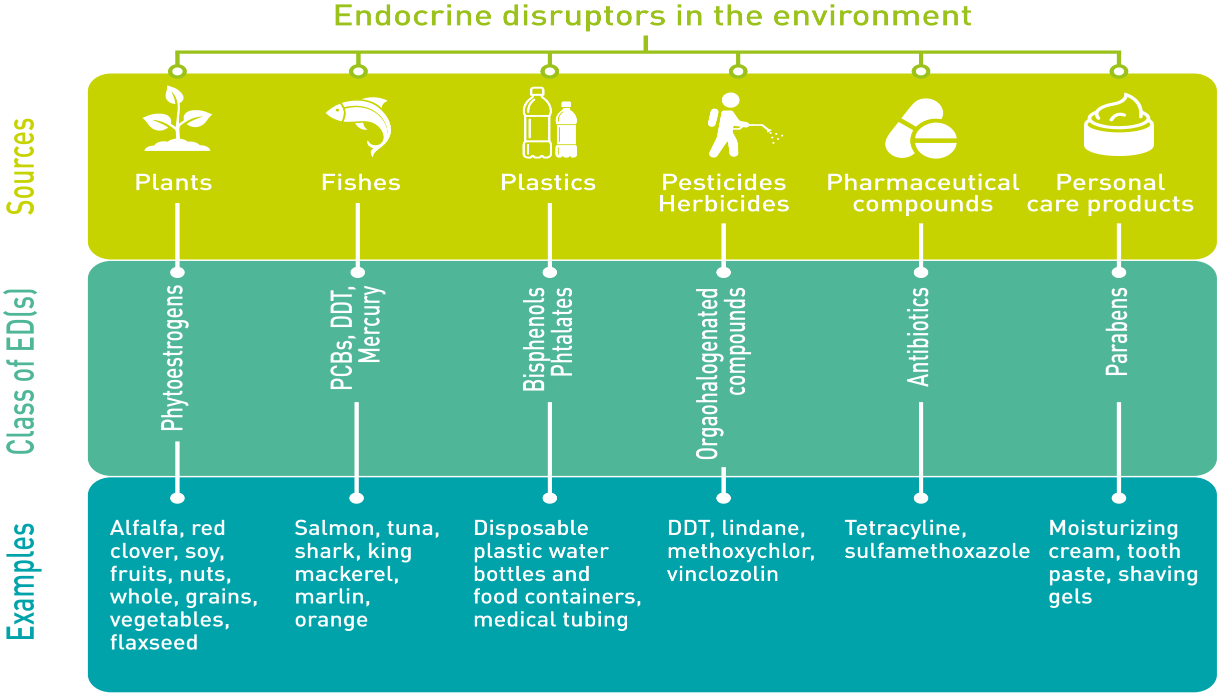


Figure 2.23 | Common sources of endocrine disruptors in the environment (Barrios-Estrada et al. 2018).

particular, six substances (e.g., azithromycin, amoxicillin, venlafaxine, salicylic acid, acetaminophen and ibuprofen) were measured at median concentrations higher than 20 ng L^{-1}. Pharmaceuticals were also found in coastal and oceanic waters adjacent to the Strait of Gibraltar (Biel-Maeso et al. 2018).

The impacts of exposure to some ECs have caused concern for both people and wildlife. Many of these substances may cause disorders of the nervous, hormonal and reproductive system, thus posing adverse health outcomes (Rezg et al. 2014; Bilal et al. 2018, 2019; Hernandez-Vargas et al. 2018; Ullah et al. 2018; Rasheed et al. 2019). These synthetic chemicals exhibit geno- or cytotoxic activity and can cause obesity, diabetes, cardiovascular and reproductive disorder or even leads to cancer (Tiwari et al. 2012). Etteieb et al. (2016) have shown that the components responsible of cytotoxicity in water samples from Medjerda river in Tunisia were mainly cyclopentasiloxane, decamethyl (D5), cyclohexasiloxane, dodecamethyl (D6), D-limonene, and ergoline-8-methanol, 8,9-didehydro-6-methyl. Some ECs, such as 17-α-estradiol, bisphenol A and phtalates were reported to alter marine community structure (Essid et al. 2013; M'Rabet et al. 2019).

2.3.4 Biological pollutants

Numerous viruses or bacteria of human or animal origin can spread in the environment and infect people via water, air and food, mostly through ingestion and occasionally through skin contact. These viruses and bacteria are released into the environment by various routes including water run-offs and aerosols. Furthermore, they can infect humans exposed to contaminated surface waters and ground water used for agriculture irrigation with severe consequences for human health (de Giglio et al. 2017). In most semi-arid areas, groundwater and surface waters constitutes an important and strategic resource, particularly as water stress increases and water resources of good quality become scarce (El Ayni et al. 2013). Molecular epidemiology and regular surveillance are necessary to elucidate the public health hazards associated with exposure to environmental viruses and bacteria (Cabral 2010; Rodriguez-Lazaro et al. 2012) especially in the South region where the water contamination combined to water scarcity strongly have large socio-economic impacts (UN-Water 2014). Climate projections for the Mediterranean climate areas estimate general warming and changes in precipitation distribution. Mediterranean coastal rivers are subject to flash floods during extreme events that transport the majority of the annual loads of bacteria and other contaminants (Chu et al. 2011). The frequency of extreme summer precipitation events increased over large regions of the Mediterranean (Giorgi and Lionello 2008) (*Sections 2.2.5* and *3.1.3.3*), increasing so the supply of fecal bacteria and viruses to the coastal zone. In a global context, wastewater management will be the key to preventing environmental dispersion of human

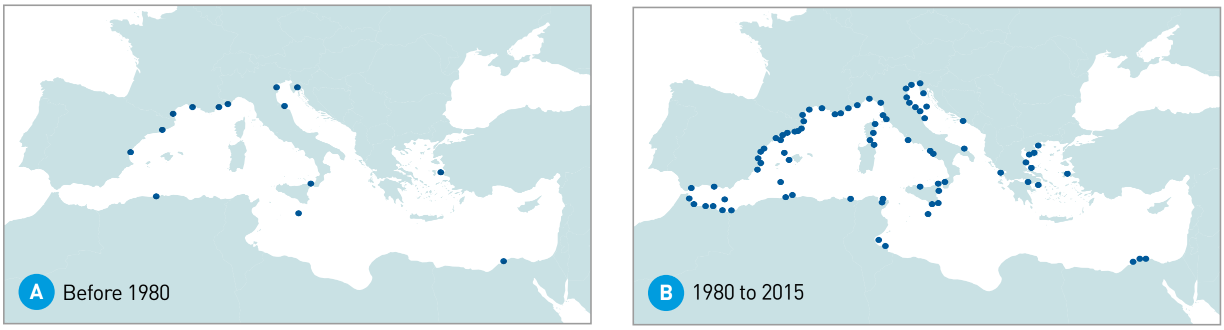


Figure 2.24 | Harmful algal blooms recorded before 1980 (A) and between 1980 and 2015 (B) along the Mediterranean coast (Cecchi et al. 2016).

fecal pathogens in future climate change scenarios (Rusiñol et al. 2015).

Harmful Algal Blooms (HABs) are sporadic phenomena triggered by massive proliferations of phytoplankton species reaching high cell concentrations (Sellner et al. 2003) that are suspected to have greater occurrences due to global warming (Hallegraeff 2010). HABs have environmental impacts (red-tide, mucilage production, anoxia) (Rodger et al. 2011; D'Silva et al. 2012) and represent serious economic threat for fisheries, aquaculture and tourism (Hoagland et al. 2002). They may also harm human health, since 40% of blooming microalgae are able to produce toxins responsible of different human intoxications (Santi Delia et al. 2015). HABs can occur in both freshwater and marine environments. In the Mediterranean Basin, marine ecosystems have received more attention although occurrence of HAB in freshwater lakes are reported (Cook et al. 2004; Romo et al. 2013) and are suspected to increase with climate change in the region (Romo et al. 2013) with consequences for potable water supply (Lévesque et al. 2014). Before 1980, HABs were rarely documented in the Mediterranean Sea. Since then, adverse events and several toxic episodes have been reported in different coastal regions *(Fig. 2.24)* (Cecchi et al. 2016; Garrido et al. 2016). Nowadays, harmful and toxic phytoplankton species become dominant in many coastal environments of the Mediterranean Sea.

Most toxic events in the Mediterranean Sea are mainly related to the dinoflagellates *Alexandrium* (known to induce Paralytic Shellfish Poisoning - PSP) and *Dinophysis* (producers of toxins causing the Diarrheic Shelfish Poisoning - DSP) (Vila et al. 2001; Penna et al. 2007). *A. minutum* is the most observed dinoflagellate, with recurrent blooms (10^3-10^8 cells l^{-1}) in the Ebro Delta and the Gulf of Gabès, inducing significant fish mortality (Abdennadher et al. 2012; Garcés and Camp 2012). Blooms of *A. catenella* (10^4 cells l^{-1}) have been observed both in the northern (Thau Lagoon) and the southern Mediterranean Sea (Bizerte Lagoon, Tunisia), causing sometimes shellfish contamination (Laabir et al. 2013). The epi-benthic dinoflagellate *Prorocentrum lima* (producer of DSP toxins) has been detected on most Mediterranean coasts (Garcés and Camp 2012), sometimes with high densities (>10^7 cells l^{-1}) (Aissaoui et al. 2014; Moncer et al. 2017). Blooms of *Karenia selliformis* (10^3–10^5 cells l^{-1}), associated with intensive fish mortality, were reported for many years in the Gulf of Gabès (Feki et al. 2013). Recently, human health problems are caused by blooms of *Ostreopsis cf. ovata* (10^3-10^4 cells l^{-1}) in Italy, Spain, Algeria and France (Ciminiello et al. 2014). New records of *Gambierdiscus* and *Fukuyoa* in the West and East of the Mediterranean Sea increase the risk of Ciguatera intoxication (Laza-Martinez et al. 2016).

Toxic diatoms *Pseudo-nitzschia* (producers of toxins causing the Amnesic Shelfish Poisoning - ASP) showed also blooms (10^3-10^7 cells l^{-1}) in Mediterranean coasts of Spain, France, Greece, Italy and Tunisia, and contamination of mussels by ASP were reported (Sakka Hlaili et al. 2016). Mussel contamination by ASP toxin were reported in Spanish and Tunisian waters and have been linked to the blooms of *Pseudo-nitzschia* spp. and *Nitzschia bizertensis*, respectively (Giménez Papiol et al. 2013; Bouchouicha-Smida et al. 2015).

Toxic and harmful algal blooms continue to increase in magnitude, frequency and geographical distribution around the world and over the Mediterranean Sea (Hallegraeff 2010). The chronic eutrophication and climatic change including global warming are reported as significant factors involved in this global increase of HABs and toxic events (Anderson et al. 2012; Sakka Hlaili et al. 2016).

2.4 Land and sea use changes

2.4.1 Land use changes

2.4.1.1 Past trends and recent dynamics

Mediterranean landscapes

The climatic conditions of Mediterranean Basin have played a key role for drawing its landscapes, which result from the interaction between human activity, a complex topography, and an extreme varied soil and climate (Pinto-Correia and Vos 2004). Altitudinal gradients and the distance from the sea are the main factors differentiating the landscapes of the Mediterranean Basin (Pinto-Correia and Vos 2004), and the main ecosystems contributing to outline these landscapes include the Mediterranean shores with a high number of habitats such as areas of dunes, rocks and wet areas. Moving away from the coast, Mediterranean maquis (a typical dense and closed shrub vegetation, mainly constituted by sclerophyllous species) and forests evolve, which includes evergreen shrubs or trees fully adapted to xeric conditions. In many cases, the maquis derives from the evergreen Mediterranean forest that develops in less water limiting growing conditions. Mediterranean steppic prairies represent the typical degradation of maquis that advances desertification. Finally, the Mediterranean deciduous forest extends where climates gradually shifts from typical Mediterranean to inland.

The modifications occurred in the Mediterranean landscapes are the result of land use practices that increased in intensity since the Neolithic, when in the Middle east domestication of plant and animals took the place of hunting and gathering (Blondel 2006). Human pressure on the natural ecosystem greatly varied depending on societal evolution developed over the area. In any case, wood exploitation has been key in localized periods of empires expansion. Forest destruction was the first step consequence of human pressure on the natural habitat as the effect of increasing agricultural activity and livestock and wood exploitation in the Mediterranean Sea trade cycle in order to cover the needs of the maritime empire (Barkaoui 2003). There is a long history of urbanization, reflected in countless archeological and historical settlements over the region (Diappi 2015).

As a result, the Mediterranean landscape is a complex mosaic of alternating semi-natural habitats. Grasslands and pastures represent one of the most spread land use in European Mediterranean areas in the plain and low hilly areas (Cosentino et al. 2014) and they can provide forage for grazing animals or hay for conservation. The use of terraces in hilly areas permitted the cultivation on slopes of olive groves, vineyard and sowing crops while at the same their cultivation represented a means to reduce soil erosion, prevent run-off and increase water saving (Blondel 2006). The Dehesa-Montado System (typical of Spain and Portugal) is characterized by low density trees (represented by evergreen Mediterranean oaks) combined with crop production or pastoral activities, mainly represented by animal grazing. This system integrates the three main rural activities (forest/cork product harvesting, livestock husbandry, and agriculture) within a single landscape that consists of grass and trees. This system that combines extensive grazing of natural pastures, cereal cultivation and harvest of wood products, has shown remarkable stability, biodiversity, and sustained productivity over 800 years or longer as the result of the maintenance of botanically rich mosaic-like herbaceous plant layers (Joffre and Rambal 1993). In addition to agricultural production, these complex systems contributed, at the same time, to several ecosystem services such as preservation of the environment and its natural resources securing the sustainability of the system (Blondel 2006; Hao et al. 2017).

Despite small-scale traditional farming systems has been practiced for long time and it is still adopted in many parts of the Mediterranean region, huge changes in agricultural practices have taken place during the last 50-100 years across several Mediterranean areas as driven by increasing profitability of new agricultural systems (Debolini et al. 2018). The greatest changes involved uprooting of ancient and small-scale vineyards, orchards and olive groves, which turned into industrial scale fruit or olive plantations. Similarly, mixed rotational farming systems were simplified and replaced usually by intensive monocultures, requiring high inputs (i.e., high fertilization rate and water requirement) (Debolini et al. 2018). Intensive and large-scale farming systems also required the creation of new infrastructure, such as basins to cope with water shortage, which contributed to change the natural landscape. All these changes caused unsustainable pressure on the surrounding environment, resulting in either loss of wildlife-rich habitats and socio-economic viability over large parts of the region due to land-abandonment of small-scale farmers.

Recent changes in Mediterranean landscapes

The rate of change of landscapes in the Mediterranean Basin has increased since the second half of the 20th century. Many regions in Mediterranean Europe experienced the abandonment of marginal lands, especially in arid and mountain areas (Lasanta et al. 2017) *(Section 3.2.3.1)*, and the following development by shrubs and tree species. Many studies show the abandonment of typical features like farming terraces, olive orchards, and upland grasslands leading to non-managed reforestation; for example, in 29% of the Iberian Peninsula for the 1989-2004 period (Hill et al. 2008); all-over Italy during 1990-2013, small forest patches cover increased a 27.4% (Sallustio et al. 2018), while 24% of pastures were turned into forests in areas of Tuscany from 1954 to 2005 (Amici et al. 2017); in Italian mountains, 16.3% of agricultural areas disappeared during the 1990's (Conti and Fagarazzi 2015); similarly in pre-alpine France during 1956-1991 (Taillefumier and Piégay 2003); in areas from the Eastern Mediterranean region of France, 14.2% of crops and 78.2% of pastures were converted into forests from 1958 to 2010 (Abadie et al. 2018); a 35.6% of vineyard areas in Serbia was transformed into meadows and pastures during 1985-2013 (Perović et al. 2018); Mediterranean islands as Elba, where up to 52% of agricultural areas were abandoned during the 1954-2000 period (Carta et al. 2018), and Lesvos, showing recent (2001-2011) slight decreases in agricultural land (Van der Sluis et al. 2016).

The remaining agricultural systems have generally become more intensive, with a shift towards livestock production and an increase of industrial inputs (fertilizers and pesticides), as it has been reported for Spain, especially since the 1960's to 2008 (Guzmán et al. 2018), and punctual areas of Greece and Italy, from 2001 to 2011 (Van der Sluis et al. 2016) *(Section 3.1.2.1)*.

Conversely, scarce and mainly pre-21st century studies from North Africa show extreme land degradation due to overexploitation (Le Houérou 1995), principally by grazing pressure but also by forest conversion to agriculture and fuel-wood recollection. For the total North Africa and Middle East regions, the rate of deforestation increased from the 1980's to the 1990's by 160%, the fastest increase worldwide (Hansen and DeFries 2004). For example, in Morocco, it has been registered forest regression and degradation from 1962 to 1992 (Rejdali 2004), while in Rogassa (Algeria) a long-term experiment (1975-1993) demonstrated the main role of overgrazing in such degradation (Slimani and Aidoud 2004). Recent studies based in new observations and remote sensing show similar desertification trends in most parts of the Maghreb (Hirche et al. 2018). Grazing has been also the principal factor of forest degradation in northern Mediterranean islands as Crete during the 1977-1996 period (Hostert et al. 2003). Moreover, increases over 10% in livestock density have been observed between 2001 and 2011 in Portofino (Italy) and Lesvos (Greece) (Van der Sluis et al. 2016), and up to 40.1% in Nisyros (Greece) from 1991 to 2001 (Petanidou et al. 2008), showing that land abandonment does not always result in forest encroachment.

Changes in Mediterranean landscapes have been particularly intense in metropolitan areas and their surroundings. These landscapes are growing very rapidly all-over the Mediterranean (17% between 1990 and 2000) (Underwood et al. 2009) but especially in coastal areas. Urbanization mainly occurred at the cost of arable land (e.g., in Barcelona) (Basnou et al. 2013) and forested areas, as generally reported in the Mediterranean (Gerard et al. 2010). However, in some periurban areas, agricultural land has also increased following the growth of cities, as in Murcia (Spain) between 1995 and 2007 (García-Ayllón 2018). Examples could be found also in eastern Mediterranean, such as in Erdemli (Turkey), where the total length of the roads increased 23.6% between 2004 and 2015 following the growth of periurban agriculture (Alphan 2018).

2.4.1.2 Principal impacts of land use changes

Forestry and other natural resources

New forests after land abandonment could alter biodiversity patterns in the Mediterranean (Fabbio et al. 2003), as has been demonstrated for the range of certain bird species (Gil-Tena et al. 2010). New forests are established by tree species whose dynamics have been favoured by recent land use changes, even more than climate (Améztegui et al. 2010). Meanwhile, other species as oaks are less benefited by such changes (Acácio et al. 2017), although general patterns show in fact successional dynamics towards Quercus dominance at the expense of Pinaceae (Alfaro-Reyna et al. 2018). Fire regimes are also altered, as fuel continuity is increased facilitating fire spread, which in turn could result in more landscape homogeneity (Loepfe et al. 2010). Also, forest continuity could increase forest insect pest spread (Hódar and Zamora 2004). The effect of increased forest cover in the diminution of water resources is more conflictive although the pattern is clearer in catchments with records of large and rapid forest expansion (Gallart et al. 2011) *(Section 3.1.1.3).* During the first stages of land abandonment there is also a great risk of land degradation due to soil and nutrient loss (Thornes 2009). Nevertheless, the contribution of these new forests to carbon storage is certain (Vilà-Cabrera et al. 2018).

Despite the natural forest recovery after land abandonment, forests in the Mediterranean Basin are still interested by many different threatening factors, such as wildfires, overgrazing, incorrect management and extreme climate and meteorological events (drought, windstorms) and this in turn could lead eventually to desertification (Vilà-Cabrera et al. 2018). Wildfires become more and more frequent due to drier summers coupled with wood expansion due to land abandonment (Pausas and Fernández-Muñoz 2012). Although evidence indicates that fires are decreasing due to increased efforts in fire suppression all-over Mediterranean Europe in more recent periods (Turco et al. 2016), there is large potential risk of mega-fires in the near future (Loepfe et al. 2011). Changes of traditional silvicultural schemes able to produce high productive goals to a more extensive management or forest abandonment has led to deep modifications of composition and structure.

Another major factor affecting degradation of Mediterranean forests is grazing by domestic animals that utilize understory especially in period of reduced forage availability in pastures (such as summer or, in certain cases, winter). The traditional grazing in forest formation should not be banned as when the stocking rate is adequate, this result in a proper sustainable forest management that can reduce potential fuel biomass and can preserve this tradition landscape (Kairis et al. 2015) while, on the contrary, overgrazing can produce erosion, reduction in soil cover, losses of nutrients and in this way is it can be considered one of the most important factors of desertification in Mediterranean areas (Papanastasis and Kazaklis 1998). Droughts, heat waves or windstorms can have a negative effect on many forests in the Mediterranean Basin producing reductions in forest growth and of forest declines (Vayreda et al. 2012) that prelude to land degradation and, in turn, desertification. All these factors produce stresses to forests that can be exacerbated in the next decades by climate change (Valladares et al. 2014).

Land degradation is the principal consequence of plant cover loss (by uncontrolled forestry, overgrazing, fires, etc.), which could lead to desertification in combination with increasing aridity and extreme climatic events (Thornes 2009). In mountain environments, forest and understory cover loss, principally by overgrazing, have been clearly associated to higher erosion rates (Cheggour et al. 2012), as well as recent increases in forest cover were linked to the opposite (Barreiro-Lostres et al. 2017). Soil erosion is a serious problem throughout the Tunisian Dorsal (the easternmost part of the Atlas mountain range). It has been estimated that 7% of the area is badly damaged by erosion and 70% of the area is moderately damaged (DG/ACTA 1993). This degradation is an accumulated effect of agricultural strategies adopted over the Tunisian semi-arid areas during the last three millennia (Jebari 2009). If we only consider short-term effects, the degradation can be partly attributed to the building of large dams during the 1960s and 1970s. This was done without giving sufficient attention to proper management of upper catchment areas (Jebari et al. 2010). However, the contribution of the specific bioclimatic conditions of the Mediterranean climate in this degradation should not be underestimated. The soils are better characterized by the degradation of rock material rather than their organic matter content (Cerdan et al. 2004; Cudennec et al. 2007). Consequently, they are not well developed and often shallow. The human influence is crucial on catchment scale in terms of landscape degradation that affects the hydrological regime (Jebari et al. 2010). In the last hundred years, continuous changes were undertaken by the introduction of new crop cover (in fact, the most important change leading to better water management in the southern part of the Mediterranean may come from improving water efficiency in agricultural irrigation) (Berndtsson et al. 2016), deforestation, urbanization, river network modification, dam buildings and embankment. Fortunately, better water resource planning, reservoir maintenance, shortage, flood management, and hydro-agricultural infrastructure design are currently promoted (Verkerk et al. 2017) *(Section 4.5.1).*

Urbanization is considered a major driving force of biodiversity loss and biological homogenization (Grimm et al. 2008), causing landscape fragmentation, dramatic loss of open habitats and of the land use gradient, replacing adjacent land uses such as agricultural and more natural vegetation. Urbanization is also one of the main drivers of introduction of non-indigenous species, generating high propagule pressure, and frequent and intense disturbance with complex consequences for biodiversity (Basnou et al. 2015; Clotet et al. 2016). The strong human pressure has also contributed to increase water shortages, pollution, forest fires, and the abandonment of ancient pastoral regimes. Recent studies also demonstrate the negative consequences of new artificial areas in coastal dunes habitats, both affecting carbon stocks (Carranza et al. 2018), and generating more complex effects when stabilizing the natural changing dynamics of dune systems (Manzano et al. 2019).

Crops and livestock

Food production in the Mediterranean region is changing rapidly, due to multiple local and global social and environmental changes. The increased number of urban and displaced people increase demand for food in urban areas, with limited agricultural production and with great water restrictions (FAO 2017a). Scarce resources, such as fisheries, are being exhausted (see next section). Evidence for the limited capacity to cope with these challenges can be documented in recent history. For example, water reserves were not able to cope with extensive droughts in the last two decades in Spain, Morocco and Tunisia, causing many irrigation dependent agricultural systems to cease production (Faurès et al. 2002; Garrido et al. 2006; FAO 2015).

Livestock production, mainly located in semi-arid and arid lands has shifted from extensive modes to systems heavily dependent on feed grain (32% of total food imports), inducing high poverty rates and rural exodus and rendering production sensitive to climatic shifts elsewhere (*Sections 3.1.2.1* and *4.5.1*).

Besides soil erosion, the major land degradation processes in the Mediterranean Basin are soil sealing, compaction mainly due to agricultural intensification, salinization, and contamination due to industrial activities. Soil organic carbon stocks tend to decrease when transforming grasslands, forest or other native ecosystems to croplands and to increase when restoring native vegetation on former croplands or by restoring organic soils to their native condition. Permanent and traditional woody cultivation such olive tree and grapevine may compensate this trend due to their positive contribution of their carbon uptake.

Human society will have to rely on an increase of output per unit area in agriculture and forestry. Intensively used agricultural systems are often N-saturated and the augmented use of fertilizer increases the leaching of N into aquifers and aquatic ecosystems and thus carries costs to environmental services such as water quality. In summer irrigated crops conditions are propitious for high N_2O losses. Emission factors for N_2O, distinguishing the effects of water management, crop type, and fertilizer management. Mediterranean agricultural soils produce large CH_4 emissions in flooded crops (e.g., rice) through methanogenesis, representing 6% of all CH_4 production from agricultural sources *(Section 3.2.3.2).*

During the past two decades, rural areas were reshaped by technological improvements in resources exploitation, the accelerating abandonment of traditional rural life and an increase in the mobility of individuals (Pinilla et al. 2008; Domon 2011). This pathway has led in many developed countries to a particular land-cover change pattern that consists in low plains and coastal areas that are being increasingly utilised for human activities due to their higher potential for agricultural productivity, while mountain or marginal areas are being abandoned because no more economically viable for production (Statuto et al. 2016; Nori 2018). Considering the increasing demand of food for an ever-growing population, leading to an increased productivity and intensification efforts in producing areas (Phelps and Kaplan 2017), this pattern has noticeable effects on the patchwork alternating semi-natural habitats that characterized the Mediterranean environment and the relevant natural ecosystem services. Management practices of grassland in in hilly Mediterranean areas were progressively reduced because of reduction of animal grazing and abandonment. This produced remarkable effects on floristic simplification, loss of biodiversity, reduction of habitat for wildlife or to the survivor itself of the resource due to shrubs encroaching (Papanastasis 2004; Argenti et al. 2011). Perennial cultivation, such as olive tree grove, originally planted in marginal areas on terraces and representing a quite stable ecosystem managed with few chemical inputs, were replaced by intensive modern plantations managed under an intensive and highly mechanized system. This intensification resulted into a progressive abandonment of marginal areas because of their low economic viability leading to a shift of land use to pasture for sheep and goats, since the land is not suitable for any other kind of cultivation (Loumou and Giourga 2003).

Conversely, the intensification process towards highly mechanized and high-density plantation is boosting farmers' income but it is also causing some environmental drawbacks. The combined effect of a more intensive management and cultivation extension is rising the issue of contamination by excess in the use of synthetic fertilizers and other agrochemicals to increase land productivity (Beaufoy and Pienkowski 2000; Beaufoy 2001). Intensification results into a degradation of habitats and landscapes and the exploitation of scarce water resources, thus putting the naturally scarce resources of olive growing areas to an edge. Drip irrigation, associated to an improved efficiency of irrigation, often has in fact no effect on efficiency but increases global water consumption. The use of this technique decreases the need for human power, allowing the increase of cultivation area and fostering multiple cropping (Kuper et al. 2017; Molle and Tanouti 2017). Soil erosion is also a growing issue due to the widening of cultivated area, as in tree crops a significant fraction of the soil is vulnerable to the action of rainfall and runoff. The intensification of agricultural land use has therefore raised the question of the long-term sustainability of agroecosystems (Liebig et al. 2004).

Different land uses as a single driver of change

Demography, technology, socio-economic factors and climate change have gradually transformed Mediterranean landscapes. Land uses are in fact the combination between the use of natural and food resources, constructions, road networks, etc., and land use changes result in the balance of their consequences. Natural habitats as affected by human activities are consequently reduced in size and continuity finally resulting into a loss of connectivity, i.e., the capability of the landscape to help or to prevent movements of organisms across habitat components (Taylor et al. 1993). A reduced or lack of connectivity may have consequences on biodiversity through losses of ecological fluxes between habitat patches and therefore trends in connectivity across different landscapes should be evaluated to consider proper actions to counteract potentially negative impact of human pressure on animal or vegetal biodiversity (Hernández et al. 2015). Over the Mediterranean Basin, two main trends, reforestation following the abandonment of agricultural areas in hilly and mountainous areas and the relevant expansion of agricultural and artificial areas in the coastal areas, plains and valleys, had different impacts on connectivity. In particular, reforestation after agricultural abandonment was correlated to a slight improvement in the connectivity of the European forest in the period 1990-2000 (Saura et al. 2011). At the same time, the spread of monoculture in the plain resulted in a de-fragmentation process. Both these trends produced a simplification and homogenization of the landscape, in terms of number, dimensions and typology of the patches that shape the agro-ecological territory.

2.4.1.3 Future projections

Land use change is expected to have different consequences on the productivity of several ecosystems and the carbon balance. The expected warmer and dryer conditions on southern Mediterranean Basin will likely shift crop cultivation to North, where water deficit is projected to be less harsh (Ceglar et al. 2019). Whilst the less adaptable crop systems will likely suffer changed pedological and climatic conditions, the most resilient crops, such as olive tree and grapevine may have the potential to resist to this trend due to their high adaptability to cope with high temperatures and water scarcity. Moriondo et al. (2013) and Hannah et al. (2013) predicted a gradual northward shift of this cultivation in the medium term (Tanasijevic et al. 2014). Increasing temperature joint with the expected reduce rainfall rate may lead detrimental consequences for those cultivations such as corn, rice and spring wheat requiring wetter conditions. Some crops may be replaced with more resilient crops such as barley, sorghum and hay, which, however, may not well fit with the market demand and the production chain of the Mediterranean area. For most of the main Mediterranean vegetable and cereals, a decrease in production is expected in the absence of specific high input agronomic strategies such as fertilization and irrigation (Bregaglio et al. 2017; Ruiz-Ramos et al. 2018; Brilli et al. 2019) whose requirement is expected to increase (Tanasijevic et al. 2014; Saadi et al. 2015).

Climate change impacts are expected to also affect managed forests, leading to shift in typical forest communities to higher altitudes (Gitay et al. 2001). These impacts will likely affect the whole woody spinneret, influencing timber extraction and plantations, and management practices. These latter practices (e.g., fuelwood collection, forest grazing, and road expansion) can degrade the forest ecosystem conditions, particularly when applied over new forest area. Accordingly, depredated soil and forestry systems may indirectly favor the introduction of pests and pathogens, changing fire-fuel loads, changing patterns and frequency of ignition sources, and changing local meteorological conditions (Nepstad et al. 1999). Grassland and pastures will likely experience a further decrease in extension due to a progressive rural abandonment and emigration to urban areas, often associated with low-income level in mountain areas and lack of job opportunity (Sturaro et al. 2013), and the impacts of climate change. This latter will particularly impact natural pastures, which are acknowledged to be very sensitive and vulnerable to climate conditions.

The predicted climate warming is also expected to lead changes of grasslands structure and composition, increasing the soil-water competition with trees that will be found to place at higher altitude as effect of higher temperatures. In temperate climate, warming may length the forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al. 2010; Hatfield et al. 2011; Izaurralde et al. 2011), whilst Mediterranean pastures will likely show production decrease due to prolonged drought conditions. Modern agricultural practice can partly overcome expected production due to changed cultivation areas, but plant adaptation would require more time to be able to adapt to the new climate. Also, higher input needed to cope with changed agronomic conditions can lead to wrong perspective of the crop, forest and grassland production trend as well as extensive environmental damage. More specifically, a larger use of fertilizer or other high inputs may result in short-term increases in food production for long-term losses in ecosystem services, such as water quality degradation (Zalidis et al. 2002; Malagó et al. 2019), soil erosion, reduced fertility, or overgrazing (Wood et al. 2000). All these changes are expected to affect the carbon balance.

Land use is an important control of carbon storage; therefore, ecosystem shifts and harsher climatic conditions may lead to different forms of stress (i.e., water and nutrient stress, pedological stress, climatic stress, abiotic, etc.) which, in turn, reduce the potentiality of the different ecosystems in terms of carbon storage (i.e., biomass reduction, less growth and development). All these changes can have negative consequences in the perspective of CO_2 mitigation capacity (Foley et al. 2005), since is expected a decrease of total carbon sequestration capacity from agro and forestry systems, increased carbon fluxes from soils due to quicker decomposition process and lower carbon mineralized in soil.

2.4.2 Sea use changes

Fisheries (over) exploitation is the main driver of marine population decline and has led to the bad state of most highly commercial stocks and the low abundance of top predators. Climate change and variability may be responsible for catch fluctuations of some stocks (especially the small pelagic fishes), for distribution shifts but also for altering catch composition in favour of warm-water species. Recent theory predicts fish size decreases in response to increased sea surface temperature and low oxygen supply. Excessive exploitation will certainly lead to even lower stock biomasses, especially for top predators. Further sea warming will very likely lead to a higher percentage of warm-water species in the catch and smaller fish sizes.

2.4.2.1 Trends in fisheries exploitation

In the Mediterranean Sea, which together with the Black Sea, constitutes FAO Major Fishing Area 37, fishing has been practiced since antiquity. Today, Mediterranean fisheries are diverse among areas and the fishing vessels and techniques vary geographically as a result of different environmental, oceanographic, biological, climatic, cultural and socio-economic conditions prevailing in each area (Papaconstantinou and Farrugio 2000), with a strong contrast between the northern and southern coastlines. The high number of islands, ports and shelters across the Mediterranean and the contrast between north and south renders the enforcement of fisheries regulations and management very difficult. Mediterranean fisheries are highly multispecies in nature targeting over 200 fish and invertebrate species (Dimarchopoulou et al. 2017) and are operated through a large number of small sized and low tonnage fishing vessels with no large industrial fleets (Stergiou et al. 2016). The number of small-scale coastal vessels operating in Mediterranean EU waters is about 86% of the total (around 72600 vessels) with the remaining 9% being trawlers and 5% being purse seiners (Colloca et al. 2017). Although the number of all types of Mediterranean EU fishing vessels declined since 1991, the actual fishing effort has been increasing due to new technologies and higher capacity vessels (Colloca et al. 2017).

Small pelagic fisheries operate all year round but in many Mediterranean Sea subareas they show a strong seasonality that is reflected upon their catches and is derived from fishing regulations and consumer habits. According to the monthly distribution of landings and fishing effort, the main fishing season in most areas is concentrated in spring and summer months (Lloret et al. 2004b).

2.4.2.2 Current status of marine fisheries resources

In the Mediterranean Sea, recent publications based on scientific surveys, stock assessments and catch data, generally agree that the majority of Mediterranean fisheries stocks are declining in biomass as a result of their overexploitation (Colloca et al. 2013, 2017; Vasilakopoulos et al. 2014; Tsikliras et al. 2015). Local reports also confirm the bad status of Mediterranean fisheries, e.g., in Greek seas (Tsikliras et al. 2013b) and in the Ligurian Sea (Abella et al. 2010), often attributed to inadequate management practices (Tsikliras 2014; Cardinale et al. 2017). The long-lasting overexploitation of the Mediterranean Sea has been driving the decline in biomass of most commercial fish and invertebrate stocks across the basin and the near depletion of several of them (Froese and Kesner-Reyes 2002; Vasilakopoulos et al. 2014; Osio et al. 2015; Tsikliras et al. 2015; Stergiou et al. 2016; Colloca et al. 2017; Froese et al. 2018). The overall stock status is rather uniform across the Mediterranean ecoregions with low stock biomass being the common characteristic. However, the stock specific biomass levels vary among ecoregions (Froese et al. 2018).

The catch history of Mediterranean Sea stocks unmasked the overexploitation of many stocks since the 1950s, when about 40% of them were declining in biomass (Froese and Kesner-Reyes 2002). Recent literature reveals that fisheries overexploitation occurs across the entire area (Tsikliras et al. 2013a) and locally, e.g., in Greek Seas (Tsikliras et al. 2013b). Several Mediterranean stocks have been reported overfished based on data from landings (Tsikliras et al. 2013b, 2013a), scientific surveys (Stergiou and Tsikliras 2011), or stock assessments (Colloca et al. 2013). Other studies confirm that almost all species targeted by the fishing fleets are being overexploited in the Mediterranean Sea (Cardinale et al. 2017; Fernandes et al. 2017).

Based on the catch-based method, the cumulative percentage of collapsed and overexploited stocks appeared to exceed 60% across the Mediterranean Sea in 2010 (Tsikliras et al. 2013a) with the exploitation pattern differing among the Mediterranean subareas (Tsikliras et al. 2015). The western Mediterranean has been reported to be in a better state with less overexploited and collapsed stocks and more developing ones compared to the central and eastern parts of the sea (Stergiou et al. 2016). Similarly, based on various fisheries indicators, the western and central Mediterranean are in better condition compared to the eastern part of the sea (Tsikliras et al. 2015). According to the official stocks assessments that were then available, the percentage of overexploited stocks exceeds 90% in most areas (Colloca et al. 2013) and even reaching 95% in some (Osio et al. 2015). The model approach of Osio et al. (2015) estimates that 98% of the unassessed demersal fish species are potentially overexploited in most areas. Cardinale et al. (2017) reported that the stocks of all target species that have been assessed are overexploited with the average ratio of F/F_{MSY} (actual fishing mortality to the level that would provide maximum sustainable yield) ranging from 1.7 (giant red shrimp *Aristaeomorpha foliacea*) to 8.1 (hake *Merluccius merluccius*). Steadily increasing exploitation rates and deteriorating gear selectivity have been recently reported as two conditions that lead to shrinking fish stocks (Vasilakopoulos et al. 2014). The most recent assessment of 169 Mediterranean stocks showed that 126 of them (75%) were subject to ongoing overfishing (Froese et al. 2018).

2.4.2.3 The future of marine resources

The Gill-Oxygen Limitation Theory (GOLT) predicts a reduction in the size of fish due to their inability to compensate, via their gill surface, for the increased metabolic rate that results from higher temperatures. Fish individuals that survive are expected to shrink in size (Cheung et al. 2013a). The Mediterranean Sea is among the semi-enclosed areas where local species extinctions and range shifts were predicted to be most common (Cheung et al. 2009). The GOLT theory may also explain the poleward shift of marine organisms (Cheung et al. 2013b) and their expansion to deeper waters (Perry et al. 2005) both of which occur in the Mediterranean Sea (Tsikliras and Stergiou 2014) and may have an impact on Mediterranean fisheries in terms of catch and revenue (Cheung et al. 2010).

Besides fish distribution shifts and declines in local fish stocks, scientific projections suggest that marine resources and biodiversity will suffer increasing stress if temperatures are not held below 2°C above preindustrial levels (Gattuso et al. 2015). Sea warming and deoxygenation combined with fishing pressure and other stresses could affect growth, and distribution of fish populations, resulting in changes in the potential yield of exploited marine species and economic losses (Sumaila et al. 2011) as fisheries are expected to decline (Cheung et al. 2010). Reaching the goals of the UNFCCC Paris Agreement would benefit ocean life and economies by protecting millions of metric tons of high valued catch with 75% of maritime countries benefiting from this protection (Sumaila et al. 2019).

Fisheries in the Mediterranean will not be sustainable in the future unless the marine exploited populations are fished less, i.e., if they are allowed to recover and rebuild their biomass (Pauly and Zeller 2016) through the reduction of the fishing pressure that is applied upon them (Froese et al. 2018). Ecosystem-based approach has also an important role that will ensure that both higher and the lower trophic levels are rebuilding (Pikitch et al. 2004) and fully marine protected areas are a key management tool to accomplish rebuilding of the biomass of marine populations, ensure ecosystem health and resilience against sea warming (Roberts et al. 2017).

2.5 Non-indigenous species

The human-aided introduction of non-indigenous species into new biogeographic regions – has been one of the main increasing global drivers of ecological change for over a millennium (Elton 1958). Non-indigenous species homogenize biodiversity across the globe, resulting in shifted and sometimes more simple ecological communities (Mooney and Hobbs 2000; Rilov and Crooks 2009). They can displace native species out of their natural habitats through competition, consumption, or parasitism. This displacement results in affected communities with reduced native species diversity, altered species composition as well as in major changes in ecosystem functioning (Vilà et al. 2011; Cameron et al. 2016). Moreover, these changes alter supporting, provisioning, regulating ecosystem services that people depend upon, impacting human well-being (Katsanevakis et al. 2014b; Vilà and Hulme 2017).

Rates of introduction and impacts have accelerated dramatically in the past few decades due to various human activities and related pathways of non-indigenous species introduction (Carlton 1989; Crooks and Suarez 2006). In the marine environment, the growth of seaborne trade with its huge fleets facilitates the dispersal of organisms attached to the hulls of ships and inside ballast water (Crooks and Suarez 2006; Katsanevakis et al. 2013). Aquaculture, live marine seafood and bait, and aquarium trade have also become important vectors for the introduction of marine non-indigenous species, as well as the artificial connections of water bodies with very different biotas (Rilov and Crooks 2009), and major catastrophes like tsunamis (Carlton et al. 2017). In terrestrial ecosystems, intentional introductions prevail over unintentional. For non-indigenous plants, ornamental and horticultural introductions escaped from cultivation account for the highest number (Lambdon et al. 2008) and are increasing steadily (Van Kleunen et al. 2018). Terrestrial non-indigenous vertebrates follow similar patterns as plants. However, most terrestrial non-indigenous invertebrates have been introduced accidentally; many are major pests in forestry and agriculture (Roques et al. 2010).

2.5.1 Non-indigenous species in the Mediterranean Sea

The first introduction of marine species into the Mediterranean Sea dates back to the late 18th century (Poli 1791). Since then, due to maritime shipping expansion and after three centuries of accumulating human pressures, this basin has become a hotspot of introduction of non-indigenous species (Rilov and Galil 2009; Coll et al. 2010). Non-indigenous species in the Mediterranean Sea mostly arrive from the Indo-Pacific region either directly (by swimming or drifting) or indirectly as foulers or as hitchhikers inside ballast water in a process called Lessepsian migration (Por 1978). But there are many other vectors that deliver non-indigenous species into the Mediterranean and have varying importance depending on the region (Rilov and Galil 2009). Today, the total

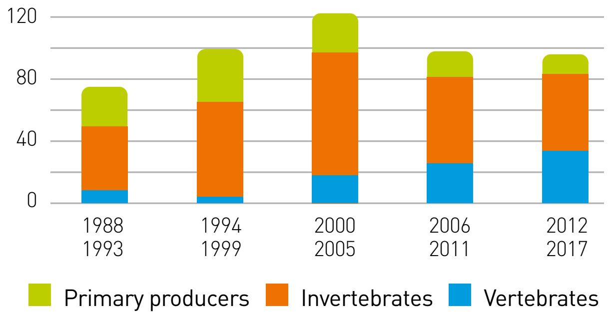


Figure 2.25 | Number of new non-indigenous species per 6 years in the Mediterranean since 1988 (Zenetos 2019).

known number of non-indigenous species is still debated, but the last count puts it close to a thousand species (Zenetos et al. 2017). For some of the species, the impact on local biodiversity, and possibly also ecosystem functions and services, seems obvious, but in most cases, the impact is unknown because of lack of research (Katsanevakis et al. 2014b). The Mediterranean Sea is warming rapidly (Nykjaer 2009; Sisma-Ventura et al. 2014) *(Section 2.2.4)*. Therefore, it is quite possible that the establishment of thermophilic non-indigenous species is strongly facilitated by climate change (Stachowicz et al. 2002).

2.5.1.1 Spatiotemporal trends, sources and vectors of introduction

The most recent assessment of marine non-indigenous species in the Mediterranean (November 2018) counts 957 species, including Foraminifera (Zenetos 2019). Among the introduced species during the last 30 years (491 taxa), invertebrates dominate with >58% (287 species) represented mostly by molluscs and decapods. Primary producers follow with approximately 114 species among which macroalgae, especially rhodophytes, prevail. Vertebrates (mostly fishes) follow with 90 species.

The trend in introduction of species in the Mediterranean *(Fig. 2.25)*, which culminated in the 2000-2005 period with more than 20 new species per year (122 in total), appears to be overall decreasing after 2005 *(Fig. 2.26)*. As opposed to invertebrates and primary producers, vertebrates continue increasing, with 34 species detected in the 2012-2017 period vs 26 species in the period 2006-2011. The overall decreasing rate in non-indigenous species is evident across the Mediterranean Marine Strategy Framework Directive (MSFD) areas, except for the Central Mediterranean where an increase is observed, attributed to vertebrates *(Fig. 2.26)*. 17 new fish species were detected in the central Mediterranean in the period 2012-2017 vs. 8 fish species in the period 2006-2011. These species are either spreading from the eastern Mediterranean to the central region or are newly introduced species in the area. Vertebrates (fish only) are dominated by Lessepsian immigrants but over the last decade the number of fish species related to aquarium trade which have been intentionally released to the wild (classified as escapees from confinement) is increasing (Zenetos et al. 2016; Marcelli et al. 2017; Deidun 2018).

Regarding the spatial distribution of non-indigenous species, the number of Lessepsian species is very high on the eastern Mediterranean coastline, reaching 129 species per 100 km², and declines toward the north and west (Katsanevakis et al. 2014a). The distribution of species introduced by shipping is strikingly different, with several hotspot areas occurring throughout the Mediterranean Basin. Two main hotspots for aquaculture-introduced species have been identified (the Thau and Venice lagoons). Certain taxonomic groups were mostly introduced through specific pathways-fish through sea corridors, macrophytes by aquaculture, and invertebrates through sea corridors and by shipping (Katsanevakis et al. 2014a). Hence, the local taxonomic identity of the non-indigenous species is greatly dependent on the dominant maritime activities/interventions and the related pathways of introduction. The composition of non-indigenous species assemblages differs among Mediterranean ecoregions; such differences are greater for Lessepsian and aquaculture-introduced species.

2.5.1.2 Non-indigenous species as drivers of biodiversity and ecosystem change

The introduction of non-indigenous species in the Mediterranean Sea have caused modifications in biodiversity patterns. One of the best documented and most profound impacts of the introduction of non-indigenous species on native Mediterranean ecosystems is the deforestation of algal forests and the creation of extent barrens (i.e., areas with bare rock and encrusting calcified algae; *Fig. 2.27*) by the overgrazing activity of two non-indigenous herbivore rabbitfishes: *Siganus luridus* and *S. rivulatus*. These species have become dominant in the ichthyofauna of shallow rocky habitats in the eastern Mediterranean, and have caused ecosystem-wide changes by creating and maintaining areas denuded of canopy algae (an important habitat for many coastal fishes) (Cheminée et al. 2013). This form of "deforestation" is associated with a dramatic reduction in biodiversity, biomass, and algal growth, and effects that move up the food chain to the local fisheries (Sala et al. 2011; Vergés et al. 2014b).

In the Levantine Sea, the catch of commercial fisheries is now dominated by non-indigenous species (Edelist et al. 2013; Katsanevakis et al. 2018), reflecting the decline of native biota and its replacement by thermophilic non-indigenous species (Arndt et al. 2018). In Turkish coastal waters in the Levantine Sea, non-indigenous

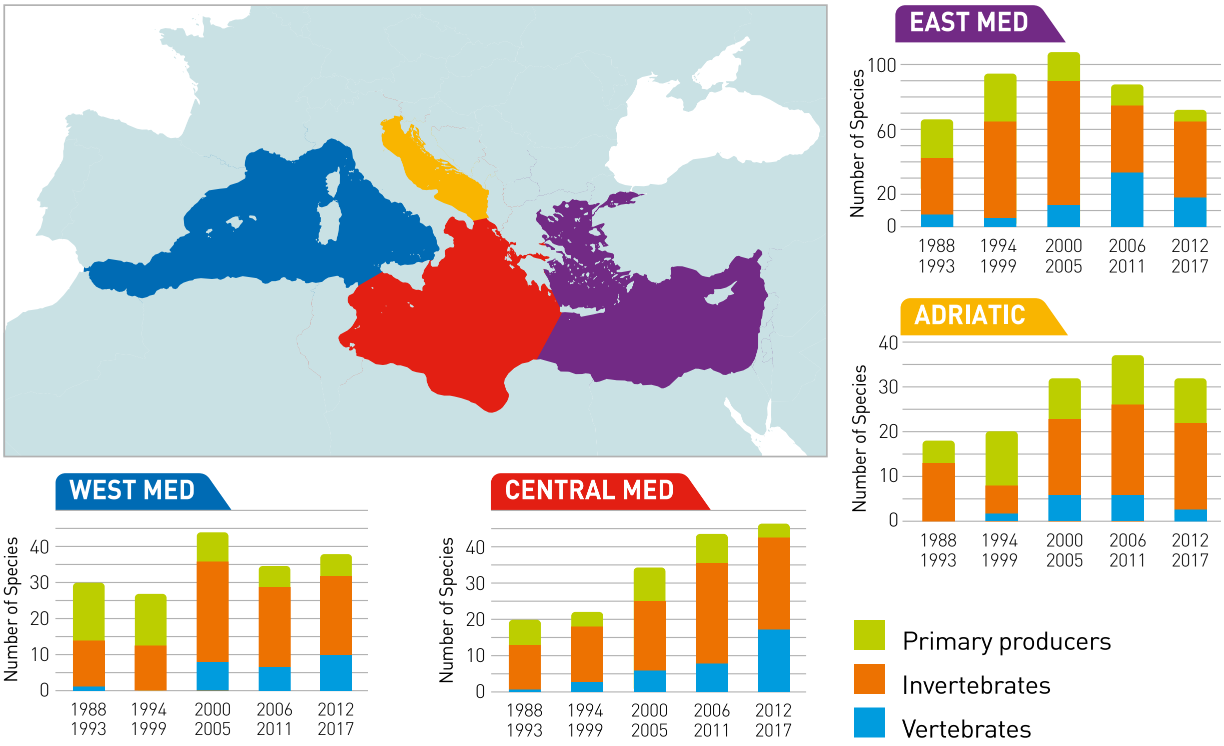


Figure 2.26 | Change in the number of new non-indigenous species per 6 years in the Mediterranean MSFD regions (Adriatic, Western Mediterranean, Central Mediterranean, Eastern Mediterranean Seas) since 1988. Notice that the scale is different for the eastern Mediterranean (Zenetos 2019).

fish species biomass exceeds 50% of the total fish biomass and 90% of the total herbivore fish biomass (Giakoumi et al. 2019). Fishers in the same area (Kaş, Turkey) perceived the introduction of non-indigenous species as the most important reason for the current fish stock depletion.

Yet, it is uncertain whether the decline of native biota in the Levantine Sea is driven mainly by biotic interactions with non-indigenous species or climate change, or both, as the Lessepsian species are thermophilic and their establishment is assisted by climate change (see discussion below). A recent meta-analysis suggests that the decline of native fish can be mostly attributed to ocean warming and not to negative interactions with non-indigenous species (Givan et al. 2017a). Multi-species collapses of native species are also at least partially attributed to climate change (Rilov 2016), with the collapse of the sea urchin *Paracentrotus lividus* experimentally demonstrated to be related to the fast ocean warming (Yeruham et al. 2015).

Analysis focused on shallow reef fish shows that non-indigenous species are very diverse ecologically, and they considerably increase the total community trait diversity of the Mediterranean (Givan et al. 2017b). Furthermore, trait similarity between non-indigenous and indigenous Mediterranean species was lower than expected, indicating that non-indigenous fish tend to occupy relatively vacant niches within the Mediterranean. Temporally, non-indigenous fish species display increased trait similarity to native Mediterranean species, suggesting that forecasting future establishment may be challenging. Givan et al. (2017b) conclude that the Mediterranean, at least in fish, is transforming into an extension of the Red Sea in terms of trait and species composition. Such biological trait analysis is also required for other taxonomic groups.

There is a serious research gap in assessing and quantifying the impacts of non-indigenous species on marine ecosystems in the Mediterranean Sea. Impact assessment is mostly based on expert judgment or correlational studies, while manipulative or natural experiments are largely lacking for assessing the impacts of most non-indigenous species in the region (Katsanevakis et al. 2014b). Disentangling the role of the introduction of non-indigenous species and climate change or other local or global stressors to derive cause-

Figure 2.27 | Ecosystem shift from algal forests to barrens due to the overgrazing activity of non-indigenous herbivore rabbitfish. Algal forests host high fish, invertebrate, and algae biodiversity whereas barrens are associated with low levels of biodiversity across all taxonomic groups. *Rabbit fish photo: Murat Draman.*

effect pathways is inherently difficult and would probably necessitate a combination of experimental and modelling approaches.

Efforts are made to assess non-indigenous species impacts with existing knowledge. Based on a conservative additive model, which downgrades reported impacts of low inferential strength, an index of the Cumulative IMPacts of invasive ALien species (CIMPAL) on marine habitats in the Mediterranean has been developed and estimated (Katsanevakis et al. 2016). The estimation of CIMPAL was based on assessments of impacts for every combination of 60 non-indigenous species and 13 habitats, and their distributions in the Mediterranean (i.e., presence in 10x10 km cells). It showed strong spatial heterogeneity in impacts. Spatial patterns varied depending on the pathway of introduction of the non-indigenous species in the Mediterranean Sea. Species introduced by shipping gave the highest impact scores and impacted a much larger area than those introduced by aquaculture and through sea corridors. Overall, non-indigenous macroalgae had the highest impact among all taxonomic groups, when estimated as the sum of impact scores across the entire Mediterranean Sea, i.e., accounting not only for the severity of the impacts but also their spatial extent. The most impactful non-indigenous species was *Caulerpa cylindracea*, which has become dominant over large areas of shallow waters in the western Mediterranean and compete with native species (Piazzi et al. 2016). Negative impacts of *C. cylindracea* have been documented on algal, sea grass, and sponge communities (Ceccherelli et al. 2002; Piazzi et al. 2005; Piazzi and Ceccherelli 2006; Baldacconi and Corriero 2009).

2.5.1.3 Further introductions, monitoring and managing non-indigenous species

The introduction of species in the Mediterranean Sea is a continuous process and it is very likely that it will continue for years to come. In most of the cases, these species fail to thrive but, evidently, some become numerically and ecologically dominant in their new environment, generating new and sometimes severe impacts of the introductions. As a consequence, in the past two decades research interests in non-indigenous species have increased, mostly stimulated by evidence on their ecological and socio-economic impacts in the Mediterranean region. This has also raised the urgency of innovative approaches to forecast, track and manage these species (Corrales et al. 2018).

One of the most recent and potentially damaging non-indigenous species for this basin is the common lionfish (*Pterois miles*), which increasingly appears in many parts of the eastern Mediterranean in the last few years (Bariche et al. 2013). Due to its rapid increase in abundance (Kletou et al. 2016) and fast geographical expansion (Azzurro et al. 2017), this harmful species has become emblematic for raising concern on Mediterranean non-indigenous species introductions but it also well illustrates a process of developing monitoring capabilities and management strategies within the Mediterranean region.

Documenting the spread of this non-indigenous species can greatly benefit by the participation of resource users, a partnership which can support monitoring objectives (Azzurro and Bariche 2017) and be used to reduce, at least locally, the abundance of non-indigenous species (Kleitou et al. 2019). More generally, participatory approaches benefit the scientific consensus, which is a key element for both documenting and responding to these introductions (Scyphers et al. 2015). This is also reflected in some of the guiding principles on the management of non-indigenous species adopted by key regional and international bodies/legislative frameworks, concerning non-indigenous species, such as those provided by the EU (Regulation 1143/2014); UNEP-MAP and by FAO-GFCM, which are converging towards finding common strategies to face Mediterranean species introductions. In this regard, the Integrated Monitoring and Assessment Programme and related Assessment Criteria (IMAP) adopted through Decision IG.22/7 by the 19th Ordinary Meeting (COP 19, Athens, Greece, 9-12 February 2016) of the Contracting Parties to the Barcelona Convention, stress the need of comprehensive monitoring and coordinated transnational actions to face the common issue of Mediterranean non-indigenous species introductions. A recent expert assessment of management options of marine non-indigenous species prioritized 11 management actions for controlling 12 model species according to their dispersion capacity, distribution, and taxonomic identity (Giakoumi et al. 2019). The actions were assessed using five criteria (effectiveness, feasibility, acceptability, impacts on native communities, and cost), combined in an "applicability" metric. Raising public awareness and encouraging the commercial use of non-indigenous species gained the highest priority, and biological control was considered the least applicable (Giakoumi et al. 2019).

To predict future change in the distribution of native species and the spread of non-indigenous species, species distribution models (SDM) are regularly used. In these models, climate matching is calculated between the area of origin (donor) and the area of potential spread (recipient). However, a recent study that matched the native range of Red Sea fish and their new range in the Mediterranean Sea showed poor matching, and thus indicated that SDMs may underestimate the potential spread of non-indigenous species (Parravicini et al. 2015). The authors call for caution in employing such models for forecasting the introduction of non-indigenous species and their response to environmental change, as uncertainty is large. Better knowledge of the fundamental niche of species (their physiological performance under different environmental conditions) can potentially improve the prediction of spread of non-indigenous species in the Mediterranean. Furthermore, an analysis combining ship movements with port environmental conditions and biogeography can be used to quantify the probability of new primary introductions through ballast water (Seebens et al. 2013).

2.5.2 Terrestrial non-indigenous species and pests

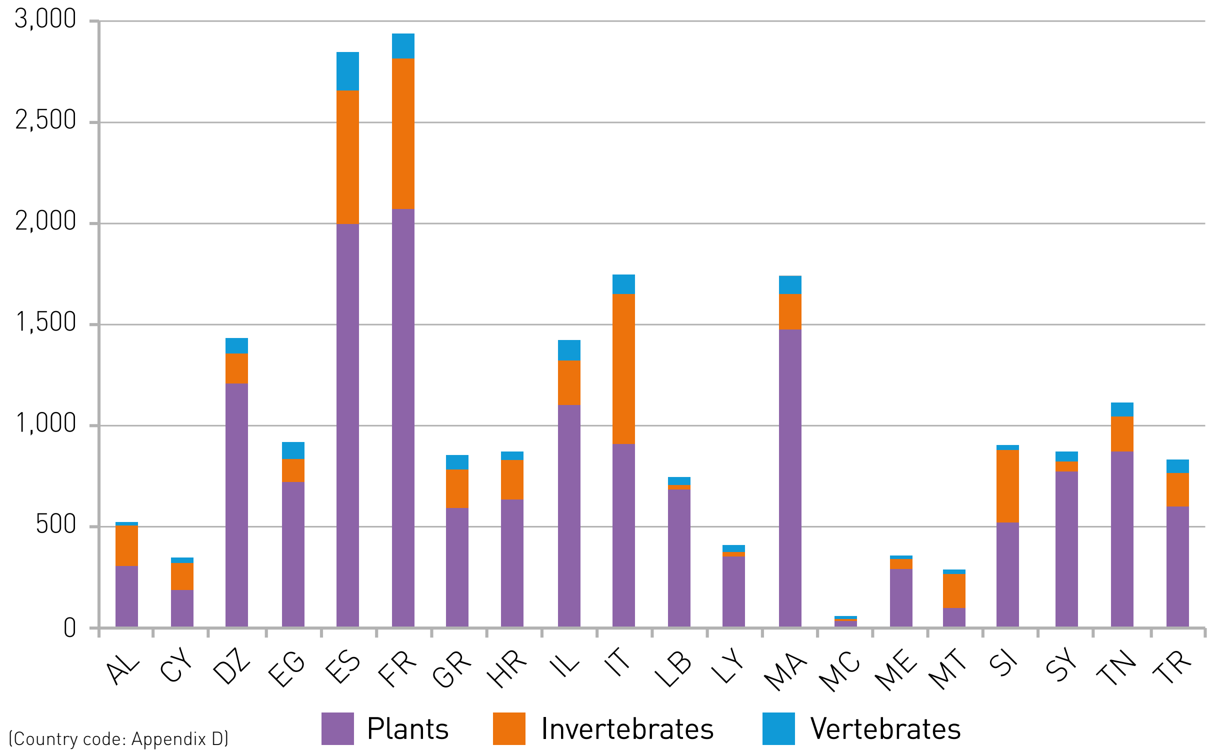
2.5.2.1 Spatial patterns and temporal trends

Degree of introduction across Mediterranean-type ecosystems and geographical areas

The information available on terrestrial non-native species in the Mediterranean Basin countries is not comprehensive, and the number of non-indigenous species is underestimated due to the incompleteness of collected data and the monitoring bias towards some taxonomic groups. For example, Abellán et al. (2016) reported more than 370 non-indigenous birds for Spain and Portugal, more than twice the number listed by DAISIE (2009) for the whole Europe.

Most non-indigenous species in the Mediterranean Basin are plants, followed by invertebrates (Fig. 2.28). Natural habitats in the Mediterranean Basin host more than 400 non-indigenous plant species (Arianoutsou et al. 2013). The taxonomic similarity of the non-native flora among Mediterranean Basin countries is very low. For example, less than 30 species are common across 4 Mediterranean European countries (Arianoutsou et al. 2010), and only 10 species are common in 8 major Mediterranean islands (Lloret et al. 2004a). However, non-native plants share similar traits, as shown by the high proportion of perennial herbs with a long flowering period, which are pollinated and dispersed by the wind (Lloret et al. 2004a, 2005).

The major part of non-indigenous invertebrate species are arthropods, especially insects (Roques 2010), with a low representation of nematodes and flatworms (Naves et al. 2016; Justine et al. 2018). Phytophagous pest species are largely dominating among non-indigenous species all



(Country code: Appendix D)

Figure 2.28 | Number and proportion of terrestrial non-indigenous plant, invertebrate and vertebrate species per country (EASIN)[8].

over the Mediterranean Basin, accounting for more than a half of the invertebrate species and about one-third are associated with woody plants (Matošević and Pajač Živković 2013; Roques 2015; Avtzis et al. 2017). Among them, Hemipterans, mostly scales and aphids, constitute the dominant group, accounting for 40-75% of the non-indigenous species in any part of the Mediterranean Basin (Roll et al. 2007; Inghilesi et al. 2013; Matošević and Pajač Živković 2013; Seljak 2013; Avtzis et al. 2017). This over-representation of Hemiptera in non-indigenous species seems related to their small size and easier of transportation with infested imported plants.

A complete plant pathogens database is not available. However, a European database of non-indigenous forest and woody pathogens indicate a list of 123 plant pathogens. In Mediterranean countries, Ascomycota is the most numerous group, while Oomycota and Basidiomycota represent 21% and 9% of the total, respectively (Santini et al. 2013). With regard to vertebrates, most non-indigenous species are birds, followed by mammals, while the number of reptiles and amphibians is low.

The impact of non-indigenous species varies largely among countries. Countries with higher Human Developmental Indexes and imports host a large density of non-native plants (Vilà and Pujadas 2001). Between countries and within countries, the density of non-native plants is related to the length of terrestrial transport networks. Areas with extensive road and rail networks, high anthropogenic disturbance, low altitude, short distance to the coastline and dry, hot climate show higher richness of non-indigenous plant species (Gassó et al. 2012). Most affected landscapes are those highly urbanized and with high population densities (Sobrino et al. 2002; González-Moreno et al. 2013). Accordingly, the most affected ecosystems by non-indigenous plants are human-modified such as ruderal, waysides or agricultural fields (Vilà et al. 2007; Hulme et al. 2008; Arianoutsou et al. 2010).

As for other non-indigenous taxa, most pests are introduced in managed habitats, such as agricultural lands and parks and gardens, forests being less affected (Matošević and Pajač Živković 2013). Among the infested plant species, non-native ornamental plants (palms, legume trees),

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[8] https://easin.jrc.ec.europa.eu

Citrus and *Eucalyptus* are slightly more colonized than native species (Roques 2015). Vertebrates also tend to occupy anthropic habitats and, to a lower extent, woodlands (at least for birds) (Kark et al. 2009). The degree of introduction of non-indigenous invertebrate species also varies among countries, Italy and France showing much more established non-indigenous species than any other European country (Roques 2010). The same trend is reported also for plant pathogens (Santini et al. 2013).

Mediterranean islands and islets host a large number of non-indigenous species, mainly plants (Brundu 2013). For example, an analysis of 37 small Italian islands showed that they are affected by 203 non-native plants, with a remarkable increase of acacias and succulents in the last decades (Celesti-Grapow et al. 2016). The main determinants of non-indigenous plant species richness in small islands are tourist development and the percentage of artificial land-cover. However, at the local scale, para-oceanic island ecosystems such as the Balearic Islands have a relatively lower number of non-native plants than their mainland counterparts (Vilà et al. 2010). Yet, some species can be introduced into more ecosystem types in islands than in the mainland (Gimeno et al. 2006). In general, there are large differences in the taxonomic composition of non-indigenous insect assemblages between islands and continental countries, e.g., France and Corsica, Italy and Sicily (Liebhold et al. 2016), and Greece and Crete (Avtzis et al. 2017).

Temporal trends of non-indigenous species and pests

The rate at which humans have moved species beyond their native ranges has tremendously increased over the last 150–200 years (di Castri 1991; Reichard and Hamilton 1997), and more so in the last decades (Genovesi et al. 2009; Cardador et al. 2019). Although all taxonomic groups have shown a general rise during this period consistent with the exponential increase in trade and travel (Jeanmonod et al. 2011; Seebens et al. 2017; Cardador et al. 2019), little is known about how temporal dynamics of non-indigenous species varies among taxa. Where time series are available, the number of non-indigenous species established in Europe has increased exponentially in terrestrial ecosystems (Jeschke and Strayer 2005; Hulme et al. 2008; Lambdon et al. 2008; Santini et al. 2013). Abellán et al. (2016) analyzed data on bird introductions in Spain and Portugal since 1912 and found that most of them (99.9%) were recorded from 1955 onwards, with a sharp increase after the 1980s that mirrors the number of non-native birds imported into these countries. Cage birds (mainly Passeriformes and Psittaciformes) constitute the bulk of the species introduced during the last 40 years through escapes of individuals kept in captivity as pets. Although the information is less detailed, and reptiles and amphibians have smaller numbers of recorded non-indigenous species than birds, both groups have also increased their numbers during the 20th century in parallel with the rise in human immigration into Europe (Jeschke and Strayer 2006) and the international trade (Jenkins 1999).

The rate of establishment of non-indigenous insect species has also increased during the last decades (Roques 2010, 2015; Matošević and Pajač Živković 2013; Avtzis et al. 2017). A fast and quite linear increase, with about 10 new species per year, was noticed in Italy since World War II (Inghilesi et al. 2013), and an even higher rate of increase was noted in Croatia since 2007 (Matošević and Pajač Živković 2013). The species newly established during the last three decades tend to spread all over the Mediterranean Basin significantly faster than those that arrived between 1900-1990s (Roques et al. 2016). Such a rapid spread was especially impressive in some species, often relying on multiple introductions in different countries being used as bridgeheads (Rugman-Jones et al. 2013; Kerdelhué et al. 2014; Garnas et al. 2016; Roques et al. 2016; Bras et al. 2019; Lesieur et al. 2019).

Non-indigenous plant pathogenic species have increased exponentially in the last four decades (Santini et al. 2013). Since then, new non-indigenous plant pathogenic species have been introduced mainly from North America, and recently from Asia. Hybrid pathogens also appeared. Countries with a wider range of environments, higher human disturbances or international trade host more non-indigenous species. Rainfall influences the diffusion rates. Environmental conditions of the new and original ranges and systematic and ecological attributes affect pathogen success (Santini et al. 2013).

For plants, the success of introduction in terms of their area of occupancy is larger in species introduced a few centuries ago than species introduced in the 20th century (Lambdon and Hulme 2006), while for birds, establishment success is positively related to time since first introduction (Abellán et al. 2017).

Pathways of introduction (intentional and accidental) of non-indigenous species and pests

The majority of non-indigenous plants have been introduced into the Mediterranean Basin intentionally, as ornamentals that have escaped from gardens associated with anthropic developments and housing (e.g., touristic urbanizations) but also to embellish infrastructures (Hulme et al. 2008). Furthermore, many non-native trees (e.g., *Acacia, Pinus, Eucalyptus*) have been planted at large scales as forestry species and also in restoration programs for dune-stabilization, riverine water flux control, soil fertilization or afforestation of agricultural abandoned land. Many plant species have also been introduced unintentionally (accidentally) as "hitchhikers" or seed contaminants.

The main pathway of introduction for vertebrates, for example birds, are accidental escapes from private collections (Abellán et al. 2016). International wildlife trade is one of the main (if not the main) sources of current vertebrate non-indigenous species. When the EU banned the imports of wild birds, there was a rapid trade shift from wild-caught birds to captive-bred birds (which have lower potential to establish populations than wild-caught birds) (Carrete and Tella 2008, 2015; Cabezas et al. 2013) and a sharp decrease in the number of new introduced avian species in the wild (Cardador et al. 2019). However, this positive effect of the EU ban on wild-caught birds coincides with a significant increase in the trade in reptiles (Cardador et al. 2019).

For invertebrates, the vast majority of species introductions have been accidental (Hulme 2009; Roques 2015). A few introductions have been intentional, mostly for biological control between 1950 and 1999 (Rasplus et al. 2010), but such species always represent less than 15% of the total number of non-indigenous species per Mediterranean country, except in Israel (17.4%) (Roll et al. 2007). Since the majority of invertebrates established in the Mediterranean Basin are phytophagous, the major pathway of unintentional introductions appears to be via international trade in live plants (Rabitsch 2010; Inghilesi et al. 2013; Eschen et al. 2015; Roques 2015). Seed trade has also provided a few species and pests (Auger-Rozenberg and Boivin 2016) as well as firewood, logs and fallen timber (Meurisse et al. 2019). The trade of vegetable and fruit commodities also constitute an important pathway for non-indigenous pests (Desneux et al. 2010; Abbes et al. 2012; Cini et al. 2014). Hitchhiking is another significant pathway of pests as stowaways using wood packaging material (Rassati et al. 2015; Javal et al. 2019; Lesieur et al. 2019), transport infrastructure and vehicles (Javal et al. 2019; Kirichenko et al. 2019) or used tires such as for mosquitoes (Rabitsch 2010). Several other examples are associated with beekeeping (Mutinelli et al. 2014).

For plant pathogens, all the introductions occurred unintentionally. The exact pathway of introduction is almost unknown for most species. However, the most probable is the trade of living plants (57%) or wood (10%). Less than 10% of the introductions occurred through any of the other pathways (Santini et al. 2013). Introductions of even harmless fungi in a new environment give them the opportunity of mating with local or introduced related species giving rise to hybrid progenies. The hybridization process may result in an increase of pathogenicity in one of the species or in the emergence of a completely new plant disease, both of which may threaten the original host plant, and new and naïve host species (Ghelardini et al. 2017).

2.5.2.2 Non-indigenous species as drivers of biodiversity and ecosystem change

The introduction of non-native plants can decrease local flora and fauna diversity and change the community composition and functional structure of affected ecosystems (Vilà et al. 2006; Zahn et al. 2009; Rascher et al. 2011). Native plants that are most vulnerable to such introductions are those with small population sizes (Lapiedra et al. 2015). At least 12 endemic or critically endangered plant species from the "Top 50 Mediterranean Island Plant" list are threatened by non-native plants (de Montmollin and Strahm 2005). For birds, the impact of non-indigenous species is higher on island species, and in those species with small distribution ranges (Clavero et al. 2009). Destabilized ecosystems, including systems used for food and agricultural production, tend to be more vulnerable to the spread of non-indigenous species (e.g., Marvier et al. 2004; Chytrý et al. 2008). However, there is little evidence to support the hypothesis that highly diverse ecosystems are inherently more resistant to non-indigenous species than less-diverse systems (e.g., Keller et al. 2011).

Changes in ecosystem functioning after the introduction of non-indigenous plants are highly context-dependent and include alterations in decomposition rates, light and water soil availability, and changes in soil carbon and nitrogen pools (Vilà et al. 2006; Castro-Díez et al. 2009; Rascher et al.

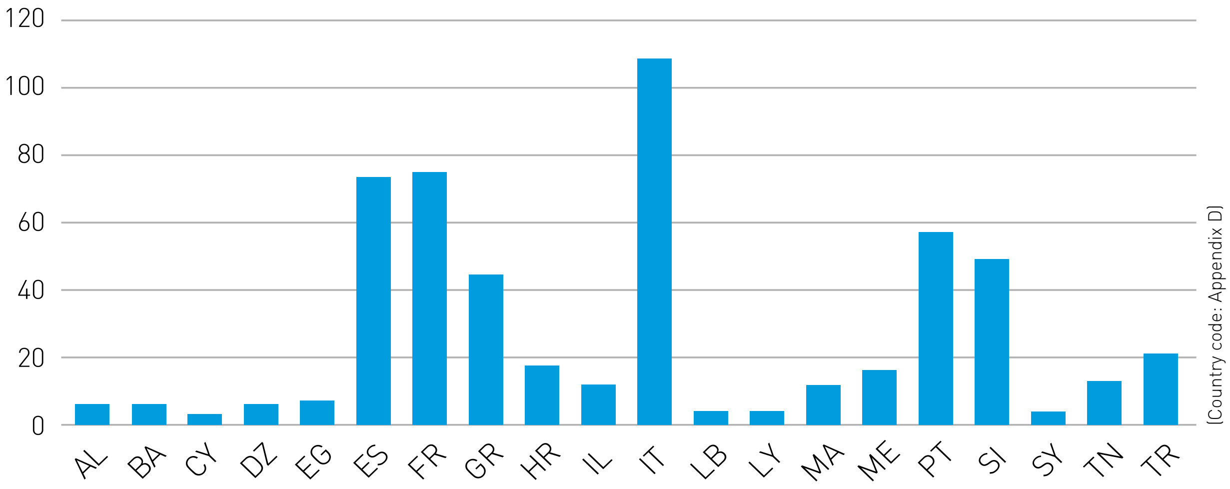


Figure 2.29 | Number of non-indigenous woody plant pathogens per country (Santini et al. 2013).

2011). Plant introductions can disrupt the positive relationship between native species diversity and multifunctionality (Constán-Nava et al. 2015) and may trigger regime shifts by changing plant succession (Stinca et al. 2015).

The impacts of vertebrates can be dramatic through competition for resources, predation and as vectors of diseases (Genovesi et al. 2009). For example, the introduction of non-native ungulates is a major threat to endangered plants, especially in islands (Pisanu et al. 2012). Some native amphibians have collapsed after the introduction of non-native anurans (Lillo et al. 2011). Non-indigenous parakeets can also interact with native species and have an impact on native populations and communities, largely in the form of harassment, displacement from nest sites and food competition (Hernández-Brito et al. 2014, 2018; Menchetti and Mori 2014; Menchetti et al. 2016; Covas et al. 2017). NIS arthropods can also negatively impact native biodiversity and ecosystem processes by destroying host plant populations, causing disturbances in native genetic resources or, indirectly, affecting the affected communities because of new species assemblages (Kenis et al. 2009; Kenis and Branco 2010; Auger-Rozenberg and Boivin 2016).

Some non-indigenous species can damage productive sectors, most notably agriculture and forestry, with important economic consequences. Non-native insects impact major crops in many countries of the Mediterranean region (Abbes et al. 2012; Abdallah et al. 2012; Mutke et al. 2016). Some non-indigenous bird species such as Monk and ring-necked parakeets can also cause important damages to crops (Senar et al. 2016; Turbé et al. 2017).

Forests as well as urban trees in the Mediterranean Basin can be severely economically impacted by non-indigenous pathogens *(Fig. 2.29)* (Santini et al. 2013; Ghelardini et al. 2017) and arthropods (Kenis and Branco 2010) some of which can be considered pests (Santini et al. 2013; Rassati et al. 2015; Auger-Rozenberg and Boivin 2016; Branco et al. 2016; Mendel et al. 2016) and can also transmit pathogenic fungi (Montecchio et al. 2014). For example, after World War II, chestnut blight epidemic in the mountains of southern Europe aggravated food shortages for local human populations and increased migration to urban areas (Adua 1999). Besides, canker stain disease of the plane tree was considered a nasty non-indigenous species of urban trees, until it was introduced into Greece, where the Oriental plane is endemic. The disease is presently destroying natural river wood ecosystems in Greece (Ghelardini et al. 2017; Tsopelas et al. 2017) and it is also spreading in neighbouring countries such as Albania (Tsopelas et al. 2017) and Turkey (Lehtijärvi et al. 2018). Currently, the pinewood nematode is massively killing pines, changing the landscape in Portugal (Naves et al. 2016).

Human health can also be affected by non-indigenous species. Of major concern are non-native plants that are allergenic; their advanced flowering phenology enlarges the period of airborne prevalence of allergens (Belmonte and Vilà 2004). Non-indigenous birds of the order Psittaciformes (parrots) are potential reservoirs of *Chlamydophila psittaci*, the etiological agent of human psittacosis, and can transmit other diseases to humans and wildlife (Menchetti and Mori 2014; Turbé et al. 2017). Some non-native invertebrates, mainly insects, can cause distress, and allergic reactions (e.g., the Asian hornet, *Vespa velutina*) or be vectors of infectious diseases, (e.g., the tiger mosquito, *Aedes albopictus*) (Lounibos 2002; Jucker and Lupi 2011; Monceau et al. 2014; Goubert et al. 2016; Roques et al. 2018; Lioy et al. 2019).

Some impacts of introduced non-indigenous species have attracted worldwide attention, e.g., on cultural heritage in Palermo (Manachini et al. 2013), on the survival of the endangered date palm, *Phoenix theophrasti* in Crete (Avtzis et al. 2017), and the severe attacks of cypress canker disease in southern Tuscany (Italy). Since researchers and policymakers rarely address the connection between non-indigenous species and damage to cultural heritage directly, the cost of these losses is often neglected or underestimated. The Mediterranean Basin has a long history of civilization and it is rich in cultural heritage that can be threatened by non-indigenous species. For example, in southern Tuscany (Italy), severe attacks of the cypress canker disease (caused by the North American fungal pathogen Seiridium cardinale) are threatening the survival of trees flanking a monumental avenue (Danti and Della Rocca 2017).

2.5.2.3 Further introductions, spread and impacts of non-indigenous species and pests

Existing tools for predicting the risk of introduction and research needs

Horizon scanning, prioritization and Pest Risk Analysis (PRA) are essential tools for focusing limited resources to predict the species which can have a high rate of spread, inflict high impacts, and can be cost-effectively managed. PRA are defined by the International Plant Protection Convention as "the process of evaluating biological or other scientific and economic evidence to determine whether a pest should be regulated and the strength of any phytosanitary measures to be taken against it" (FAO 2017b). An important step in the PRA scheme is the "Pest management section" which assesses phytosanitary measures for relevant pathways and their effectiveness in preventing the entry, establishment and spread of non-indigenous species.

Since 2006, European and Mediterranean Plant Protection Organization (EPPO) has formed expert working groups (EWG) to conduct PRA comprised of experts on the pest and cropping systems, mapping and modelling experts, along with experts on EPPO's PRA scheme, risk managers and EPPO PRA Core Members, all which acts to ensure consistency. EPPO is an international organization responsible for cooperation and harmonization in plant protection within the European and Mediterranean region. One of EPPO's main aims is to provide assistance and guidance to member governments on the administrative, legislative and operational measures necessary to prevent the introduction and spread of non-native plant pests (Smith 1979; Roy et al. 2011). Since 1999, EPPO has maintained an Alert List of plant pests and non-indigenous plants which acts as an early warning for pests, which can present a risk to the EPPO region. EPPO has also developed a prioritization tool for non-indigenous plants that classifies species into one of three lists: minor concern, observation list or list of non-indigenous plant species (EPPO 2012a, 2012b). Those species included in the list of non-indigenous plants are assessed for a PRA, where a higher priority is given to those species with a limited distribution in the EPPO region (EPPO 2012b).

In addition to the EPPO PRA tools, there are also a number of other PRA protocols (Roy et al. 2018) that can be applied to the Mediterranean Basin. To better improve PRA and the risk assessment process, a greater level of transparency and consistency between protocols would be beneficial (Vanderhoeven et al. 2017; González-Moreno et al. 2019). EU Mediterranean member states need to follow the EU Regulation that includes restrictions on keeping, importing, selling, breeding and growing non-indigenous species (European Union 2014).

A quite novel empirical approach to identify potential pests is the use of sentinel plantations of Mediterranean trees, e.g., cork oak, evergreen oak and cypress, in other continents as a priori identification of non-indigenous insect and pathogens capable of colonizing such plants. For example, such plantations in China provided a list of 39 potential non-indigenous insects of which five could be highly damaging (Roques 2015) and several pathogens (Vettraino et al. 2015). The development at potential ports of entry of trapping programs using lures presenting a generic attractiveness for some insect groups is expected to allow early detection of emerging non-indigenous species, even when not listed on quarantine lists (Rassati et al. 2014, 2015; Fan et al. 2019).

Non-indigenous species likely to be introduced into the Mediterranean in the next 20-50 years

As temperature increases, current major non-indigenous species are predicted to shift northwards at an average pace of 37-55 km decade^{-1}, leaving a window of opportunity for new non-indigenous species better adapted to xeric conditions (Gallardo et al. 2017). Regarding non-native plants, gardening practices and ornamental trade will have a major impact on the selection of these future non-indigenous species. The use of non-native drought-tolerant species for gardening and landscaping (i.e., xeriscape) is at its earliest stages in the Mediterranean, but it has already raised concerns in California because of its potential risk as a source of new non-indigenous species (Bradley et al. 2012). Global species niche modelling indicates that xeric shrublands in Mediterranean areas are among the most susceptible ecosystems to introduction by Cactaceae plant species from arid American areas (Novoa et al. 2015). Although some Cactaceae are already largely distributed across the Mediterranean (e.g., *Opuntia ficus-indica*), it is very likely that close relative species with currently restricted distribution or absence in the Mediterranean, such as *Cylindropuntia* spp., would thrive in the next decades aided by new gardening practices (Essl and Kobler 2009). Besides gardening, other relevant terrestrial plant species could be easily introduced and established as contaminants in soil, seeds or containers. For instance, *Parthenium hysterophorus* is a species not currently in the Mediterranean that has been highlighted as of high risk for the region because of its large potential negative impact on agriculture and human health (Kriticos et al. 2015).

While plants have been proportionally the main new non-indigenous species in Europe up until the 19th century, the trend has shifted towards an increasing number of introduced invertebrates and vertebrates in the 20th century (Hulme 2009). This is a pattern that is very likely to continue in the near future by increasing air and maritime cargo, where these taxa can be easily transported as stowaways. The establishment of non-indigenous invertebrates of tropical origin affecting woody ornamental plants has increased (Eschen et al. 2015), meaning that many ornamental plants, especially palms, fig trees and exotic legumes, are at risk for further introduction as well as *Citrus* and *Eucalyptus* trees (Floris et al. 2018). The recent establishment of ambrosia beetles of tropical origin directly threatening plants of the Mediterranean maquis (Faccoli et al. 2016; Francardi et al. 2017) suggests that such process is going to be amplified with global warming. A list of fruit flies likely to be introduced has been recently proposed (Suffert et al. 2018). Special attention should be paid to major agricultural pests currently not present in the Mediterranean but with the potential to be introduced and cause a major impact. The EPPO A1 quarantine list considers up to 128 species of insects, mites, nematodes and gastropods, currently absent from the EPPO region, recommended for quarantine measurements. For instance, Lepidoptera species such as *Spodoptera* or *Helicoverpa* spp. are polyphagous species that could easily thrive in the Mediterranean if they become established. *Spodoptera frugiperda,* a pest native to the Americas, has quickly spread in Africa causing large yield loss. A recent modelling exercise has identified small pockets of suitable habitats in the Mediterranean area but the potential for permanent populations is still uncertain (Early et al. 2018).

Regarding terrestrial vertebrates, several species have been recently highlighted in a horizon scanning exercise for European non-indigenous species, including the Mediterranean (Roy et al. 2019). Of special relevance is the common myna, *Acridotheres tristis,* a non-indigenous species with very restricted populations in the region, and *Lampropeltis* spp., a family of snakes mainly native to North America and adapted to arid conditions. These species are traded as pets and can easily be introduced due to accidental escapes.

2.6 Interaction among drivers

2.6.1 Drivers impacting other drivers

The potential for interactions among drivers is a key issue for analyzing their impacts on environment and human societies, and for developing effective conservation policies (Brook et al. 2008). Climate change, pollution, land and sea use change, and non-indigenous species are often studied and managed in isolation, although it is becoming increasingly clear that a single driver perspective is inadequate when ecosystems are threatened by multiple, co-occurring drivers (Halpern et al. 2008a, 2008b). Conceptually, there are three broad categories of interaction types describing the outcome of multiple stressors, the effects can be additive/cumulative (all the different stresses derived from the implied drivers show up), synergistic (increased stress) or antagonistic (decreased stress) (Folt et al. 1999; Crain et al. 2008). Also, and particularly for the Mediterranean, how different drivers interact could result in alteration, intensification, and even in generation of new impacts (Doblas-Miranda et al. 2017).

In order to facilitate the multi-stressor approach, as a key recognized concept, this section offers two different approximations. First, we describe potential pair interactions within the individual driver classes described before, and second, we provide a few examples of characteristic disturbances of Mediterranean ecosystem that are the result of the combination among multiple drivers.

2.6.2 Pairs of interacting drivers

2.6.2.1 Climate change effects on pollution

Generally, increases in temperature enhance the toxicity of contaminants and increase concentrations of tropospheric O_3 regionally, but will also likely increase rates of chemical degradation (Lelieveld et al. 2014). In general, climate change coupled with air pollutant exposures may have potentially serious adverse consequences for human health in urban and polluted regions (Noyes et al. 2009).

The increase in the intensity and frequency of storm events linked to climate change can lead to more severe episodes of chemical contamination of water bodies and surrounding watersheds (Noyes et al. 2009). Climate change may also increase the occurrence and the global expansion of harmful algal blooms (Paerl and Paul 2012) *(Sections 2.3.3 and 2.3.4)*.

2.6.2.2 Pollution effects on climate change

Many air pollutants that are harmful to human health and ecosystems also contribute to climate change by affecting the amount of incoming sunlight that is reflected or absorbed by the atmosphere, with some pollutants warming and others cooling the Earth. These so-called short-lived climate-forcing pollutants include methane, black carbon, ground-level O_3, and sulfate aerosols. They have significant impacts on the climate; black carbon and methane in particular are among the top contributors to global warming after CO_2 (Shindell et al. 2009; Stohl et al. 2015). Over the Mediterranean Basin the increase and decrease of anthropogenic aerosols during the second half of the 20th century have had an important role in the dimming-brightening phases, because of their direct action on the incoming solar radiation *(Section 2.2.3.1)*.

Pollution by heavy metals or organic compounds can also affect ecosystem functioning by inhibiting CO_2 fixation performed by photosynthetic organisms, thereby increasing global warming (Rochelle-Newall et al. 2008; Magnusson et al. 2010; Ben Othman et al. 2012) (*Sections 2.2.3* and *2.3.2*).

2.6.2.3 Impact of climate on land and sea use

Effects of climate change on land use

Recent accelerated climate change has exacerbated existing environmental problems in the Mediterranean Basin caused by the combination of changes in land use, increasing pollution and biodiversity decline (Cramer et al. 2018). Sea-level rise, combined with land subsidence, may significantly reduce the area available for agriculture. The effects of sea level rise in North Africa, especially

Impacting (column) – Impacted (row)	Climate change	Pollution	Land and sea use changes	Non-indigenous species
Climate change		2.6.2.2	2.6.2.4	?
Pollution	2.6.2.1		2.6.2.7	?
Land and water use changes	2.6.2.3	2.6.2.6		2.6.2.10
Non-indigenous species	2.6.2.5	2.6.2.8	2.6.2.9	

Table 2.3 | Main interactions among drivers

on the coast of the Delta region of Egypt, would impose additional constraints to the agricultural land *(Section 3.2.2.1)*, and also the salinization of coastal aquifers *(Section 3.1.2.2)*.

Similarly, with 42% of the population living in coastal areas (Mediterranean Wetlands Observatory 2018), important direct effects of climate change on coastal settlements include dry-land loss due to erosion and submergence, damage of extreme events (such as wind storms, storm surges, floods, heat extremes, and droughts) on built environments, effects on health (food- and water-borne disease), effects on energy use, effects on water availability and resources, and loss of cultural heritage (Hunt and Watkiss 2011) *(Section 2.2.8.2)*. Coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water, and sewerage are highly sensitive to a range of extreme weather and climate events including temporary and permanent flooding arising from extreme precipitation, high winds, storm surges, and sea level rise (Horton et al. 2010; Handmer et al. 2012; Hanson and Nicholls 2012; Aerts et al. 2013). The tourism development experienced a comparable pattern, requiring host facilities and corresponding services. In Algeria, for example, construction projects have been carried out among the coastal paleo-dunes despite the existing Littoral Law 02-2002 (coastal protection) and the Law 01-3-2003 related to the Impact Expertise (Senouci and Taibi 2019). A similar situation exists in the industrial sector (e.g., desalinisation plant and electricity power station built on the beach).

Increases in temperature and decreases in precipitation could alter fire regimes affecting forest cover and could increase the intensity and frequency of drought resulting, in combination with other factors, in desertification (*Sections 2.4.1.2* and *2.6.3*). Future changes in climate could decrease food production *(Section 2.4.1.2)* and may alter the use of land all over the Mediterranean *(Section 2.4.1.3)*. Future changes in the quantity and intensity of rain could affect the water cycles and increase the risk of floods (*Sections 2.2.6* and *2.6.3*).

Climate change and variability drives dynamics of marine species

Climate change and variability has led to concomitant changes in Mediterranean marine ecosystems and resources, with various implications on species diversity and composition, where species with limited locomotive capacity or confined in fragmented habitats seem more likely to be affected (Lejeusne and Chevaldonné 2006; Ledoux et al. 2015). Examples of this changing environment, among others, are the mass mortality events of gorgonians and other sessile metazoans in northwestern Mediterranean (Garrabou et al. 2009; Rivetti et al. 2014) and the continuous decline of *Posidonia* meadows (Marba and Duarte 2010), the increase in the frequency of red tides and of gelatinous carnivore outbreaks (Conversi et al. 2010), the "tropicalization" of marine fauna in favour of the more thermophilic ones (Bianchi 2007), and the increase spread of microbial pathogens associated with water temperature rise (Danovaro et al. 2009) *(Section 4.1.1.1)*.

At the end of 1980s and especially during the mid-1990s the Mediterranean Sea underwent regime shifts (Conversi et al. 2010; Alheit et al. 2019) that inflicted major atmospheric, hydrological and ecosystem changes, also affecting marine resources, mainly fisheries. There have been various studies linking ocean-atmospheric processes such as the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO) and the Western Mediterranean Oscillation (WeMO) indices to alterations on the distribution and biomass of pelagic fish, as well as their catch composition (Alheit et al. 2019). Pelagic fish populations, more than other fish species, act as sentinels of these environmental changes. For example, during mid-1990s in the Mediterranean the highly correlated sea surface temperature and AMO index show a sharp increase (Marullo et al. 2011; Macías et al. 2013), whereas the dynamics of many fish species - mainly pelagic - show a conspicuous change around that time.

It is not yet clear how these changes impact pelagic fish population dynamics, combined with the pressures imposed by anthropogenic activity. Fifty-nine taxonomic groups (species or groups of species) showed an abrupt change in their landings in the mid-late 1990s (Tzanatos et al. 2014) with approximately 64% of these changes being correlated with sea surface temperature, mostly inversely correlated. The landings of some species (European sardine *Sardina pilchardus,* squids *Loligo* spp., Norway lobster *Nephrops norvegicus,* and hake *Merluccius merluccius*) decreased conspicuously in the mid-1990s, whereas those of other species (European anchovy *Engraulis encrasicolus* and greater amberjack *Seriola dumerili*) increased (Tzanatos et al. 2014). A study of the fisheries landings of 30 fish and invertebrate taxonomic groups revealed regime shifts at the mid-1990s, concurrent with the sea temperature increase in the eastern and western basins (Vasilakopoulos et al. 2017). The late 1990s was determined as the turning point for the northward expansion of warm-water species in the Mediterranean (Azzurro et al. 2011). This was confirmed by Raitsos et al. (2010) who showed a clear increase of non-indigenous species entering into the eastern Mediterranean Sea in 1998. Earlier, Pinnegar et al. (2003) reported that the diversity of the western Mediterranean finfish landings increased dramatically after 1995 as a result of new species entering the catch.

Round sardinella *(Sardinella aurita),* a warm-water small pelagic fish species distributed along the southern Mediterranean coastline has been reported to have expanded its distribution to the northern Aegean (Tsikliras 2008), the northern Adriatic (Sinovčić et al. 2004), the Gulf of Lions (Francour et al. 1994), and the northwestern Mediterranean (Sabatés et al. 2006, 2009). A significant positive relationship between round sardinella landings and sea surface temperature anomalies has been reported for the western (Sabatés et al. 2006) and eastern Mediterranean (Tsikliras 2008). The northward distributional shift coincides with the beginning of positive temperature anomalies in the mid-1990s (Tsikliras 2008; Sabatés et al. 2009; Stergiou et al. 2016). Similarly, concomitant with the sea surface temperature change in the western Mediterranean, the landings of bluefish *(Pomatomus saltatrix)* quadrupled due to a northward expansion of the species (Sabatés et al. 2012) and, at the same time, anchovies returned to high biomass, as a result of increasing sea surface temperatures in the Adriatic Sea (Vilibić et al. 2016).

The effect of the AMO and NAO signals across the Mediterranean Sea sub-regions (western, central and eastern) on the small (European sardine *Sardina pilchardus,* European anchovy *Engraulis encrasicolus,* round sardinella *Sardinella aurita* and European sprat *Sprattus sprattus*) and medium (Atlantic mackerel *Scomber scombrus,* Atlantic chub mackerel *Scomber japonicus,* Atlantic horse mackerel *Trachurus trachurus,* Mediterranean horse mackerel *Trachurus mediterraneus*) pelagic fishes have been recently studied in the western, central and eastern Mediterranean Sea (Tsikliras et al. 2019). The pelagic fishes of the central and eastern Mediterranean respond most strongly to AMO variability and those of the central and western Mediterranean also respond to the NAO, while the effect of the NAO on pelagic fishes of the eastern Mediterranean was not significant (Tsikliras et al. 2019). Generally, various indicators revealed that the time of the pelagic fish response to the AMO and NAO signals varied among the Mediterranean sub-regions (Alheit et al. 2014; Tsikliras et al. 2019).

Finally, the mean temperature of the catch, an indicator that assesses the effect of global warming on the exploited marine communities (Cheung et al. 2013b), has been increasing across the Mediterranean showing that the ratio of thermophilous (warm-water) to psychrophilous (cold-water) marine species has been changing in favour of the former. This is indicative of either an increase in the relative proportion of thermophilous species in the catches or a decrease in the relative proportion of the psychrophilous ones (Tsikliras and Stergiou 2014).

2.6.2.4 Effects of land use on climate change

Changes in crop use (Tribouillois et al. 2018), especially in forest cover, affect the balance between sink and release of CO_2 and the emissions of biogenic volatile organic compounds (BVOCs) in the atmosphere (Doblas-Miranda et al. 2017) (*Sections 2.4.1.2* and *3.1.2.1).*

Modification of surface albedo by land use changes also entail a highly potential impact on climate change (Benas and Chrysoulakis 2015). Changes in forest or dehesa/montado cover due to reforestation could reduce albedo (Rotenberg and Yakir 2011; Godinho et al. 2016), while fires increase radiations returns to the atmosphere (Sánchez et al. 2015), with contrasting effects on local climate. Agricultural cover may decrease or increase albedo (Giannakopoulou and Toumi 2012; Carrer et al. 2018), while urban sprawl definitely increases the radiation absorption and therefore local temperature (Salvati et al. 2019) *(Section 3.1.3.1).*

Change of land use and irrigation practices increase evapotranspiration and have a net cooling effect in some areas of the Mediterranean region (Zampieri and Lionello 2011; Thiery et al. 2017; Gormley-Gallagher et al. 2020).

2.6.2.5 Links between trends in non-indigenous species and climate change

Impact of climate change on marine non-indigenous species

The introduction of non-indigenous species and global warming interact in complex ways (Stachowicz et al. 2002), and are linked also in the Mediterranean Sea (Occhipinti-Ambrogi 2007).

This connection strongly depends on the species and the mode of its introduction, establishment and colonization. Overall, there is a strong trend of "tropicalization" of temperate areas through the movement of warm-loving (thermophilic) species toward the poles in areas of rapid ocean warming, and with increasingly strong impacts on local communities (Vergés et al. 2014a, 2016). These are not considered as introductions of non-indigenous species per se. But ocean warming may facilitate the establishment and spread of thermophilic non-indigenous species. The success of establishment of an introduced species depends on how suitable the ocean climatic parameters are in the region of introduction. Because successful non-indigenous species are typically generalists with broader climatic tolerances, they are usually considered able to cope better with climate change than native ones (Walther et al. 2009).

There is limited evidence for effects of climate change on the introduction of non-indigenous species. Theoretically, at the trailing "warm" edge of species distributions, the populations of sensitive cold-affinity species should reduce (and eventually extirpate) and that of warm affinity species (including thermophilic species) should increase (Bates et al. 2014). In the Mediterranean Sea, tropicalization evidently occurs (Vergés et al. 2014a), mainly in the Levant, by Lessepsian introductions, and ocean warming was suggested to facilitate the successful establishment of non-indigenous species (Raitsos et al. 2010). Ocean warming probably also helps to spread both native thermophilic species and successful Lessepsian species westward along the basin's temperature gradient, and also northward into the Aegean and Adriatic seas, or even the Ligurian Sea, but there very few direct empirical studies to demonstrate that. Recent analysis of fish trawl data from the southeast Mediterranean (Israel) does strongly suggest that non-indigenous species are indeed promoted by warming while natives are declining (Givan et al. 2017a).

Some studies suggest that habitats degraded by global warming are more likely affected by non-indigenous species than nearly-pristine habitats, envisaging explicitly or not, a cause and effect link between climate warming and the success of introductions (Stachowicz et al. 2002; Bianchi 2007; Galil 2007; Occhipinti-Ambrogi 2007). However, field observations do not support this idea, but reveal instead conflicting results that have provoked intense debate (Boudouresque and Verlaque 2010). For example, in the Mediterranean Sea, well-structured and conserved habitats (such as coralligenous or *Cystoseira* forests) are able to mitigate and delay the proliferation and spread of the non-indigenous alga *Caulerpa cylindracea,* probably because the complexity of substrata (enhanced by gorgonians or canopy algae presence) is a key factor limiting its colonization and spread (Ceccherelli et al. 2002; Bulleri and Benedetti-Cecchi 2008; Verdura et al. 2019). In contrast, mass mortality of structural native species and subsequent increase of turf-forming species due to an extreme climatic event indirectly promoted the introduction of *C. cylindracea* in a coralligenous habitat (Verdura et al. 2019). However, in other non-indigenous algae such is *Lophocladia lallemandii,* introduction is favoured by more complex and rich communities (Cebrián et al. 2018), and thus simplification derived from climate change effects is expected not to enhance the capacity of *Lophoclaria* to establish itself, but prevents its spread.

Using natural laboratories to test the thermal performance curves and sensitivity to acidification of key native and non-indigenous species, as well as the impact of climate change related environmental alteration on species interactions and communities and their ecosystem functions, are critical for better understanding and forecasting of the interactions between climate change and the introduction of non-indigenous species (Rilov et al. 2019a). For example, heat polluted areas and CO_2 vents (Hall-Spencer et al. 2008), as well as laboratory experiments in near-natural mesocosm systems (Wahl et al. 2015). Such recent measurements and experiments in the southeastern Levant have shown that some non-indigenous species (foraminifera) are tolerant to extreme thermal stress (Titelboim et al. 2017), that under warming and acidification conditions most Lessepsian species perform better than native species (Guy-Haim et al. 2016; Guy-Haim 2017), and demonstrated that different thermal performance of two Red Sea foraminifera explain why one species was introduced and the other did not (Titelboim et al. 2019). Furthermore, mesocosm work showed that a *Cystoseira* community becomes more heterotrophic and more dominated by non-indigenous species (but species richness does not change), demonstrating the profound impact of the combination of climate change and the introduction of non-indigenous species on ecosystem function (Guy-Haim et al. 2016; Rilov et al. 2019b).

Impacts of climate change on terrestrial non-indigenous species

There are five non-exclusive consequences of climate change on non-indigenous species: (1) altered transport and introduction mechanisms, (2) establishment of new species, (3) altered impact of existing non-indigenous species, (4) altered distribution of existing non-indigenous species, and (5) altered effectiveness of control strategies (Hellmann et al. 2008) *(Section 2.5.1.3)*.

The influence of climate change on terrestrial non-indigenous species highly depends on species physiological strategy and reproductive adaptations (Bale and Hayward 2010; Antunes et al. 2018). Generalized ecosystem models of plant functional groups applied to Mediterranean islands indicate that climate change might promote the introduction of broadleaved trees (e.g., *Ailanthus altissima*) more than C_4 tropical grasses (e.g., *Amaranthus retroflexus*) (Gritti et al. 2006). Many non-indigenous species from temperate and cold climates might only be able to shift their ranges northward or to expand in altitude because they will be limited by drought and high temperatures (Storkey et al. 2014; Gallardo et al. 2017). While non-indigenous species whose native ranges are drier and warmer than their introduced ranges can be at an advantage to occupy niches at southern latitudes (Gallardo et al. 2017). Therefore, some species might loose and some gain suitable areas for introduction. Regions which will get drier are predicted to lose the highest number of potential non-indigenous species.

For introduced gardening plants, the climatically suitable areas with future climate change are unequally distributed across Europe with more suitable areas in the East than in the West of the Mediterranean Basin (Dullinger et al. 2017). This will be the case for *Cortaderia* which suitable area can increase 69-116% for 2060 (Tarabon et al. 2018) or for *Nassela* that can increase up to 47% for 2018 (Watt et al. 2011).

Similarly, weeds in crops can experience range shifts, niche shifts and trait shifts with climate change that will influence the agronomic practices to reduce their interference to crop production (Peters et al. 2014). Weeds in cereals crops will also advance towards northeastern Europe and remain or contract their distribution in warm areas of the Mediterranean region (Castellanos-Frías et al. 2014).

Climate change can advance the phenology of non-indigenous plant species including their fecundity (Chuine et al. 2012), pollen production and seed maturation (Leiblein-Wild et al. 2016). Changes in pollen production can exacerbate the problem caused by allergenic non-indigenous plants such as the American *Ambrosia* because the allergenic risk is predicted to increase under all climate scenarios tested (Rasmussen et al. 2017).

Besides the influence of climate change on the establishment and spread of non-indigenous species, a remaining question is whether their impacts on native species increase in combination with climate change. A few greenhouse experiments have explored the interaction between competition of non-indigenous species and drought on the performance of native species (García-Serrano et al. 2007; Matesanz et al. 2008; Werner et al. 2010) and have found a non-synergistic effect. The interaction of climate change and introduction of non-indigenous species is a research area that requires further experimentation for productive systems such as the effect of weeds, pests and pathogens on crops and forestry (Ramesh et al. 2017).

2.6.2.6 Impacts of pollution on land and sea use

One of the major drivers relative to greenhouse gases pollution may be the CO_2 fertilization affecting forests. The balance between faster growth due to the fertilization effect and hydric stress due to most likely warmer and drier conditions have generated a considerable debate in the Mediterranean area (Keenan et al. 2011; Peñuelas et al. 2011). However, the most recent studies mainly corroborate that the effects of CO_2 fertilization will be negligible under the predicted climate conditions for the region (Camarero et al. 2015; Nunes et al. 2015; Gea-Izquierdo et al. 2017), despite some exceptions (Koutavas 2013; Barbeta and Peñuelas 2017). The potential effects of nitrogen deposition on Mediterranean forest growth also seem to be low (Ochoa-Hueso et al. 2014).

2.6.2.7 Impacts of land and sea use change on pollution

Intensive farming increases releases of nutrients and pesticides in aquifers while higher releases of methane in the air. The effects of the increase of livestock production on greenhouse gas emissions are assessed in *Section 3.2.3.2.*

Urban sprawl is associated to higher traffic related emissions *(Sections 2.3.3* and *2.4.1.2)*.

2.6.2.8 Pollution effects on non-indigenous species

Pollution can make environmental conditions less tolerable for native species, and provide space and nutrients for opportunists, including non-indigenous species (Crooks et al. 2011).

2.6.2.9 Effects of land and water use on non-indigenous species

Habitat destruction causes disturbance, which opens space for non-indigenous species (Hobbs and Huenneke 1992).

2.6.2.10 Effects of non-indigenous species on land and sea use

Outbreaks of forest non-indigenous insects could alter forest cover *(Section 2.5.2.2)*.

2.6.3 More complex interactions among drivers

2.6.3.1 Floods

Floods are an illustrative example of the combination of different drivers such as climate change (extreme precipitation events), land use change (catchment changes on river forests, forest cover, etc.) and even indirect drivers (among them and principally, urban sprawl in risk areas) (*Sections 3.1.3.3* and *3.1.4.1*).

2.6.3.2 Desertification

Puigdefábregas and Mendizabal (1998) analyzed FAO data from Morocco, Algeria and Tunisia during the period 1950-1993, associating desertification to socio-economic boundary conditions and over-exploitation by showing clear increases in population (pressure) and in the use of unsustainable land use practices in the Mediterranean, principally irrigation *(Section 6.6)*.

Desertification is in fact the result of two different factors in origin operating in combination, prolonged drought of climatic origin and land exploitation of human origin (Le Houérou 1996). In Mediterranean arid lands, mainly during the 20th century, short-term planning of agricultural policies and overexploitation, mainly in the form of overgrazing but also fuelwood collection and ground water exploitation, contributed to soil quality decline and massive erosion. Deteriorating conditions have a great impact on the lives of inhabitants of Mediterranean drylands and force most of them to migrate (Mohamed and Squires 2018) (*Sections 3.2.1.4*, *4.3.1* and *6.6*).

2.6.3.3 Wildfires

One relevant consequence of the Mediterranean Climate characterized by dry summers are forest fires. Those can be exacerbated by drought conditions (Turco et al. 2018) but in turn they can affect drastically the flood generation both due to the erosion and the loss of forest mass. Although some forest fires can be provoked or as a result of recklessness, they mostly depend on the state of the vegetation and the climatic and meteorological situation. Consequently, fire regimes will be affected by climate change, if not already affected (Sarris et al. 2014). The Mediterranean is a high fire-risk region, where fires are the cause of severe agricultural, economic and environmental losses and even human casualties (Moreira et al. 2011; Keeley et al. 2012; San-Miguel-Ayanz et al. 2013; Bowman et al. 2017). For instance, the fire seasons in 2017 and 2018 was severe in many regions of Southern Europe, with large wildfires associated with unusually intense droughts and heat-waves (Sánchez-Benítez et al. 2018). In Portugal, the year of 2017 was particularly tragic. An extended and extraordinarily intense fire season yielded a record total burned area of about 500,000 hectares and more than 120 fatalities (Turco et al. 2019). Instead, the summer of 2018 will be remembered by the deadliest fires ever recorded affecting Greece, when a series of wildfires close to Athens killed 99 people, the deadliest in Greece history (AghaKouchak et al. 2018).

However, although several reports, ranging from popular media through to peer-reviewed scientific literature, have led to a shared perception that fires have increased or aggravated in recent years, the quantitative evidence available indicated that fires are decreasing on recent decades in this area (Turco et al. 2016). The increased efforts in fire suppression have probably played an important role in driving the general downward trends described for most of the Mediterranean area (Moreno et al. 2014; Ruffault et al. 2015). In recent decades fire management strategies have improved thanks to new technologies and experience while climate drivers have led to an opposite trend (Amatulli et al. 2013; Batllori et al. 2013; Bedía et al. 2013; Turco et al. 2014; Dupire et al. 2017; Fréjaville and Curt 2017) *(Section 4.3.2.1)*.

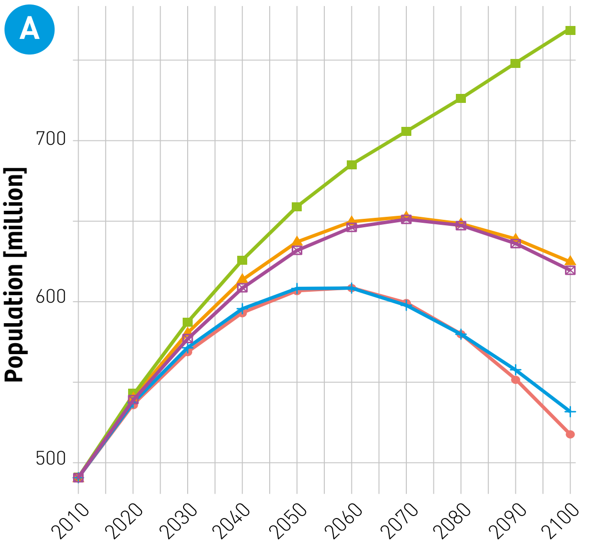
FULL NAME	SHORT NAME	THEMATIC FOCUS	NO. OF SCENARIOS	TIME HORIZON	SPECIFIC REGIONAL FOCUS	REFERENCE(S)
GLOBAL SCALE						
Special Report on Emissions Scenarios	SRES	Emission of greenhouse gases	4	2100	-	Nakićenović, 2000
Shared Socioeconomic Pathways	SSPS	Multidisciplinary with a focus on challenges to climate change adaptation and mitigation	5	2100	-	(O'Neill et al. 2014, 2017)
MEDITERRANEAN SCALE						
A sustainable future for the Mediterranean	-	Multidisciplinary and cross-sectoral with an emphasis on sustainable development	2	2025	-	Benoit and Comeau, 2005
Mediterranean scenarios (MedAction project)	-	Multidisciplinary and cross-sectoral with an emphasis on desertification	3	2030	Northern Mediterranean case studies in ES, GR, IT, PT	Kok et al., 2006
EuroMed-2030	-	Multidisciplinary and cross-sectoral with a focus on the Euro-Mediterranean relationship	4	2030	-	EC/DG for Research and Innovation, 2011
Tomorrow, the Mediterranean	-	Multidisciplinary, cross-sectoral, with emphasis on economic development	3	2030	-	IPEMED, 2011
Scenarios for the Mediterranean Region	-	Evolution of regional dynamics and role of the private sector in shaping business and political environments	3	2030	Exclusion of AL, BA, HR, IL, ME, PS, TR	World Economic Forum, 2011
Mediterranean Coastal SSPs	-	Regional and sectoral extension of the global SSPs for Mediterranean coastal regions	5	2100	-	Reimann et al., 2018
EUROPEAN SCALE						
Integrated Visions for a Sustainable Europe	VISIONS	Sustainable development	3	2020, 2050	-	Rotmans et al., 2000
Demographic and Migratory Flows Affecting European Regions and Cities	DEMIFER	Demography and European policies	5	2050	-	Rees et al., 2012
Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe	CLIMSAVE	Multidisciplinary and cross-sectoral, with emphasis on ecosystem services and provisions	4	2050	-	Gramberger et al., 2013
Territorial Scenarios and Visions for Europe	ET2050	Territorial development and cohesion	4	2050	-	MCRIT, 2015
Demographic Scenarios for the EU	-	Demographic development with a focus on aging, migration and education	3-4	2060	EU	Lutz et al., 2019
European Shared Socioeconomic Pathways	Eur-SSPs	Regional extension of the global SSPs for the European context	4	2040, 2070, 2100	Additional case study in Iberia	Kok et al., 2019

Table 2.4 | Overview of selected socioeconomic scenarios that cover Mediterranean countries, partly based on Rohat et al. (2018) and Sanna and Le Tellier (2013). ISO country codes: AL: Albania, BA: Bosnia and Herzegovina, ES: Spain, GR: Greece, HR: Croatia, IL: Israel, IT: Italy, ME: Montenegro, PT: Portugal, PS: State of Palestine, TR: Turkey.

2.7 Mediterranean socioeconomic scenarios

Environmental-change-related impacts will be driven not only by changes in climatic conditions, but also by changes in socioeconomic conditions. Prevailing socioeconomic conditions, in particular, determine a society's resilience to climatic hazards. When assessing future risks due to climate change, it is therefore crucial to account for plausible changes in socioeconomic conditions using a range of socioeconomic scenarios (González-Moreno et al. 2013).

A large number of socioeconomic scenarios have been developed in the past decades, focusing on a multitude of disciplines, sectors, and regions. Few of these scenarios were developed specifically for the Mediterranean region and even those usually only cover some of the Mediterranean countries, with a strong bias toward northern Mediterranean countries that are members of the European Union. *Table 2.4* provides an overview of a range of socioeconomic scenarios developed in the last two decades that cover socioeconomic developments



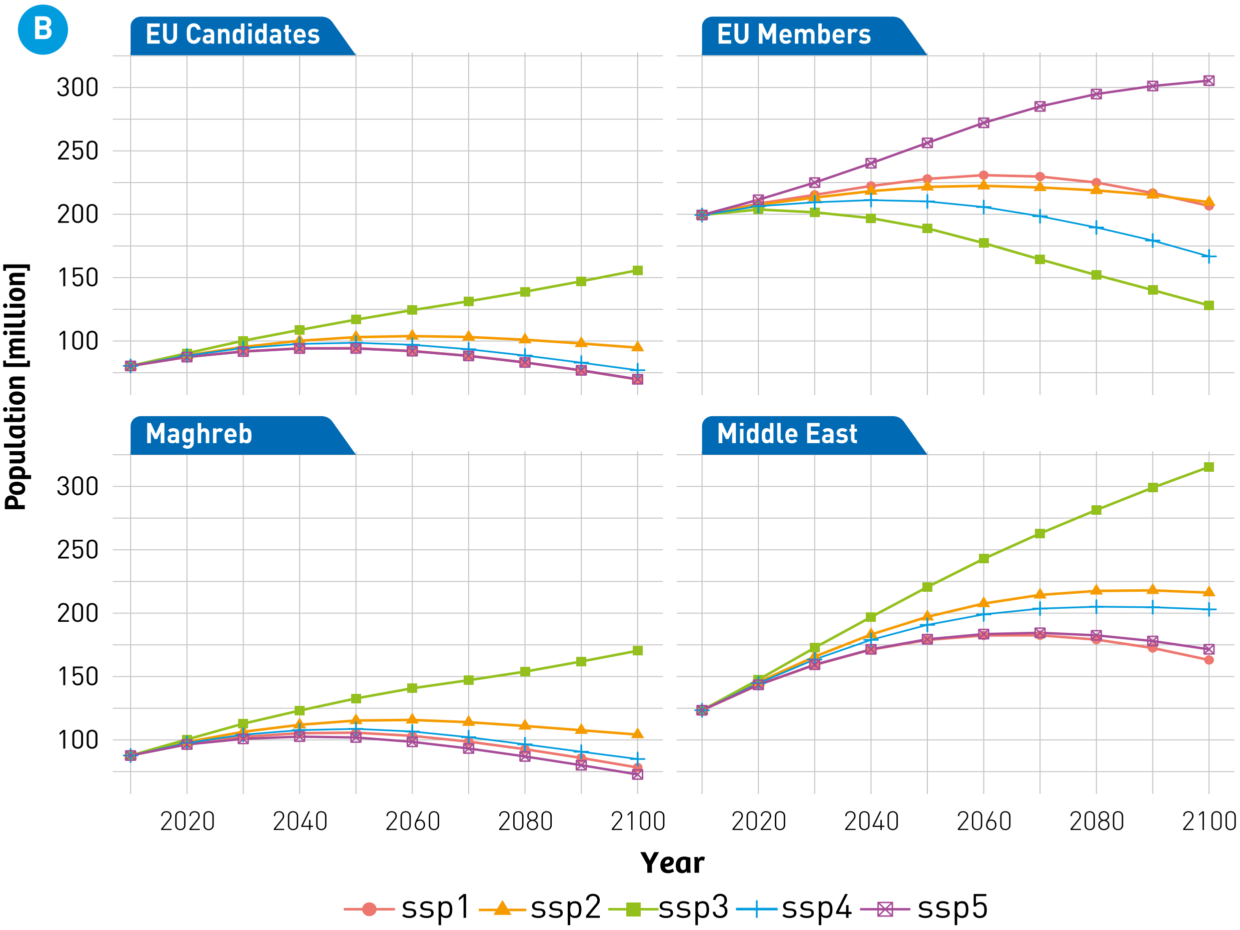
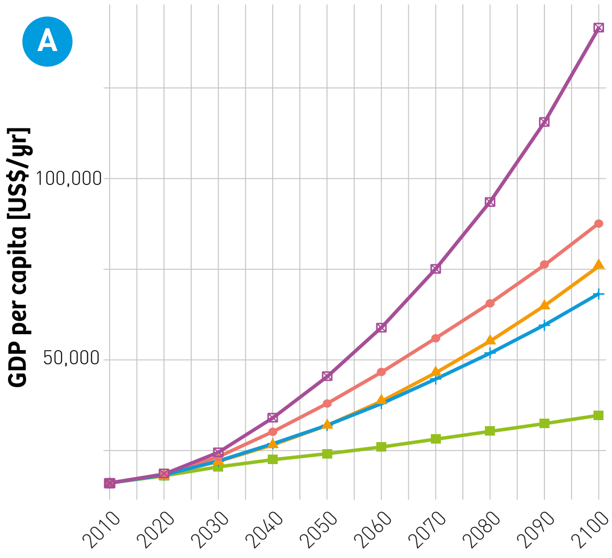


Figure 2.30 | **Mediterranean population projections under the different Shared Socioeconomic Pathways (SSPs),** A) total Mediterranean population, B) population by geographical region (Kc and Lutz 2017).

in the Mediterranean either fully or partially in terms of geographic coverage.

The most recent socioeconomic scenarios that account for socioeconomic developments in the entire Mediterranean region (as defined in this report) are the state-of-the-art global-scale Shared Socioeconomic Pathways (SSPs). The SSPs explore broad-scale societal trends in the course of the 21st century both qualitatively, in the form of scenario storylines, and quantitatively, in the form of national-level projections of key variables such as population (Kc and Lutz 2017), urbanization (Jiang and O'Neill 2017), and Gross Domestic Product (GDP) (Cuaresma 2017; Dellink et al. 2017; Leimbach et al. 2017). The Mediterranean population is projected to range from 607 million (SSP1) to 659 million (SSP3) in 2050 and from 518 million to 770 million in 2100 *(Fig. 2.30a)*, with considerable differences across regions *(Fig. 2.30b)*. The largest share of the population is projected to live in Egypt under all SSPs, except SSP5 where France is the most populous country in 2100 due to very high work migration into northern Mediterranean countries (O'Neill et al. 2017).



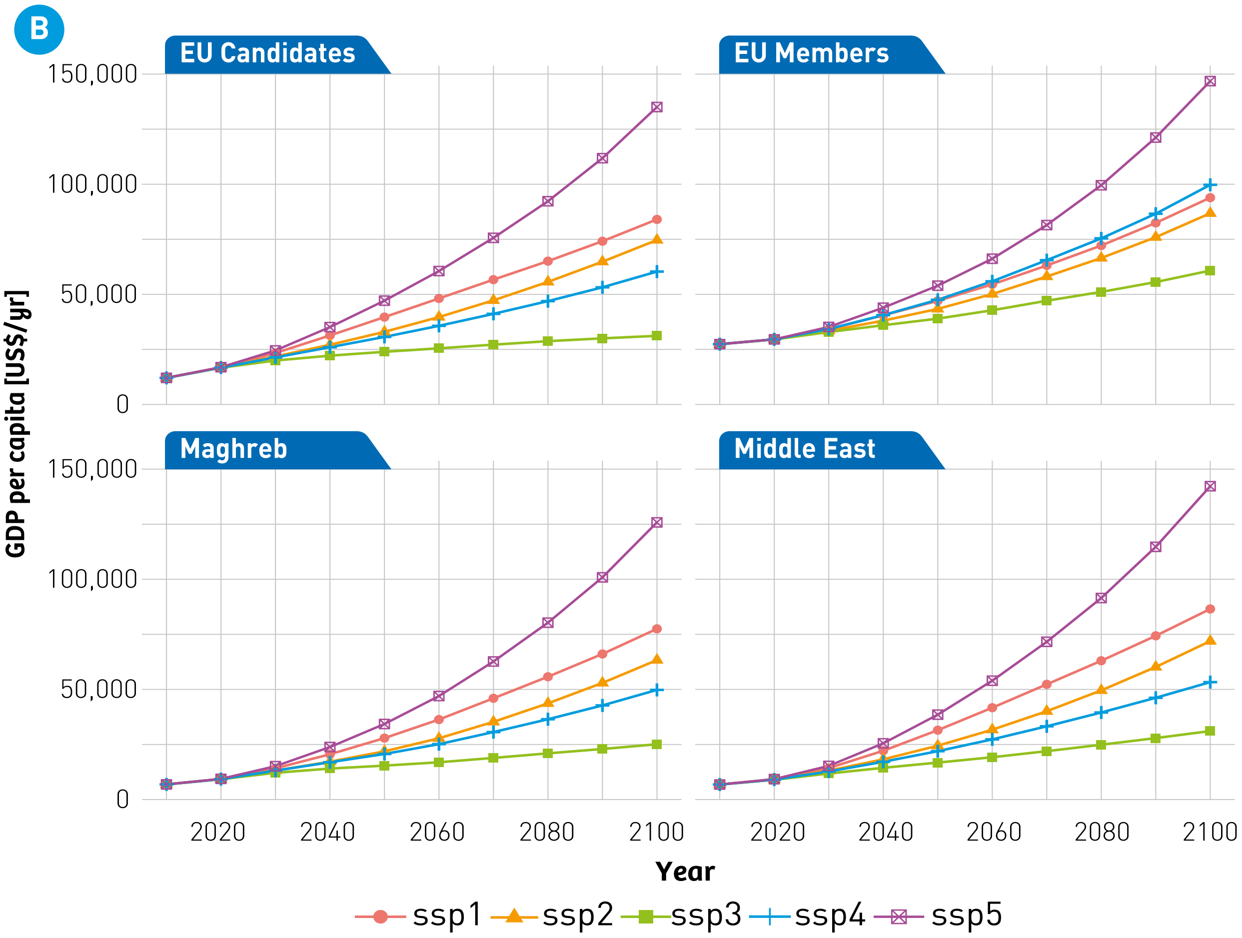


Figure 2.31 | Mediterranean Gross Domestic Product (GDP) projections under the different Shared Socioeconomic Pathways (SSPs), A) Mediterranean average GDP per capita, B) average GDP per capita by geographical region (Dellink et al. 2017).

The regional average GDP per capita is projected to grow from 16,000 US\$ yr^{-1} in 2010 to between 24,000 US\$ yr^{-1} (SSP3) and 45,000 US\$ yr^{-1} (SSP5) in 2050 and to roughly 35,000 US\$ yr^{-1} (SSP3) to 142,000 US\$ yr^{-1} (SSP5) in 2100 *(Fig. 2.31a)*. The differences in average GDP per capita are small between (potential) EU candidate countries, countries from the Middle East and the Maghreb region. EU member states have the highest average GDP per capita under all SSPs *(Fig. 2.31b)*.

In order to increase the usefulness of SSPs for impact, adaptation, and vulnerability assessments (van Ruijven et al. 2014), spatially explicit population projections that account for spatial changes in population distribution in the course of the 21st century have been produced, using the national totals as input data. These are available for all Mediterranean countries at a horizontal resolution of 7.5 arc minutes (Jones and O'Neill 2016) and 30 arc seconds (Merkens et al. 2016; Gao 2017). Further, downscaled GDP projections are available for SSPs 1-3 at a resolution of 30 arc minutes (Murakami and Yamagata 2019). All of these projections are based on the underlying global SSP assumptions.

As the global assumptions do not necessarily reflect the socioeconomic developments at the regional scale, extensions of the global-SSPs for the Mediterranean coastal zone have been developed (Reimann et al. 2018). These Mediterranean coastal SSPs account for region-specific developments as well as for changing attractiveness of coastal regions for human settlement across the SSPs, while at the same time ensuring consistency with the global SSPs (Zurek and Henrichs 2007). The Mediterranean coastal SSPs consist of qualitative narratives for each coastal SSP – SSP1 "Green Coast", SSP2 "No Wind of Change", SSP3 "Troubled Waters", SSP4 "Fragmented Coast", and SSP5 'Coast Rush' – differentiating between regional socioeconomic developments in northern versus southern and eastern parts of the region; and of spatially explicit population projections for all Mediterranean riparian countries at a resolution of 30 arc seconds *(Fig. 2.32)*.

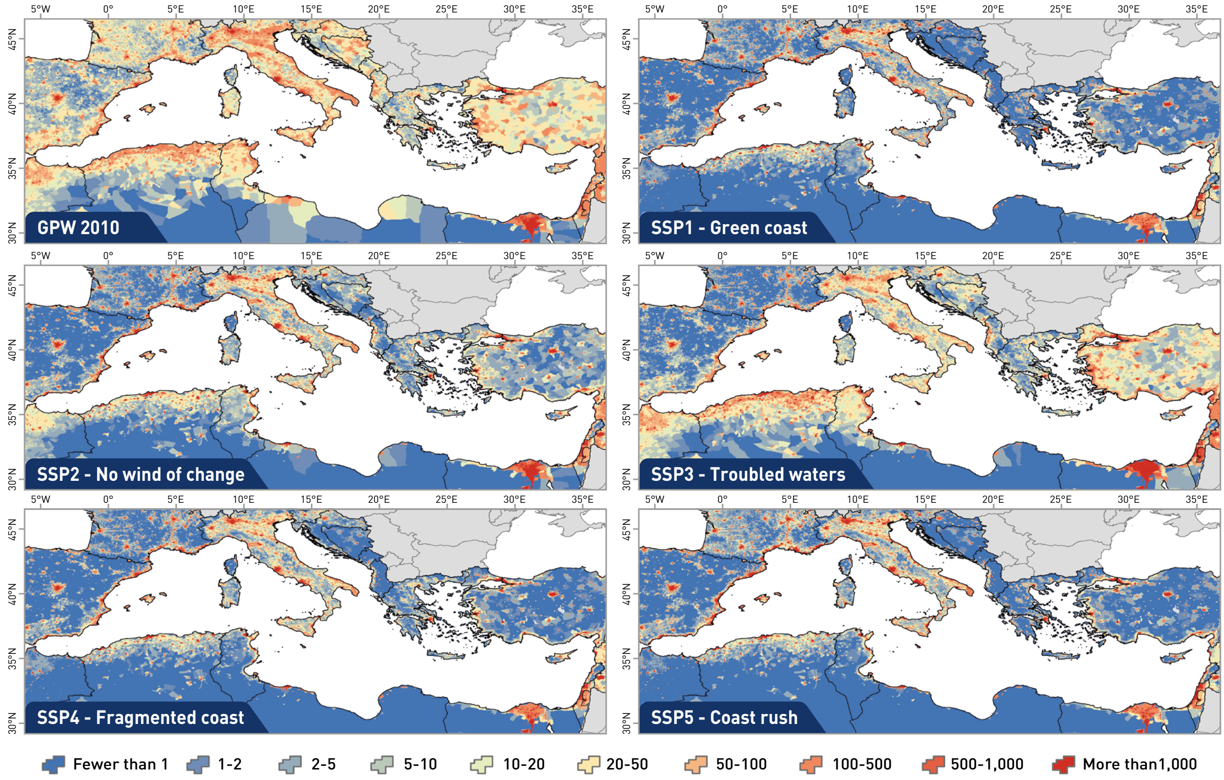


Figure 2.32 | Spatially explicit population projections produced for the Mediterranean Coastal SSPs. Selected population grids for the base year 2010 and each SSP in 2100 (Reimann et al. 2018), GPW = Gridded Population of the World (Center for International Earth Science Information Network - CIESIN - Columbia University 2016).

BOX 2.1

How much has the Mediterranean Basin warmed since the pre-industrial period?

The UNFCCC Paris Agreement of 2015 strengthens the initial goal of the Article 2 in the United Nations Framework Convention on Climate Change (UNFCCC), "to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system", by "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". While these temperature goals refer to the global average, it is a natural question to ask, for any region, how much warming has been observed "above pre-industrial levels".

This is only apparently a simple question. To provide such an estimate it is necessary to clarify the meaning of pre-industrial, the information available on its average temperature in the region, a definition of present average temperature and the method used for estimating it. These issues were at the core of the IPCC special report on global warming of 1.5°C (SR15, IPCC 2018) and specifically considered in its *Chapter 1* (Allen et al. 2018).

The period 1850-1900 has been identified (Allen et al. 2018) as a suitable approximation for the estimate of the pre-industrial average temperature, because it combines typical pre-industrial solar and volcanic forcing, low anthropogenic greenhouse gas concentrations, and sufficient coverage of instrumental temperature observations. The choice of the period 1850-1900 is not completely free of problems, because it is indeed already affected by increasing greenhouse gas concentrations, with a partial compensation caused by aerosols. Further, strong volcanic eruptions occurred in the period 1880-1900. In this box, we follow SR15 but also the indications of the World Meteorological Organization (WMO 2017) and compute average pre-industrial temperature for a 30-years period, the central 1861-1890 period of the 1850-1900 "pre-industrial" period.

The number and distributions of instrumental observation have changed significantly over time, and station density could become critically low in African and Asian areas of the Mediterranean Basin. Further, the collection of observations over sea is systematically more problematic than over land, notably prior to the 20th century. Rather than analyzing station data, we seek consistency with global estimates and we use the HadCRUT4 dataset (Morice et al. 2012) and the CRUTEM4 (Jones et al. 2012) data sets for the land+sea and land only analysis, respectively. These are two widely used gridded global data sets with a resolution of 5 degrees longitude/latitude since 1850 until present. Other data sets at higher spatial resolution are available (such as the recently updated version of CRU TS) (Harris et al. 2020), but they do not reach back far enough into the 19th century for the estimation of pre-industrial conditions. For this analysis, the Mediterranean Basin is defined as the domain from 10°W to 40°E of longitude and from 30°N to 47.5°N of latitude. For the averaging, an interpolation (based on the closest neighbours) to 1° spatial resolution was undertaken.

Obviously observed temperature values are not yet available for the period 2020-2034. This prevents computing the level of warming in 2020 using a simple 30-year average. Here, we make the conservative assumption that warming in the future will continue at the same rate of the last 50 years and compute the 2020 temperature by extrapolating the linear trend of the 1970-2019 period *Fig. 2.33*). In 2020 the Mediterranean Basin is 1.5°C warmer than in the preindustrial with a likely uncertainty range of +0.11°C. Land areas have warmed more than the sea. If only land areas are considered, the 2020 temperature is 1.8°C warmer than pre-industrial with a likely uncertainty range of +0.12°C.

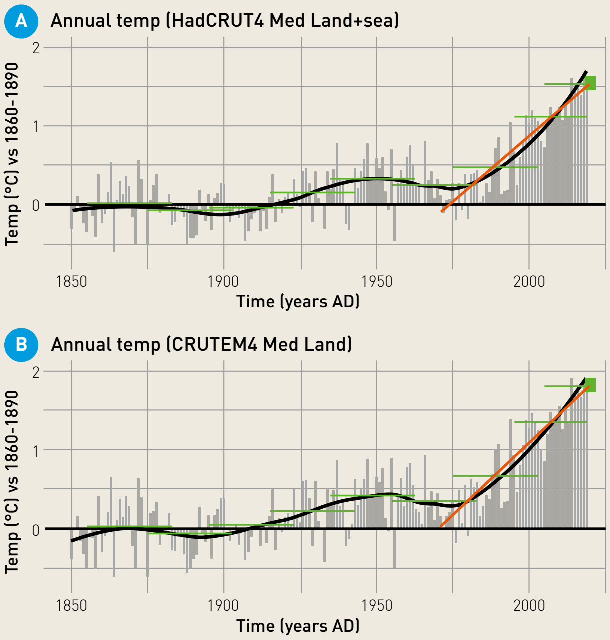


Figure 2.33 | Time series (grey bars) of the annual average temperature of the Mediterranean Basin (30°N to 47.5°N and 10°W to 40°E) considering the whole region (panel A) or only its land areas (panel B). The analysis is based on the HadCRUT4 data set for the land+sea analysis (Morice et al. 2012) and on the CRUTEM4 data set for the land analysis (Jones et al. 2012)(Jones et al, 2012). To avoid edge effects, before calculating the averages, the data have been interpolated to 1° spatial resolution. The values are expressed as anomalies from the pre-industrial period (1860-1890). The blue horizontal lines represent the 30-yr averages by steps of 20 years. The red curve is the linear trend linear trend calculated for the 1970-2019 period, extrapolated up to 2020. The black line is the smoother time-series. The blue square represents the likely interval (probability >0.66) for the present warming.

BOX 2.2

Representative Concentration Pathways (RCPs)

Representative Concentration Pathways (RCPs) are greenhouse has concentration pathways, developed by the IPCC in order to explore the physical outcomes of different climate policies, notably regarding the mitigation of greenhouse gas emissions.

RCP2.6: The RCP2.6 was developed by the IMAGE modeling team of the Netherlands Environmental Assessment Agency (van Vuuren et al. 2011). The emission pathway is representative for scenarios in the literature leading to very low greenhouse gas concentration levels. It is a so-called "peak" scenario: its radiative forcing level first reaches a value around 3.1 W m^{-2} mid-century, returning to 2.6 W m^{-2} by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially over time.

RCP4.5: It was developed by the MiniCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (Clarke et al. 2014). It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions. It is often considered as an intermediate scenario.

RCP8.5: The RCP8.5 was developed by the MESSAGE modeling team and the IIASA Integrated Assessment Framework from the International Institute for Applies Systems Analysis (IIASA), Austria (Riahi et al. 2011). The RCP8.5 is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels, reaching +8.5 W m^{-2} additional surface radiative forcing in 2100. It is often considered as a "business-as-usual" scenario.

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3

RESOURCES
1-WATER

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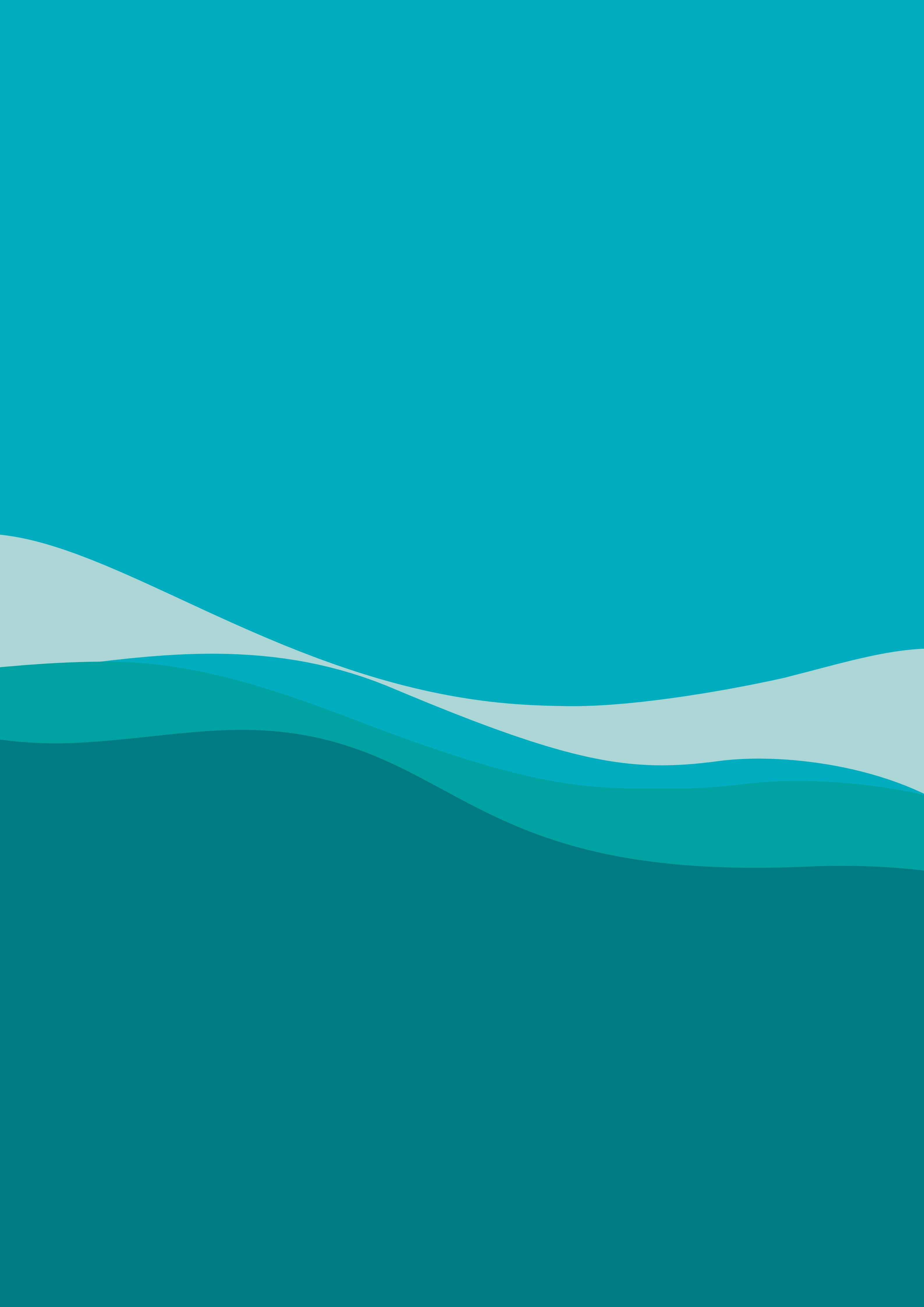
This chapter should be cited as: Fader M, Giupponi C, Burak S, Dakhlaoui H, Koutroulis A, Lange MA, Llasat MC, Pulido-Velazquez D, Sanz-Cobeña A 2020 Water. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 181-236, doi:10.5281/zenodo.7101074.*



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3.1 Water

Executive summary

Water resources in the Mediterranean are scarce. They are limited, unevenly distributed and often mismatching human and environmental needs. Three quarters of the resource are located in the northern Mediterranean while three quarters of the needs are in the south and east. As a consequence, approx. 180 million people in the southern and eastern Mediterranean countries suffer from water scarcity (<1,000 m^3 $capita^{-1}$ yr^{-1}). The main water user is agriculture, in particular on the southern and eastern rim. The percentage of irrigated land of the total cultivated area is 25% for the Mediterranean Basin and is currently increasing, likely with higher rates under even drier climate conditions in the future. Water demand for both tourism and agriculture peak in summer, potentially enhancing tensions and conflicts in the future. Municipal water use is particularly constrained in the south and will likely be exacerbated in the future by demographic and migration phenomena. In parallel, northern countries face additional risks in flood prone areas where population and urban settlements are rapidly increasing.

Climate change, in interaction with other drivers (mainly demographic and socio-economic developments), has mainly negative consequences for the water cycle in the Mediterranean Basin, including reduced runoff and groundwater recharge, increased crop water requirements, increased conflicts among users, and increased risk of overexploitation and degradation. These impacts will be much more important for global warming higher than 2°C.

Strategies and policies for water management and climate change adaptation are strongly interconnected with all other sectors (e.g., the Water-Energy and Food Nexus). Technical solutions are available for improving water use efficiency and increasing reuse. Seawater desalination is increasingly used as adaptation measure to reduce (potable) water scarcity in arid and semi-arid Mediterranean countries, despite known drawbacks in terms of environmental impacts and energy requirements. Promising solar technologies are under development, potentially reducing emissions and costs. Reuse of wastewater is a solution for agriculture and industrial activities but also recharge of aquifers. Inter-basin transfers may lead to controversies and conflicts. Construction of dams contributes to combat water and energy scarcities, but with trade-offs in terms of social and environmental impacts. Overall, water demand management, which increases water use efficiency and reduces water losses, particularly in urban environments, is crucial for a sustainable development. Maintaining Mediterranean diet or coming back to it on the basis of locally produced food and reducing food wastes may save water but also carbon emissions while having nutritional benefits.

3.1.1 Water resources in the Mediterranean Basin

3.1.1.1 Water availability

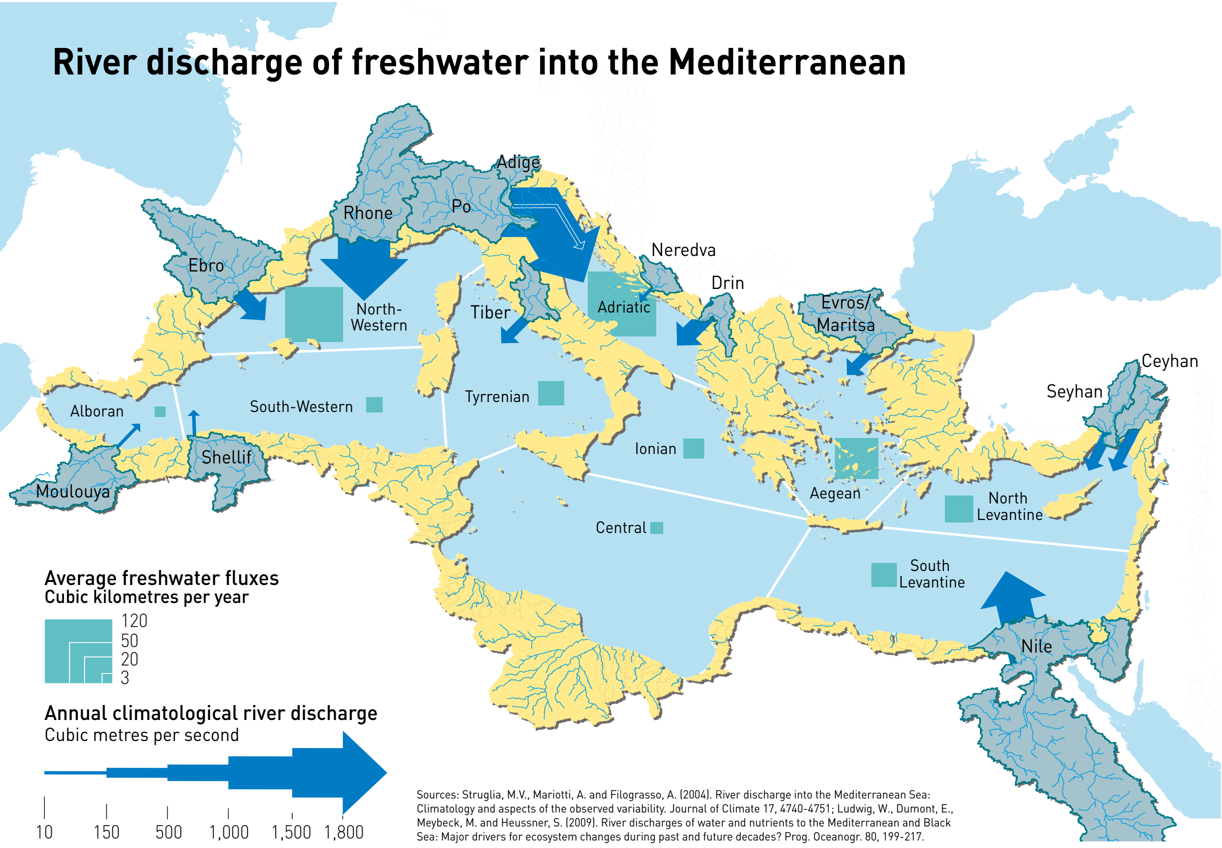
The total renewable freshwater resources of the countries belonging to the Mediterranean Basin are estimated to between 1,212 km^3 yr^{-1} and 1,452 km^3 yr^{-1} (Ferragina 2010; FAO 2016a), distributed unevenly. Northern Mediterranean countries hold approx. 72 to 74% of the resources, while the eastern Mediterranean (including Turkey) and the southern Mediterranean countries (including Egypt and the Nile) share the remaining approx. 26 to 28% (Ferragina 2010; FAO 2016a). Besides the heterogeneous distribution of total freshwater resources, the partitioning of surface and groundwater differs as well. In northern Mediterranean countries, 96% of the renewable water is surface water, whereof 25% are contributing as base flow to river discharges after percolating to the aquifer. The 25% are referred to as shared surface/groundwater resource. Only 4% of the total water is recharging the groundwater (FAO 2016a). In the southern Mediterranean, the share of renewable groundwater resources is 11% of its total renewable freshwater. In eastern Mediterranean countries it even amounts to 20% (FAO 2016a). Especially in southern and eastern Mediterranean countries non-renewable "fossil" groundwater resources account for almost 66% of the total groundwater (MED-EUWI 2007; Lezzaik and Milewski 2018).

As aquifers and rivers are often situated across political borders, the dependency among countries concerning freshwater resources is common (Ganoulis 2006; Iglesias et al. 2007, 2011). In the southern and eastern Mediterranean, more than 60% of the surface water is transboundary and all Middle East and North Africa countries share at least one aquifer (World Bank 2018). Expressed as a dependency ratio, i.e., percentage of renewable freshwater resources originating in another country, the mean dependency of the northern Mediterranean countries is 22%, the eastern 27% and the southern 18% (FAO 2016a).

The total human population of Mediterranean countries is rising and is expected to increase from 466 million people in 2010 to 529 million people in 2025 (UNEP/MAP 2016). Thus, while only covering 2.6% of the freshwater resources, 7.4% of the world's population has to be supplied with water (MED-EUWI 2007). Contrary to the total population development of the Mediterranean region, some single country projections show a decrease in population of 1% to 5% until 2025 and even 16% to 62% until 2100. Most of the countries with a negative population growth rate are in the northern Mediterranean region (Albania, Bosnia and Herzegovina, Greece, Italy, Malta, Montenegro, Macedonia, Portugal) except for Lebanon, which belongs to the eastern part (UN 2019). Comparing available freshwater resources to the population of the Mediterranean regions, the northern part has 36% of the population and 72% to 74% of the renewable freshwater, the east 24% and 19.5% to 21% and southern Mediterranean 40% and 5% to 8.5% respectively (FAO 2016a). As a result, 180 million people in the southern and eastern Mediterranean suffer from water scarcity (<1,000 m^3 capita^{-1} yr^{-1}) and 80 million people from extreme water shortage (<500 m^3 capita^{-1} yr^{-1}) (Ferragina 2010). In the northern Mediterranean however, an average water availability of 1,700 m^3 capita^{-1} yr^{-1} is given, in some Balkan states even a supply of 10,000 m^3 capita^{-1} yr^{-1} (Milano et al. 2013).

3.1.1.2 Rivers

River basins draining into the Mediterranean Sea cover an area of over 5 million km^2 including the entire Nile river basin but not the rivers draining Portugal into the Atlantic Ocean (Ludwig et al. 2009; Lionello et al. 2012). Portugal is considered a Mediterranean country and three large-scale river basins are shared between Spain and Portugal, i.e., Duero with 96,200 km^2, Tejo with 69,900 km^2 and Guadiana with 65,200 km^2 (Wolf et al. 1999). Besides a few major river basins (>80,000 km^2, *Fig. 3.1*), most catchments are medium to small-scale (Lionello et al. 2012).



Sources: Struglia, M.V., Mariotti, A. and Filograsso, A. (2004). River discharge into the Mediterranean Sea: Climatology and aspects of the observed variability. Journal of Climate 17, 4740-4751; Ludwig, W., Dumont, E., Meybeck, M. and Heussner, S. (2009). River discharges of water and nutrients to the Mediterranean and Black Sea: Major drivers for ecosystem changes during past and future decades? Prog. Oceanogr. 80, 199-217.

Figure 3.1 | Major river basins draining into the Mediterranean (Struglia et al. 2004).

In terms of discharge the ten largest rivers are the Rhône, Po, Drin-Buna, Nile, Neretva, Ebro, Tiber, Adige, Seyhan and Ceyhan rivers (Ludwig et al. 2009). Seven of these rivers are located in the northern Mediterranean countries, two in the eastern Mediterranean (Turkey) and one (the Nile) in the southern Mediterranean. Consequently, 71% of the mean annual discharge into the Mediterranean Sea originates from the northern part, whereas the eastern countries are contributing 12% and the southern 17% (Struglia et al. 2004). The large share of the southern countries comes mostly from the Nile, while 25% of the discharge in the northern countries is discharged by the Rhône and the Po River (Struglia et al. 2004; PERSEUS – UNEP/MAP 2015). Estimates of the total annual freshwater flux into the Mediterranean and Black Sea range from 305 to 737 km^3 yr^{-1} (Struglia et al. 2004; Ludwig et al. 2009).

The seasonal distribution of discharge is highly variable, depending on the climatic and geographical features of the river basins. Due to the Mediterranean climate, precipitation is mostly available for river discharge during autumn, winter and spring. Some Mediterranean rivers have an ephemeral or intermittent character (Argyroudi et al. 2009). In the mountain ranges of the Mediterranean region, precipitation mostly falls in form of snow in winter and is stored until late spring. During snowmelt in late spring this freshwater is contributing to the river discharge (Nogués-Bravo et al. 2008; García-Ruiz et al. 2011; Lionello et al. 2012). Most mountain ranges are more humid than lowland regions in the Mediterranean and therefore a source of water throughout the year (López-Moreno et al. 2008). A number of mountain ranges are almost entirely located in the Mediterranean Basin (Pyrenees, Apennines, Dinaric Alps, the Taurus and Pinthos mountain ranges and the Atlas Mountains), but also the main Alps contribute to the discharge into the Mediterranean Sea (e.g., through the Rhone, Adige and Po) (Lutz et al. 2016).

Many Mediterranean river basins are transboundary. The Nile River crosses ten countries before entering Egypt and then the Mediterranean Sea. Only 9% of the total basin area belongs to Egypt (Wolf et al. 1999). The Jordan is another important transboundary river, subjected to great water scarcity and political tensions between riparian states (Hoff et al. 2011). The largest northern transboundary river basins flowing into the Mediterranean Sea are the Ebro Basin in Spain, the Po Basin (shared by Italy, Switzerland and France) and the Rhone Basin (shared by France and Switzerland) (Wolf et al. 1999).

3.1.1.3 Groundwater

Groundwater resources are the main source of the water supply in many Mediterranean countries (e.g., Libya, Palestine and Israel) (FAO 2003; Leduc et al. 2017). Of the total abstracted 60,000 km^3 yr^{-1}, 54% are supplying the northern Mediterranean, 18% the eastern Mediterranean and 28% the southern Mediterranean countries (MED-EUWI 2007). Accessibility to the groundwater resources depends on several factors, for example the aquifer type. Three aquifer types are most common in the Mediterranean region: The karstic carbonated aquifer is the most common aquifer type. It is mainly recharged by surface water drainage, springs or adjacent aquifers. The levels of the groundwater and the volumes of karstic aquifers are highly diverse. Nevertheless, they are frequently used for water abstraction. Alluvial aquifers emerge in valleys or deltas of large rivers, providing a distinct layer of interaction between surface water and groundwater, often with a water table close to the surface. The two major Mediterranean alluvial aquifers are located in Italy (Po delta) and Egypt (Nile delta). The third aquifer type originates from sedimentary formations. Usually it comprises a large volume at a great depth and is not renewable. Connections to surface water fluxes are therefore not common. Considering the fact that no recharge is given, the groundwater of this aquifer type is referred to as "fossil". The spatial distribution of fossil groundwater resources is mainly concentrated in the southern Mediterranean countries (e.g., the Nubian sandstone aquifer in southern Mediterranean) (Aureli et al. 2008).

The recharging of groundwater is spatially variable. In the total Mediterranean region, 92% of the total recharge is contributing to northern, 3% to the eastern and 5% to the southern countries. In the southern countries the abstraction of renewable groundwater resources is exceeded by 24% and so an overexploitation of mainly fossil groundwater is necessary to meet the demand. In northern as well as in eastern Mediterranean countries on average 31% and 92% of their renewable groundwater respectively is abstracted (Aureli et al. 2008). The situation in those regions also differs among countries. For example, overexploitation of renewable water resources is found in Palestine and Jordan, leading to depletion of the aquifers (Saghir et al. 2000).

Potential groundwater resources in the Mediterranean are not only subjected to pressures resulting from unequal distribution and accessibility but also quality issues. Agricultural activities, leakage from urban areas or saltwater intrusion are the main sources of groundwater pollution, which can lead the resource to become unusable (Garrido and Iglesias 2006; Ferragina 2010).

Further, aquifers are often crossing political borders making an integrated management difficult. 274 underground water fields (aquifers) are known in the Mediterranean (Ferragina 2010). One of the largest aquifers, the Nubian Sandstone Aquifer, is located in the southern Mediterranean region and is shared by four countries from which two are bordering to the Mediterranean Sea (Libya and Egypt). Approximately 37% of the water is located in Egypt and 34% in Libya, which obtains 90% of its water supply from groundwater (Margat and van der Gun 2013; Leduc et al. 2017).

3.1.1.4 Lakes and reservoirs

"Large dams" are all dams higher than 15 m from their lowest foundation to crest and also dams between 5 m and 15 m impounding more than 3 million m^3 and in the Mediterranean the countries with the highest numbers are Spain (1,064), Turkey (974), France (720) and Italy (541) (ICOLD 2019). The two biggest dams in the European Mediterranean area are the Kremasta dam in the Aspropótamos River in Greece and the Alqueva dam in the Guadiana River in Portugal, whose capacity are 4.75 and 4.15 km^3, respectively. Although during the last two centuries the size and number of large storage capacity reservoirs have increased, it is now growing very slowly, due to the low availability of unused suitable places and the increase of environmental concerns (EEA 2018). The largest natural freshwater lake in Southern Europe is the Lake Skadar shared by Albania and Montenegro, which volume is 1.9 km^3 (Lasca et al. 1981).

3.1.1.5 Country-level water availability

Available and exploitable water resources of the Mediterranean region per country are listed in *Table 3.1*. It is important to differentiate availability

	Population (x1,000)	Renewable water resources (km^3 yr^{-1})	Exploitable water resources (km^3 yr^{-1})	Renewable water resources per capita (m^3 yr^{-1})	Exploitable water resources per capita (m^3 yr^{-1})
Albania	2,930	30.2	13	10,307.2	4,436.9
Algeria	41,318	11.67	7.9	282.4	191.2
Bosnia and Herzegovina	3,507	37.5	-	10,692.9	-
Croatia	4,189	105.5	-	25,185.0	-
Cyprus	1,180	0.78	0.54	661.0	457.6
Egypt	97,553	57.5	49.7	589.4	509.5
France	64,980	211	100	3,247.2	1,538.9
Greece	11,160	68.4	29	6,129.0	2,598.6
Israel	8,322	1.78	1.636	2,13.9	196.6
Italy	59,360	191.3	123	3,222.7	2,072.1
Jordan	9,702	0.937	-	96.6	-
Lebanon	6,082	4.503	2.08	740.4	342.0
Libya	6,375	0.7	0.635	109.8	99.6
Malta	430.8	0.0505	0.015	117.2	34.8
Monaco	38.7	-	-	-	-
Montenegro	629	-	-	-	-
Morocco	35,740	29	20	811.4	559.6
North Macedonia	2,083	6.4	3	3,072.5	1,440.2
Palestine	4,921	0.837	0.715	170.1	145.3
Portugal	10,330	77.4	13	7,492.7	1,258.5
Serbia	8,791	162.2	-	18,450.7	-
Slovenia	2,080	31.87	-	15,322.1	-
Spain	46,354	111.5	46.3	2,405.4	998.8
Syrian Arab Republic	18,270	16.8	20.6	919.5	1,127.5
Tunisia	11,532	4.615	3.625	400.2	314.3
Turkey	80,745	211.6	112	2,620.6	1,387.1

Table 3.1 | Available and exploitable water resources in the Mediterranean region per country (Data Source: FAO, 2003, 2016).

and exploitability to assess the water situation of a country. Not all water can be used due to technical or environmental limitations, like a minimum required flow or uneconomical groundwater pumping (FAO 2003). The availability as well as the potential usable water vary among countries and so does ratio of water that can be exploited to the total available water.

3.1.2 Water use per sector

3.1.2.1 Overview across economic sectors

In the southern Mediterranean countries most water is used for agriculture (76%) whereas the industrial consumption and the public amount only to 4% and 20%, respectively, of the total abstracted water (Hamdy et al. 1995; FAO 2016a). In the eastern part, agriculture uses 79% of the abstracted water, whereas the industrial and public sector have a relatively small share with 6% and 13%, respectively (FAO 2016a). The northern Mediterranean countries have also the largest water usage in agriculture (36%) (FAO 2016a). Industrial (incl. cooling 48%) and public use (16%) are much higher than the rest of the Mediterranean regions (Hamdy et al. 1995; FAO 2016a). Looking at country values, agricultural use dominates generally water demand with some prominent exceptions, for example Slovenia and France having predominant industrial water demand *(Fig. 3.2)* (Burak and Margat 2016).

The part of overall water abstraction for different uses from surface water and groundwater varies between countries, from 100% of groundwater resources in Malta to approx. 20% in France (Leduc et al. 2017). In most of the Mediterranean, water demand is satisfied by freshwater withdrawal but in northern Africa the proportion of demand covered with fossil groundwater is high, as are the use of treated municipal water in Israel and desalinated water in Cyprus and Malta (*Fig. 3.3*, *Table S3.1*). Water demand in Northern Africa is thus met increasingly by non-renewable water resources, estimated at 16 km^3 yr^{-1}, of which more than 60% is withdrawn from fossil resources and more than 30% is due to overexploitation of renewable groundwater (WWC 2009).

3.1.2.2 Agriculture

In the Mediterranean countries, water withdrawal for the agricultural sector is about 193 km^3 yr^{-1}, 64-69% of total water withdrawal (FAO 2016a; Malek and Verburg 2018). These amounts depend mainly on climate, from very low levels in some Balkan countries to more than 80% in the countries with arid and semi-arid climate. The quality of water used for irrigation is a matter of concern, as low water quality may cause water-borne diseases and crop damage which would reduce agricultural production (Etteieb et al. 2017). In some countries (e.g., Egypt), non-conventional, water is used in the agricultural sector from brackish water collected from drainage canals and municipal wastewater. Using municipal waste water, even

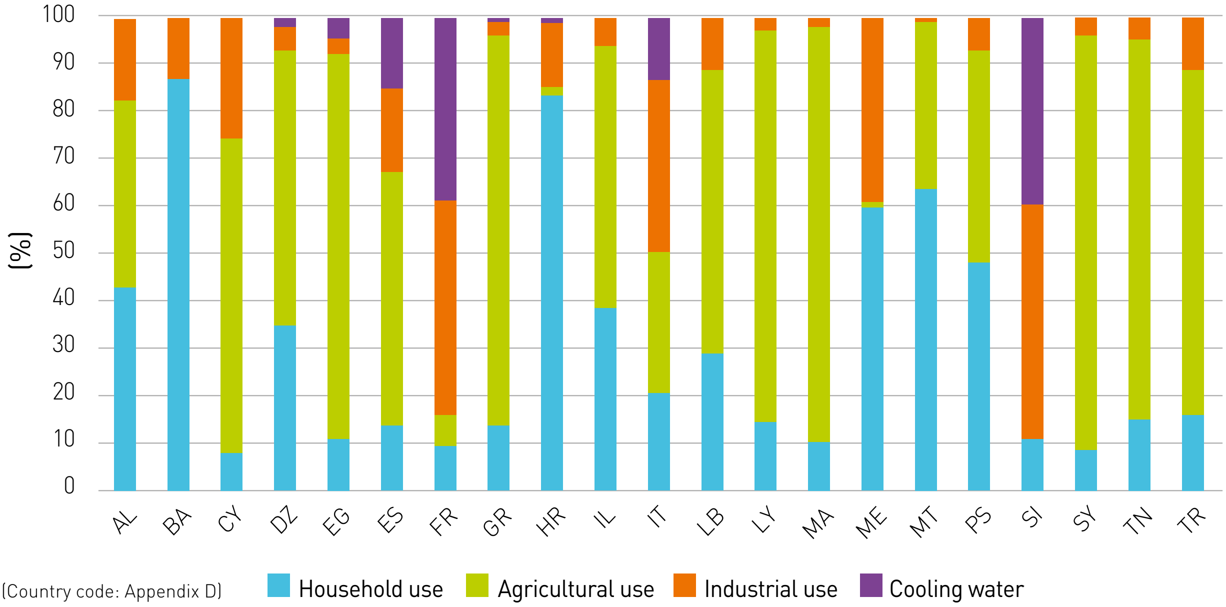
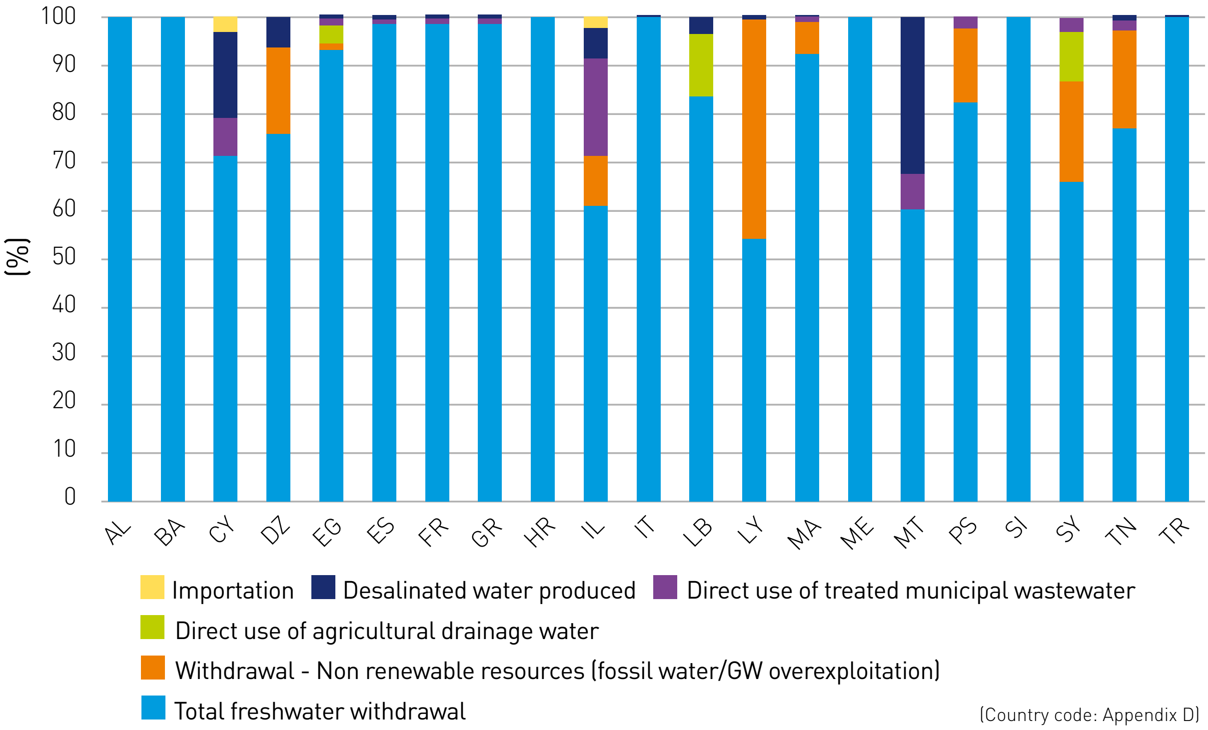


Figure 3.2 | Water demand per sectoral use as percentage of total water demand (Burak and Margat 2016).



(Country code: Appendix D)

Figure 3.3 | Sources of water supply as percentage of total water supply (Burak and Margat 2016).

after conventional treatment, while it is beneficial in regions suffering of water scarcity, should be applied only on selected plants and carefully monitored, because of the nutrient content, as well as bacteriological pollution, not to create sanitary issues (El Ayni et al. 2011).

The total area of the Mediterranean currently equipped for irrigation is about 27 million ha (FAO 2016a). Its percentage of agricultural land is the largest in Egypt (almost 100%), very high in Israel (76.3%), Turkey (71%), Lebanon (78.8%), Greece (70.9%), Cyprus, (65.6%) and Italy (60.7%). In a given year, only a part of the equipped area is actually irrigated (about 86% or 23.2 million ha) due to lack of water for irrigation, inadequate maintenance, operation and governance, obsolete irrigation systems, etc. Average water consumption for irrigation of the agricultural sector in the Mediterranean countries is estimated to about 8,340 m^3 ha^{-1}. It goes from a few thousand m^3 ha^{-1} in the Balkan area (Albania, Montenegro, Bosnia and Herzegovina, Croatia and Slovenia) to much higher values, such as in Portugal (20,800 m^3 ha^{-1}), Egypt (18,000 m^3 ha^{-1}), Syrian Arab Republic (12,000 m^3 ha^{-1}), Lebanon (8,700 m^3 ha^{1}), Malta (7,900 m^3 ha^{-1}), Jordan (7,500 m^3 ha^{-1}), Greece (6,800 m^3 ha^{-1}), Tunisia (6,500 m^3 ha^{1}), Turkey (6,400 m^3 ha^{-1}) and Morocco (6,300 m^3 ha^{-1}). These differences are, besides the specific climatic conditions, due to different cropping pattern, irrigation methods, and overall efficiency of water withdrawal, storage, conveyance, distribution and application. Many Mediterranean countries widely use surface irrigation, such as Turkey (87.8% of irrigated area), Syrian Arab Republic (77.8%), Egypt (75.6%), Morocco (71.6%) etc.

There is a trend in several Mediterranean countries towards the substitution of surface irrigation with more efficient localized irrigation (Rodríguez-Díaz et al. 2011), e.g., in southern Spain and the Maghreb oases (Ibáñez et al. 2008), it is also reflected in the National Strategy for Irrigation Water Saving launched by the Moroccan government within the overall Green Morocco Development Plan. The trend towards more efficient irrigation systems may not have led to absolute water savings due to simultaneous changes towards water-demanding, more profitable crops (e.g., vegetables) and/or expansion of irrigated areas (Ward and Pulido-Velazquez 2008). Yet, the implementation of water-saving irrigation systems has led to higher water productivity in terms of tons and revenues produced per unit of water applied (Rodríguez-Díaz et al. 2011; Shah 2014). The implementation of pressurized systems has also led to higher energy requirements and, thus, higher greenhouse gas emissions. Daccache et al. (2014) state that irrigation modernization in the Mediterranean could save 8 km^3 of water per year, but it would also increase CO_2 emissions by 2.42 Gt CO_2e (+135%). The new development of solar pumps in drylands and desertic environments has created a substantial decrease of the fossil water table and increased the risk of salinization (Zammouri et al. 2007; Gonçalvès et al. 2013).

Changes in irrigation systems affect key variables of the water cycle such as soil evaporation, infiltration and percolation, water storage in soils, groundwater recharge, runoff and return flow. These changes affect the availability of water resources. For example, implementing drippers instead of flooding irrigation reduces in most cases soil evaporation, surface runoff, groundwater recharge and return flows (Cooley et al. 2009), potentially causing water scarcity in downstream areas. This transformation can also generate significant environmental issues in groundwater dependent ecosystems influencing the biodiversity and functioning of aquatic and terrestrial ecosystems (Kløve et al. 2011), in coastal aquifer vulnerable to seawater intrusion (Kouzana et al. 2009; Mazi et al. 2014), and in terms of soil salinization (Clemmens et al. 2008).

In some regions, there is still conversion of natural ecosystems to croplands, to non-natural grasslands/grazing areas and, especially, a widespread conversion of all uses to urban areas. This affects hydrological variables, such as soil evaporation, plant transpiration, infiltration, percolation, water storage in soils, groundwater recharge, runoff and return flow. For example, deforestation was found to reduce spring and summer evaporation by more than 1 mm day^{-1} and decrease precipitation in the western Mediterranean (Gaertner et al. 2001).

3.1.2.3 Tourism

Most tourist modalities are highly dependent on sufficient water resources and at the same time a major actor in water use that may contribute to the overexploitation of existing supplies and degradation of freshwater ecosystems (de Stefano 2004). In 2017, the Mediterranean received 289 million visitors (76% of which in the countries of the North of the basin including Turkey) reaffirming the position of this area as the largest single tourist destination in the world (UNTWO 2018). In the Mediterranean, tourist activity is at its highest in summer coinciding with peak demands by irrigated agriculture which may create tensions regarding water availability likely to be exacerbated in the future due to climate change (Toth et al. 2018).

Although usually higher than that of permanent residents, water consumption by tourism is strongly influenced by the tourist modality as well as location. Gössling et al. (2012) estimated wide variations of consumption, ranging from 84 l person^{-1} day^{-1} for campsites in Spain to close more than 2,000 l person^{-1} day^{-1} in hotels in Thailand. A correspondence between hotel category and water consumption has been found with establishments in upper categories consuming more water than establishments in lower categories (Gössling et al. 2015; Rico et al. 2020) but hotel-based tourism shows also less consumption per capita than residential tourism based on house rentals (Rico-Amoros et al. 2009). High water use is related to the presence of outdoor amenities such as lawns, swimming pools or golf courses (Gössling et al. 2015). In the Mediterranean, small insular states dedicate a significant part of their total water supply to tourism (5% in Cyprus and more than 7% in Malta) while in the large countries, tourism represents at the most 1% of total water use at the country level but sometimes 5% or more of domestic use (Gössling et al. 2012).

Overall, tourism-related water consumption appears to decrease, at least in the developed mass tourism destinations of the northern part of the basin (Rico et al. 2020), due to increasing efficiencies and also to the use of non-conventional resources such as recycled water (Gabarda-Mallorquí et al. 2017), or due to the exchange between agriculture and tourism of water flows of different qualities (Rico-Amoros et al. 2013). These options respond to increasing episodes of water stress linked to climate change in the region which may also increase coastal erosion and jeopardize beaches and natural and cultural heritage sites, especially in the southern and eastern countries (Bocci and Murciano 2018).

3.1.2.4 Industry and energy

Water use in the industrial sector of Mediterranean countries is estimated at 59.6 km^3 yr^{-1}. Additionally, 38 km^3 yr^{-1} are used for the cooling of thermal power plants (Burak and Margat 2016). The two figures combined would represent around 30% of water use in the Mediterranean Basin. Most of this consumption occurs in the large developed countries of the North (France, Italy and Spain) which concentrate 80% of water used in the industrial sector and 87.5% of water used for cooling purposes (France alone concentrates more than 60% of water used for cooling). In the East and South, Turkey represents 7% of industrial water use and Egypt 2% (Förster 2014; Burak and Margat 2016).

In most countries, chemical and especially petrochemical facilities are the main industrial users of water. More than 200 petrochemical plants and basic chemical plants are located along the Mediterranean coast and in adjacent river basins, including at least 40 major oil refineries with important concentrations in Spain, France, Italy, and some Northern African countries such as Algeria and Egypt (IDAEA 2015). Mining and manufacturing of basic metals is the main water-using industry in Serbia and Turkey while water use for food processing is present in most countries although in small quantities (Förster 2014).

The abstraction of water for industrial activities decreased in most of the developed North of the basin during the first decade of the 21st century and overall demand for water from the energy and industrial sectors is projected to decline in the following decades in these areas mainly as a result of improving efficiencies. Treated wastewater is increasingly used in some industrial sectors. For example, the petrochemical complex of Tarragona, Spain, the largest in the Mediterranean, will cover around 80% of the $27x10^6$ m^3 of water used annually with reclaimed water in 2020 (Molist et al. 2011). In contrast, demand in the industrial sector of the South and the East is projected to increase significantly and could account for over 7% of the total water demand by 2025 (Verdier and Viollet 2015).

Hydropower constitutes a large part of the 228 GW (38%) of the installed capacity for electricity production in the Mediterranean. Around 80% of this capacity is located in France, Italy and Spain, although possibilities for further development in these countries are severely limited. *Table 3.2* indicates the percentage of electricity produced from hydropower in several countries. Of these, the only country where electricity production from hydropower is expanding is Turkey, especially in the Tigris and Euphrates river basins. Hydropower is very sensible to climate change *(Section 3.3.3.5)*. For example, the average flow of the Rhône River (supplying 25% of hydroelectricity in France) could be reduced to a third of its current flow by 2100 (European Water Movement 2018).

Country	Electricity generated from hydropower (%)
France	12.5
Italy	25
Spain	20
Turkey	31.2
Egypt	9

Table 3.2 | Percentage of electricity generated from hydropower in selected Mediterranean countries (Bocchiola and Rosso 2014; France Hydroelectricité 2018; OME 2018; Estado de los embalses, pantanos y presas de España 2019; TSKB Ekonomik Araştırmalar 2020).

3.1.2.5 Municipal water withdrawal

Municipal water withdrawal refers primarily to the direct use of water by the population, including renewable and non-renewable sources, treated, desalinated and drainage water. It is usually computed as the total water withdrawn by the public distribution network. *Table 3.3* shows the municipal water withdrawal for Mediterranean countries. A fraction of 30%, on average, of total water withdrawal is consumed for municipal use in the Mediterranean. In absolute terms, Egypt and Italy have the largest municipal water withdrawal, while when computed as percentage of total withdrawal, Bosnia and Monaco have the largest values. However, values per capita may give a more accurate picture of the situation, since population numbers differ largely from country to country (*Table 3.3,* right column). However, national statistics about drinking and sanitation water use may differ from these numbers. According to the last national study on the supply of drinking water and sanitation in Spain, for 2017 (AEAS-AGA 2018), the total water use in Spanish households (drinking, washing, cooking, toilet, shower, cleaning, etc.) was, on average, 132 l capita^{-1} day^{-1} (i.e., 48 m^3 yr^{-1} capita^{-1}, differing from the 105.5 m^3 yr^{-1} capita^{-1} shown in *Table 3.3*).

Domestic water consumption in the Mediterranean depends on regional socioeconomic and sociodemographic circumstances with large differences from place to place. *Fig. 3.4* shows the temporal evolution in municipal water withdrawal for selected Mediterranean countries according to FAO Aquastat database (FAO 2016a). Increasing withdrawal is reported for Cyprus, Jordan and Algeria during the last decades in the absolute values of municipal water, as well as in the fraction of municipal compared to total water withdrawal. On the other hand, the fraction of municipal water for France, Monaco and Spain shows a decreasing trend despite the relatively constant absolute values. Decreasing trends in municipal water use has also been reported in specific urban areas during the recent past, as for example in the city

	Population (x1,000)	Total water withdrawal (10^9 m^3 yr^{-1})	Municipal water withdrawal (10^9 m^3 yr^{-1})	Municipal water withdrawal as % of total withdrawal (%)	Municipal water withdrawal per capita (m^3 yr^{-1})
Albania	2,930	1.311	0.283	21.6	96.6
Algeria	41,318	10.46	3.600	34.4	87.1
Bosnia and Herzegovina	3,507	-	0.361	-	102.9
Croatia	4,189	0.715	0.455	63.6	108.6
Cyprus	1,180	0.311	0.110	35.4	93.2
Egypt	97,553	77.5	10.750	13.9	110.2
France	64,980	26.44	5.175	19.6	79.6
Greece	11,160	11.24	1.991	17.7	178.4
Israel	8,322	2.304	0.983	42.7	118.1
Italy	59,360	34.19	9.488	27.8	159.8
Jordan	9,702	1.044	0.457	43.8	47.1
Lebanon	6,082	1.84	0.240	13.0	39.5
Libya	6,375	5.83	0.700	12.0	109.8
Malta	430.8	0.0638	0.037	58.6	86.8
Monaco	38.7	0.005	0.005	100.0	129.2
Montenegro	629	0.1609	0.096	59.9	153.3
Morocco	35,740	10.43	1.063	10.2	29.7
North Macedonia	2,083	0.5235	0.278	53.0	133.2
Palestine	4,921	0.3752	0.181	48.3	36.8
Portugal	10,330	9.151	0.914	10.0	88.5
Serbia	8,791	5.377	0.660	12.3	75.0
Slovenia	2,080	0.9314	0.170	18.2	81.5
Spain	46,354	31.22	4.890	15.7	105.5
Syrian Arab Republic	18,270	16.76	1.475	8.8	80.7
Tunisia	11,532	4.875	0.137	2.8	11.9
Turkey	80,745	58.79	5.839	9.9	72.3

Table 3.3 | Municipal water withdrawal in absolute values, in percentage of total withdrawal and per capita. The values shown are the most recent values present in FAO AQUASTAT Database from the period 2003-2017.

of Alicante from a combination of water saving as a response to water pricing and increased environmental awareness, as well as water reuse (Morote et al. 2016).

Municipal water distribution systems of many Mediterranean countries are old and as a result, losses and leaks are estimated of the order of 35% of the total water demand (UNEP/MAP and Plan Bleu 2020). Several Mediterranean countries have set specific targets for improving water use efficiency in the context of the Mediterranean Strategy for Sustainable Development.

3.1.3 Past changes in hydrological variables

In order to isolate the impacts of climatic conditions on groundwater and surface water resources it is necessary to remove anthropogenic detractions from the results of monitoring. In many cases, this is performed by applying hydrological models (Escriva-Bou et al. 2017; Trichakis et al. 2017) that simulate first the link between the climatic driving forces and the hydrological variables in natural conditions for calibration, and then compare simulations with observations.

3.1.3.1 Evapotranspiration and soil moisture

The increasing Mediterranean temperatures translate directly into higher evaporative demand. However, observations denote a recent (1998 onwards) decline of land evapotranspiration in a global context that could be attributed to limitations in moisture supply (Jung et al. 2010). Evapotranspiration is controlled by water demand and supply limitation conditions, which are highly variable depending on the region and the season (Wang et al. 2010). Weather variables affecting evapotranspiration in arid and semi-arid climates range over a large interval making difficult the evaluation of actual evapotranspiration (Rana and Katerji 2000).

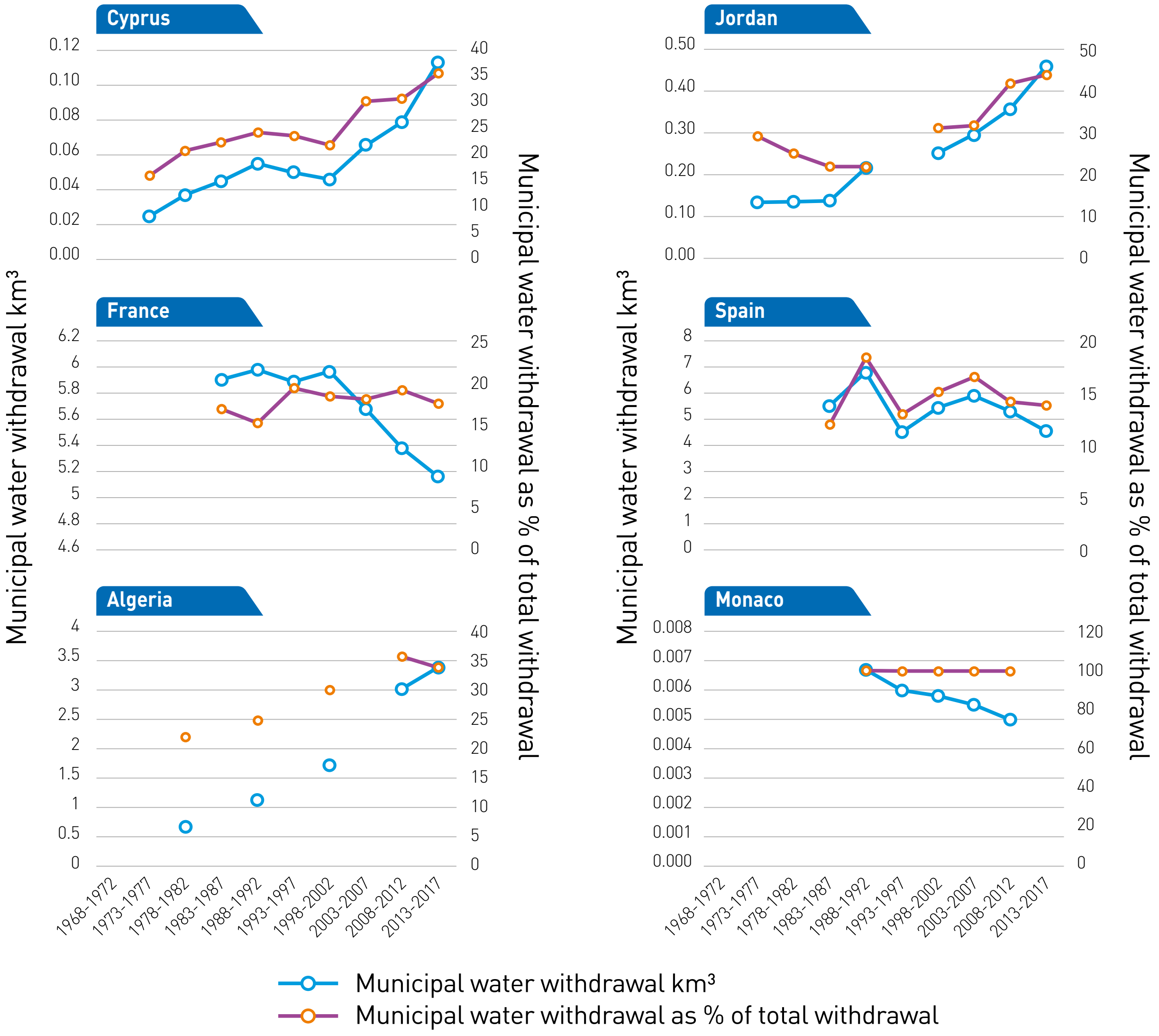


Figure 3.4 | Trends in municipal water withdrawal. Absolute (left y-axis) withdrawal values and in percentage of total withdrawal (right y-axis) for selected Mediterranean countries according to (FAO 2016a).

In several Mediterranean regions small trend changes of ±0.1 mm yr^{-1} in annual evapotranspiration have been detected from 1982 to 2008, with large regional variations. Positive multi-decadal evapotranspiration trends in Mediterranean have been found by several authors (Miralles et al. 2014; Zhang et al. 2016, 2019), as a consequence of increases in transpiration and interception components, counterbalanced by decreasing soil evaporation (Zhang et al. 2016).

Soil moisture is one of the most important water resources for agriculture, especially during the dry season, and it also affects temperature variability (D'Andrea et al. 2006). Mediterranean ecosystems respond to soil moisture shortage by directly reducing gross primary productivity (Piayda et al. 2014; Meza et al. 2018), hence soil moisture variability affects also long-term terrestrial carbon storage (Green et al. 2019). Sparse and uneven observations make it difficult to assess the past trends in soil moisture across the Mediterranean. Assessments mostly rely on hydrological and water accounting models driven by observed climate data. Such studies indicate a historical decrease in soil moisture in most of the Mediterranean region, particularly in southeastern Europe, southwestern Europe and southern France, as well as a substantial increase over western Turkey (Sheffield and Wood 2008; Kurnik et al. 2015). A progressive decrease in total soil moisture of the Mediterranean region during the twentieth century of about 2-3% that continues at an increased pace until today has been estimated through simulations (based on CMIP5 simulations) (Mariotti et al. 2015).

Spatially distributed soil moisture detection can be derived from remote sensed products. Feng (2016) analyzed the temporal trends of global soil moisture during 1982 to 2013 on European Space Agency's Climate Change Initiative soil moisture data. They found no significant trend in soil moisture in the coastal regions of south Mediterranean countries, except for Egypt that exhibits a marginally negative trend. Soil moisture in southwest Turkey decreased, but in increased in Southern Italy. Similar results were obtained by Dorigo et al. (2012) from microwave surface soil moisture measurements. These findings have to be interpreted with caution, as the depth of the soil moisture that can be detected with these equipments is limited to the first few centimeters.

3.1.3.2 Runoff and water resources

Several studies indicate an important reduction of streamflow in basins of the Mediterranean region during recent decades (Lutz et al. 2016; Suárez-Almiñana et al. 2017). For example, in the Jucar Basin (East Spain) streamflow in natural regime has experienced a reduction close to 40% since the 1980s (Suárez-Almiñana et al. 2017). Decreasing long-term flow trends are also detectable for a large part of the Mediterranean rivers (Su et al. 2018). The strong significant runoff decrease in the Mediterranean has also been identified by Gudmundsson et al. (2017) and is likely attributed to anthropogenic forces.

Overall, Mediterranean catchments are prone to drier climate and declining water resources apart from the alpine catchments in the north of the Mediterranean region, as for example in the Adige Region (Lutz et al. 2016). This reduction affects surface and groundwater resources.

3.1.3.3 Extreme events

Floods

Floods are the most frequent and among the costliest and deadliest natural disasters in the Mediterranean area (Swiss Re 2015; UNISDR 2015), where flooding has produced more than 85 billion euros of damages since 1900 (a 42.5% of total damages related to various disasters, EM-DAT)[9]. Floods and droughts present significant and increasing risks for water stress (OECD 2016) and can significantly erode poor people's assets and further undermine their livelihoods in terms of labor productivity, housing, infrastructure, and social networks (Olsson et al. 2014).

In recent decades, a mixed signal of increasing and decreasing trends in flood occurrence has been reported from many local studies over the European Mediterranean (Hall et al. 2014). In Spain and southern France, generally decreasing trends in annual maximum floods have been found (Renard et al. 2008; Stahl et al. 2010; Giuntoli et al. 2012; Mediero et al. 2014). Blöschl et al. (2019) show a common negative change in mean annual flood discharge (between -5% and -24%) in the northern and eastern Mediterranean Basin for the period 1960-2010. Although flood trend attribution is uncertain, it is often possible identify the likely key drivers of this negative trend (Merz et al. 2012). As there is not a common negative trend in precipitation, neither in maximum precipitation in those regions, causes may be related to other changes in rainfall-runoff processes at the catchment scale, such as changes in water tables caused by either overexploitation or recharge of aquifers, or land use changes, such as deforestation or forestation, urbanization, wildfires and agricultural use changes (Mediero et al. 2014). As an example, the abandonment of agricultural activities in Catalonia (northeastern Spain) has led to an increase of the forest density in the region from 30% to 70% in less than 100 years (Boada and Gómez 2011). Finally, structural flood protection measures like flood-control reservoirs have led to a decrease in flood probability although in some cases have reduced preparedness. This is known as the "levee effect" (di Baldassarre et al. 2018).

For the Po River (Italy) there is no clear trend in annual maximum floods (Montanari 2012). In Greece, around Athens, an increase in flood frequency has been observed in recent decades (Diakakis 2014). For the largest rivers in Mediterranean basins, Blöschl et al. (2017) indicate later winter floods and Mangini et al. (2018) noted a tendency towards increasing flood magnitude and decreasing flood frequency. Studies of historical flood series for more than 500 years show the great dependence of floods on land use changes and increased exposure in Mediterranean flood prone areas since the 18th century (Barriendos et al. 2003; Wilhelm et al. 2012). Flood-rich periods associated to climate anomalies (e.g., the Little Ice Age), can often be explained by natural climate variability (Glaser et al. 2010; Barrera-Escoda and Llasat 2015).

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[9] http://www.emdat.be/

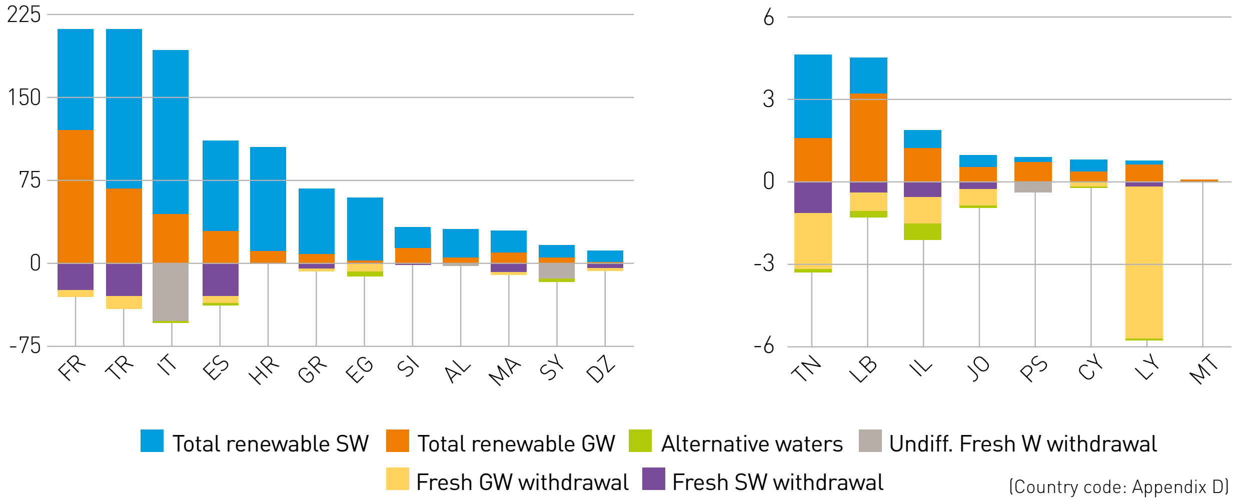

Figure 3.5 | Potentially renewable water resources (positive values) and their official exploitation (negative values) for surface water (SW) and groundwater (GW) in the Mediterranean countries in 10^9 m^3 yr^{-1}. Source: Leduc et al. (2017), based on AQUASTAT database (FAO 2016a). Country codes are: FR France, TR Turkey, IT Italy, ES Spain, HR Croatia, GR Greece, EG Egypt, SI Slovenia, AL Albania, MA Morocco, SY Syria, DZ Algeria; TN Tunisia, LB Lebanon, IL Israel, JO Jordan, PS Palestine, CY Cyprus, LY Libya, MT Malta.

Disastrous flash floods are much more frequent in some parts of the Mediterranean region than in the rest of Europe, affecting mainly the coastal areas, where population and urban settlements are rapidly increasing in flood-prone areas (Gaume et al. 2016). Flash floods and minor floods have increased since 1981 in regions of Italy, France and Spain (Llasat et al. 2013). This increase is mainly associated to non-climatic factors such as increasingly sealed surfaces in urban areas and suboptimal storm-water management systems (Gaume et al. 2016). In the eastern Iberian Peninsula, observations points to an increase in convective and heavy precipitation concentrated in fewer days, consistent with climate change expected for this part of the basin (Llasat et al. 2016) and that could explain the positive trend found in flash floods.

Droughts

In the Mediterranean region the frequency and intensity of drought has increased since 1950 (Seneviratne et al. 2012), but more severe droughts have also been recorded in the past (Quintana-Seguí et al. 2016). Gudmundsson and Seneviratne (2016) and Gudmundsson et al. (2017) suggest that anthropogenic climate change has substantially increased the probability of drought years in the Mediterranean region and conclude that there is medium confidence that enhanced greenhouse forcing contributed to increased drying in the entire Mediterranean region. This is coherent with the increasing length of dry spells observed in the Mediterranean region (Turco and Llasat 2011; Turco et al. 2017; Hoegh-Guldberg et al. 2018).

3.1.3.4 Groundwater

In the Mediterranean area there is a wide range of hydrogeological contexts, aquifer recharge conditions and groundwater exploitation rates. With changing climate and growing scarcity of water, groundwater could act as a buffer during shortages of surface water supply, as aquifers have a high storage capacity and respond with a certain time lag to climatic changes. However, increases in population, rise of living standards, development of irrigated agriculture, and new activities, especially tourism, have drastically increased groundwater depletion in many countries of the regions, and the overall very high rates of withdrawal of groundwater (FAO 2015; GEF 2015). The growing exploitation, favored by many technical innovations, is the most important driver of the change in Mediterranean groundwater resources that have been reduced significantly during the last 50 years, mainly to satisfy agricultural demand, tourism and coastal cities (Leduc et al. 2017). Declining freshwater availability due to groundwater overexploitation over the southern Mediterranean Basin is detectable from large-scale satellite gravity data (GRACE) (Gonçalvès et al. 2013; Rodell et al. 2018).

An additional factor affecting trends is that the intensification of groundwater use for irrigation has occurred without governmental control during decades, affecting both the quantity and quality of the resources (Llamas et al. 2015). In the EU countries the implementation of the Water Framework Directive (WFD 2000) and the specific Directive for protection of groundwater (Directive 2006/118/EC) have helped to strengthen the governmental control for sustainable management of water resources, including groundwater and dependent ecosystem issues (Garrido et al. 2006; de Stefano et al. 2014). Nevertheless, there are frequent cases of extreme overexploitation in which to recover a sustainable use will be difficult (Leduc et al. 2017). In southeastern Spain drawdowns up to several hundred meters have been observed (Custodio et al. 2016). Particularly severe examples are known from Libya, where a very significant drop in water levels due to pumping volumes exceeds renewal resources by nearly one order of magnitude (Wada et al. 2012). *Fig. 3.5* shows the available information about renewable water resources (positive values) and their exploitation in the Mediterranean countries. Despite significant uncertainties (Leduc et al. 2017), there are huge differences between big northern countries and southern countries (Libya and Tunisia). At a country scale, the figure only shows overexploitation for Libya and Tunisia, mainly since the late 1970s (Gonçalvès et al. 2020), although there are aquifers with significant overexploitation problems also in other Mediterranean countries (e.g., Spain).

3.1.3.5 Water quality

Inland water pollution and seawater pollution have different characteristics *(Section 2.3.1)*. Continental water discharging in the sea carries the most dangerous pollutants such as heavy metals, Polychlorinated Biphenyls (PCBs), aromatic hydrocarbons etc. (EPA 2001). Here, the reasons and sources of land-based pollution will be assessed, bearing in mind that 75-80% of the sea water pollution in the Mediterranean Basin is land-based generated (EPA 2001; Civili 2010) *(Fig. 2.21)*.

There are two types of pollution sources, point source and diffuse source. Point sources can be enumerated as untreated municipal wastewater and industrial discharges whereas diffuse sources are generated by irrigated agriculture, with river discharges carrying both point and diffuse sources.

	Urban effluent	Urban solid waste	Industrial effluent	Oil effluent	Chemical toxic product	Coastal eutrophication	Coastal urbanization
Albania	+	+	-	-	+	+/-	+/-
Algeria	+	+	+	+	-	+/-	+
Bosnia and Herzegovina	+	+	-	-	+/-	-	+
Croatia	+	+	-	+ (expected)	-	+	+
Cyprus	+/-	-	+	-	-	-	+/-
Egypt	+	+	+	+/-	-	+	+
Spain	+	-	+	-	-	+/-	+
France	+	-	+	-	-	+/-	+/-
Greece	+	+	+	-	-	+/-	+/-
Israel	+	-	+	+/-	-	+/-	+/-
Italy	+	-	+	+	-	+	+
Lebanon	+	+	+/-	-	-	-	+
Libya	+	+	+	+/-	-	-	-
Malta	+	+/-	+/-	+/-	-	-	+
Morocco	+	+	+	+	+/-	+/-	+
Gaza	+	+	+	-	-	+/-	+
Monaco	-	-	-	-	-	-	+
Slovenia	+	-	+	-	-	+/-	+
Syrian Arab Republic	+	+	+	+	-	+/-	+/-

Table 3.4 | Major environmental problems for water quality along the coastal zone of Mediterranean countries
+: Important problem; +/–: Medium problem; –: Minor problem). Source: EEA (2006).

Table 3.4 summarizes existing major environmental problems for water quality along the coastal zone of Mediterranean countries and shows the spatial heterogeneity of water quality problems. It can be observed that urban effluents are an important problem for all Mediterranean countries with the exception of Monaco.

Inland waters such as lakes and rivers have high importance for drinking water supply. Therefore, monitoring of inland water quality is done with more stringent standards with respect to some parameters that are a constraint for human consumption (e.g., pesticides) (WFD 2006). The European Commission has launched in 2005 an initiative in order to control the most important polluting sources in the Mediterranean (i.e., industrial discharges, urban solid wastes, and urban wastewater), while reinforcing the capacity of non-EU neighboring countries with regard to pollution abatement actions (MSFD 20082008/56/EC).

Transboundary pollution is a severe concern with regard to persistent organic pollutants (POPs) as their transmission can be long distances away from their sources since these are not biodegradable in water but in fatty acids of living organisms and can, thus, enter the food chain *(Section 2.3.3.4)*. In the Mediterranean region, PCBs have been used throughout urban and industrial areas (Pozo et al. 2016). In Italy, for example, PCBs were widely used as insulating fluids in electrical equipment and for many other uses (Breivik et al. 2007). In Europe, lindane usage has been estimated at 287,160 tons between 1950 and 2000 representing 63% of the total world consumption (Vijgen et al. 2011).

In the Mediterranean Sea inputs through rivers and wadis can be relevant during flash flood events, which may represent a significant portion of the yearly input of organic pollutants (Velasco et al. 2006). The total input of polyaromatic hydrocarbons (PAHs), organochlorinated phenyls (OCPs) and PCBs during two flash flood events in the coastal lagoon Mar Menor (Spain) was estimated at 0.98 kg, 1.32 kg and 0.34 kg respectively (León et al. 2017). Emerging POPs contamination has also been studied in the Albufera Natural Park (Spain), a recognized Ramsar site after 1989, where the largest contribution is via the Turia and Jucar Rivers, and also from some major irrigation channels. Emerging POPs, such as Perfluoroalkyl Substances (PFASs) and Organophosphate Flame Retardants were found in multiple environmental compartments of the Albufera wetland introduced mainly from point sources like wastewater treatment plants (WWTPs) and diffuse sources conveyed by the two rivers and irrigation channels (Lorenzo et al. 2019).

Tourism activities lead to water pollution problems as the infrastructure facilities have to comply with an increase of polluting load by 5-fold in many cases, during the summer season (Burak et al. 2004). In several coastal settlements of eastern and southern Mediterranean countries, this issue is a big challenge for the municipal management in the sense that sudden increase in population must receive the corresponding services in good quality in order to sustain touristic activities, which constitute the major income in such cities.

Eutrophication is the result of the enrichment of water bodies with nutrients such as nitrogen and phosphorus compounds which exist mainly in domestic wastewater and industrial wastewater generated by e.g., fertilizer industries and non-point sources generated from agricultural irrigation waters that carry fertilizers rich in nitrogen and phosphorus compounds (see *Section 2.3.4*). The problem emerges when overfeeding of aquatic ecosystems depletes the dissolved oxygen in water during their decomposition (decay) phase. When water becomes euthrophic, change in the initial (baseline) conditions of water quality is perceived to be detrimental and harmful for the ecosystem. Eutrophication causes the degradation of the water quality, which results in negative impacts on living and non-living environment of the receiving water body. This becomes increasingly a threat for receiving water especially in semi-enclosed bays and estuaries, coastal lagoons and deltas having high productivity. Coastal eutrophication is of medium or important significance in 13 Mediterranean countries (*Table 3.4*, *Sections 2.3.3.1* and *4.2.2.1*).

Bacteriological contamination of bathing water in particular is a threat to human health, therefore sea-outfalls have to be designed and operated in order to ensure that there is no adverse impact of pathogen microorganisms on human health. Monitoring of bathing water and the EU Directive EU 76/160/EEC on this subject has been a significant achievement for Mediterranean countries (EEA 2017), either member-state or non-member state since the quality of bathing water is a prerequisite for sustainable tourism, a major income source for all the coastal cities of the Mediterranean region.

Spreading of marine mucilage, which is an aggregate of mucus-like organic matter found in the Mediterranean Sea, is linked to climate-driven sea surface warming. The presence of mucilage makes the seawater unsuitable for bathing because of its smell and its adherence on the skins of the bathers. The mucilage can act as a controlling factor of microbial diversity across oceanic regions and could have the potential to act as a carrier of specific microorganisms, thus increasing the spreading of pathogen bacteria (Danovaro et al. 2009).

3.1.4 Projections, vulnerabilities and risks

3.1.4.1 Impacts of 1.5-2 °C global warming and associated socio-economic pathways on water

Evapotranspiration and soil moisture

Evapotranspiration is an important part of the water balance at the catchment scale, especially for the Mediterranean region where around 90% of the annual rainfall can be lost through evapotranspiration (Wilcox et al. 2003) *(Section 2.2.5.3)*. In the Maghreb region, Tramblay et al. (2018) reported that under RCP4.5, potential evapotranspiration (PET) is projected to increase (+6% to +11%) for 2036–2065 period and (+7% to +14%) for 2066–2095 period compared to historical period (1976–2005), in most areas. The relative potential evapotranspiration increase is the most important during the winter and spring months. Similar projections comparing the Temperature-based PET formula and Penman Monteith equations were reported, which indicate that the main driver of change is the temperature increase. In contrast, the projected changes in actual evapotranspiration in the Maghreb region are negative from -10% up to -35%, under RCP4.5. The strongest decline is observed in spring. This change in actual evapotranspiration is correlated to the decrease in precipitation (Tramblay et al. 2018) *(Section 2.2.5.3)*.

Overall, soil moisture is expected to decrease by the end of this century, with a significantly lower risk at 1.5°C warming as compared to higher levels (Stocker et al. 2013; Lehner et al. 2017). Under RCP2.6 and RCP 6.0 scenarios and global warming by roughly 1.3°C and 2.4°C degrees relatively to the recent past, the European Mediterranean region is expected to exhibit increase in area affected by soil moisture drought by 14.1% and 16.3%, respectively. Most of affected areas are expected to be in Greece, the southern Iberian region (Grillakis 2019) and Mediterranean area of Iberian Peninsula (Savé et al. 2012). Likewise limited to the European Mediterranean (Portugal to Greece) and warming of 1.5°C and 2°C, an increase in soil moisture drought area by 34% and 38% is expected (Samaniego et al. 2018).

A general decline of mean soil water availability is expected at the beginning of the growing season in Sicily, due to the expected reduction of winter rainfall. Higher water stress is likely to reduce the optimal rooting depth, possibly favouring a transition toward shrubs at the expense of forests (Viola et al. 2008). Bioclimatic and evapotranspiration projections for 2070 in Malta, under a RCP 6.0 scenario, show that arable lands of the country would need at least an additional 6 m^3 ha^{-1} day^{-1} of water to make up for the expected increased water loss. The already existent scarcity of surface water supply through reservoirs and ground water is likely to limit the future potential for irrigation, which has critical implications for future crop production (Galdies and Vella 2019).

Runoff

Several studies show that future reduced precipitation, associated with increased evaporation will lead to a decline of runoff in the Mediterranean region (Droogers et al. 2012; Mariotti et al. 2015; Marx et al. 2018; Thober et al. 2018) *(Section 2.2.5.3)*. The median reduction in annual runoff is projected to almost double from about 9% (likely range 4.5–15.5%) at 1.5°C to 17% (likely range 8–25%) at 2°C (Schleussner et al. 2016; Donnelly et al. 2017) and yet higher levels corresponding to stronger warming (Döll et al. 2018; Thober et al. 2018). Overall, these projections are considered robust, since all models of the multi-model ensemble agree on the same decreasing trend (Tramblay et al. 2016).

Marx et al. (2018) found that the Alpine region shows the strongest low flow increase, from 22% at 1.5°C to 30% at 2°C, because of the relatively large snowmelt contribution. For the Mediterranean region, Thober et al. (2018) project significant decreases in high flows of -11% and -13% at 1.5°C and 2°C, respectively, mainly resulting from reduced precipitation.

Several studies have shown a future potential decrease in water resources for the southern Mediterranean region (Tramblay et al. 2013b; Ruelland et al. 2015; Seif-Ennasr et al. 2016; Marchane et al. 2017; Dakhlaoui et al. 2019a, 2019b). The projected decline in surface water in the Maghreb region is significant in winter and spring (Tramblay et al. 2016). In snow-dominated catchments in the Atlas Mountains (Morocco) a stronger climate change signal points to a major decrease in spring runoff associated with reduced snow cover (Marchane et al. 2017). This could have serious consequences since these arid regions depend to a large extent on the water resources provided by the mountain ranges (Tramblay et al. 2016).

Extreme events

Floods

Flood risk, associated with extreme rainfall events, are likely to increase due to climate change, but also due to non-climatic factors such as increasingly sealed surfaces in urban areas and ill-conceived storm water management systems and major exposure and vulnerability in flood-prone regions (Alfieri et al. 2015). Floods also affect the supply of drinking water, because in circumstances of very high flows, sewage treatment plants cannot operate and, usually, pollutants are discharged into watercourses or directly to the sea. In countries such as Spain, where hydroelectric production dams are also used for flood mitigation, the forecast of heavy rains and floods obliges partially to evacuate part of the dammed water, decreasing the energy resource.

There may be important local effects beyond the effects of land use. In a study on the impacts of climate change on floods in central Italy, basins with permeable soils have been found under greater flood risk (Camici et al. 2017). In Sardinia impermeable and flat sub-basins are predicted to experience more intense flood events in future scenarios, while more permeable and steep sub-catchments will have an opposite tendency (Piras et al. 2014). The timing of floods is changing. High flows are expected to occur up to 14 days earlier per decade in the north of Italy, the south of France and eastern Greece, or later (1 day per decade) near the north-eastern Adriatic coast, eastern Spain, the south of Italy and Greece (Blöschl et al. 2017).

There are systematic differences between projections of changes in flood hazard in the south of Europe (Italy, Greece and Iberian Peninsula) in most European and global studies using large-scale hydrological models (Kundzewicz et al. 2017). Flood events with occurrence interval larger than the return period of present flood protections are projected to increase in all continents under all considered warming levels (1.5°C, 2°C and 4°C), leading to widespread increment in flood hazard (Alfieri et al. 2017). A future increase in floods corresponding to a 10-year return level in southern French basins has been projected using the ISBA land surface scheme with different downscaling methods, but with different magnitudes depending on the basins (Quintana-Seguí et al. 2011). Other studies suggest a decrease (Donnelly et al. 2017; Thober et al. 2018). This is due to different climate model types, scenarios and downscaling approaches (*Section 2.2.1.2* and *Box 2.2*), but also the use of large-scale hydrological models often not calibrated and validated for all basins. This type of global (or large scale) hydrological models (LISFLOOD, VIC, HYPE…) is not well adapted to small river basins (<500 km²) which is the typical catchment size found in the Mediterranean region.

In the western Mediterranean, the lower Rhône Basin and the Po catchment, the 100-year flood is projected to mainly increase in height (Dankers and Feyen 2009; Rojas et al. 2012; Dumas et al. 2013). For the upper Soca River in Slovenia, increasing high-flow magnitudes have also been projected as well (Janža 2011). For 2°C warming, river flood magnitudes are expected to increase significantly in Mediterranean Europe except for Bulgaria and southern Spain (Roudier et al. 2016). In contrast, Thober et al. (2018) has identified significant decreases of –11% (-13%) in high flows in the Mediterranean Region at 1.5°C (2°C) scenario, mainly resulting from reduced precipitation.

Droughts

Drought affects both the quantity and the quality of water resources. Enhanced evapotranspiration and reduced rainfall (4% decrease of precipitation per degree of global warming, *Section 2.2.5.2*) both reduce water availability (Baouab and Cherif 2015). In the Mediterranean, water availability could be reduced by 2-15% for 2°C warming, among the largest decreases in the world (Schleussner et al. 2016). Regional climate simulations project (medium confidence) an increase in duration and intensity of droughts in the Mediterranean, by the end of the 21st century, for different kind of drought such as streamflow droughts (Feyen and Dankers 2009; Forzieri et al. 2014; Prudhomme et al. 2014; Giuntoli et al. 2015; Quintana-Seguí et al. 2016), meteorological droughts (Koutroulis et al. 2011) or generally low water availability (Tsanis et al. 2011). Decreased low-flow was also projected by Marx et al. (2018) using a combination of three hydrological models with five climate models and three scenarios (RCP2.6, RCP6.0, RCP8.5). They found a decrease for Euro-Mediterranean areas (France, Spain, Italy, Balkans and Greece) ranging from -12% with +1.5°C warming up to -35% with 3°C warming. Liu et al. (2018) suggest that more urban populations will be exposed to severe droughts in the Mediterranean, and the number of the affected people will escalate further the larger will be the temperature increase.

Basin-scale studies arrive to similar results. Summer low flows are reduced between -15% and -25% for the Jordan River Basin (Smiatek et al. 2014). The intermittent flow regime of the Guadiana River (south of the Iberian Peninsula) may intensify in climate change simulations, according to the JULES land surface model with an ensemble of Euro-CORDEX simulations under RCP8.5 (Papadimitriou et al. 2016). Overall, most studies conducted with hydrological models forced by climate models in different basins, found in future projections an increase of the low flow period during summer, an increased frequency of no-flow events in France (Lespinas et al. 2014), Italy (Senatore et al. 2011; Fiseha et al. 2014; Piras et al. 2014), Spain (Majone et al. 2012), Portugal (Mourato et al. 2015), Morocco and Tunisia (Tramblay et al. 2013a, 2016; Marchane et al. 2017).

Future scenarios are most extreme when both climate and human drivers are considered. For the Durance River in southern France, regulated by large reservoirs, decrease of mean annual renewable water resources has been demonstrated, with a decrease in summer low flows, associated with a greater pressure on water demand (Andrew and Sauquet 2017). For the Mediterranean Basin in southern Europe an increase in discharge intermittency is likely to be exacerbated in the future since large amounts of water are already withdrawn for irrigation purposes (Schneider et al. 2013). For the Ebro (Spain) and Herault (France) basins an integrated modelling framework considering both hydrological processes and water demand has been applied. According to the scenarios built from nine GCM under RCP8.5 it has been found that a future increase in human activities (tourism, agriculture etc.) may have more impact on water demand than climatic changes (Grouillet et al. 2015). To conclude, water demand is already large and may severely increase in the future, in particular in North Africa, and impact water resources, and subsequently low flows (Droogers et al. 2012; Milano et al. 2013).

Projected frequency and magnitude of floods and droughts at the global scale are smaller under a 1.5°C versus 2°C of warming *(medium confidence)* (Hoegh-Guldberg et al. 2018). There is medium confidence that a global warming of 2°C (1.5°C) would lead to an increase of the area at global scale with significant increases in runoff as well as an increase in flood hazard in some regions, as compared to conditions at 1.5°C global warming (present-day condition) (Hoegh-Guldberg et al. 2018). Human exposure to increased flooding is projected to be substantially lower at 1.5°C as compared to 2°C of global warming, although projected changes create regionally differentiated risks *(medium confidence)* (Hoegh-Guldberg et al. 2018). The risks (with current adaptation) related to water deficit in the Mediterranean are high for a global warming of 2°C, but can be substantially reduced if global warming is limited to 1.5°C (Guiot and Cramer 2016; Schleussner et al. 2016; Donnelly et al. 2017).

Groundwater resources

Aquifer recharge is also likely to be affected by climate change. In the semi-arid zone of the Mediterranean, several regions show important reductions in future potential recharge for most of the considered projections. For example, decreases of net aquifer recharge by 12% on average over continental Spain in the horizon 2011-2045 under the highest emission scenario (RCP8.5) are expected (Pulido-Velazquez et al. 2018a). The standard deviation of annual mean recharge is expected to increase by 8% on average in the future, and the spatial distribution of the reduction is quite heterogeneous. Approx. 6.6% of the territory would have reductions of more than 20%, 52.3% of the area would suffer reductions between 10% and 20%, and the reduction would be between 0% and 10% over 40.9% of continental Spain. For some climate models, the simulations predict total recharge increases over the historical values, even though climate change would produce a reduction in the mean rainfall and an increased mean temperature (Pulido-Velazquez et al. 2015).
Overexploitation of groundwater is often the most important factor in lowering of groundwater levels as compared to climate change. In Tunisia, groundwater depletion is projected to reach -28% by 2050 (Requier-Desjardins 2010). Reductions in groundwater recharge and levels, independently of the drivers, might produce significant hydrological impacts, especially in the aquifers with higher vulnerability, as for example coastal aquifers where the salt-water intrusion could be exacerbated (Pulido-Velazquez et al. 2018a).

Water quality

Important challenges to groundwater quality in coastal areas will probably arise from salt-water intrusion driven by enhanced extraction of coastal groundwater aquifers and sea-level rise, as well as from increasing water pollution in the southern and eastern Mediterranean (Ludwig et al. 2010). Serpa et al. (2017), evaluating the impacts of climate change on nutrient and copper exports from a humid Portuguese Mediterranean catchment (São Lourenço), found that climate change could lead to a decline in annual total nitrogen, total phosphorus exports mostly due to a decrease in runoff and erosion induced by a reduction in rainfall, but it hardly affected copper (Cu) exports largely due to its strong immobilization in soils. The changes in water quality varied markedly according to the scenarios considered. A substantial decrease in total nitrogen, total phosphorus and Cu exports was simulated under intermediate scenario A1B (rapid economy growth with balanced energy sources). Under lower emission scenario B1, however, total phosphorus exports decreased much less while total nitrogen exports hardly changed, Cu exports also remained the same (*Sections 2.3.2* and *2.3.3*).

3.1.4.2 Impacts of higher end global warming on water

A number of recent studies of potential hydrological impacts of climate change are focusing on the ambitious warming targets of the Paris Agreement (UNFCCC 2016). Given the current trends in greenhouse gas emissions, the remaining challenges for mitigation and the risk of crossing planetary stabilization thresholds (Steffen et al. 2018), the target of limiting global warming to 1.5°C (and 2°C) is becoming increasingly more difficult to achieve (Mitchell et al. 2018). Higher levels of global warming are associated with significantly increased risks and vulnerabilities in the Mediterranean freshwater resources. The present section deals with the impacts of higher end global warming levels on water variables. Since the majority of climate-change impacts assessments have tended to be framed in terms of future time horizons, rather policy relevant warming level studies (Betts et al. 2018), the context of this assessment is also framed with impact studies using time horizons. These studies consider the high emission scenario RCP8.5 and examine hydrological impacts in time horizons close to the end of the 21st century, given that 80% of the CMIP5 models are crossing the 4°C global level above the pre-industrial period before 2100 under RCP8.5 (see *Section 2.2.4.2*).

Soil moisture

There is high agreement in the degree of change of the soil moisture in the Mediterranean region (*Table 3.5*). High warming scenario RCP8.5 projections for the end of the century (2070–2099) show an overall soil moisture drying pattern, more pronounced in western Mediterranean and mainly in the Iberian part but also in the Aegean and Eastern Mediterranean regions. The already dry regions of Tunisia, Libya and Egypt are projected to be less impacted (Berg et al. 2017). A scenario for 2°C warming relative to the pre-industrial for Mediterranean Europe shows an increase in drought areas with 38.4% of surface area affected and 3.7 months of drought conditions per year (Samaniego et al. 2018).

Region	Soil moisture change (%)
Iberian Peninsula	-6 / -14
Italy	0 / -6
Aegean	-4 / -10
Major emerging changes	-4 / -8
Egypt	9

Table 3.5 | Projected changes (%) of soil moisture for the different Mediterranean regions as indicated in Berg et al. (2017), Ruosteenoja et al. (2018).

Runoff

There is a high level of agreement for decreased discharge of the order of -10% to -50% over the Mediterranean region during the 21st century (Jiménez Cisneros et al. 2014; Schewe et al. 2014). Such reductions in mean discharge have also been found by Koirala et al. (2014) who applied a high-resolution routing scheme on the runoff output from 11 CMIP5 GCMs. In the same study, a significant decrease in high flows (Q5, i.e., flows exceeding 5% of time within a year) and more exaggerated in low flows (Q95, exceeded 95% of time within a year) is foreseen under high-end climate change. Assessments of higher resolution hydrological projections have been made by Betts et al. (2018), Koutroulis et al. (2018) and Papadimitriou et al. (2016) in order to assess hydrological changes at different levels of global warming (1.5°C, 2°C and 4°C relative to pre-industrial), under high-end climate change (RCP8.5). A set of high-resolution AGCM projections has been used to drive a land surface model (Papadimitriou et al. 2017) and simulate regional transient hydrologic responses (Wyser et al. 2016). *Fig. 3.6* shows regional patterns of changes in multi-model mean simulated annual runoff production at different levels of global warming, relative to the 1981-2010 mean runoff states, *Table 3.5* contains the corresponding

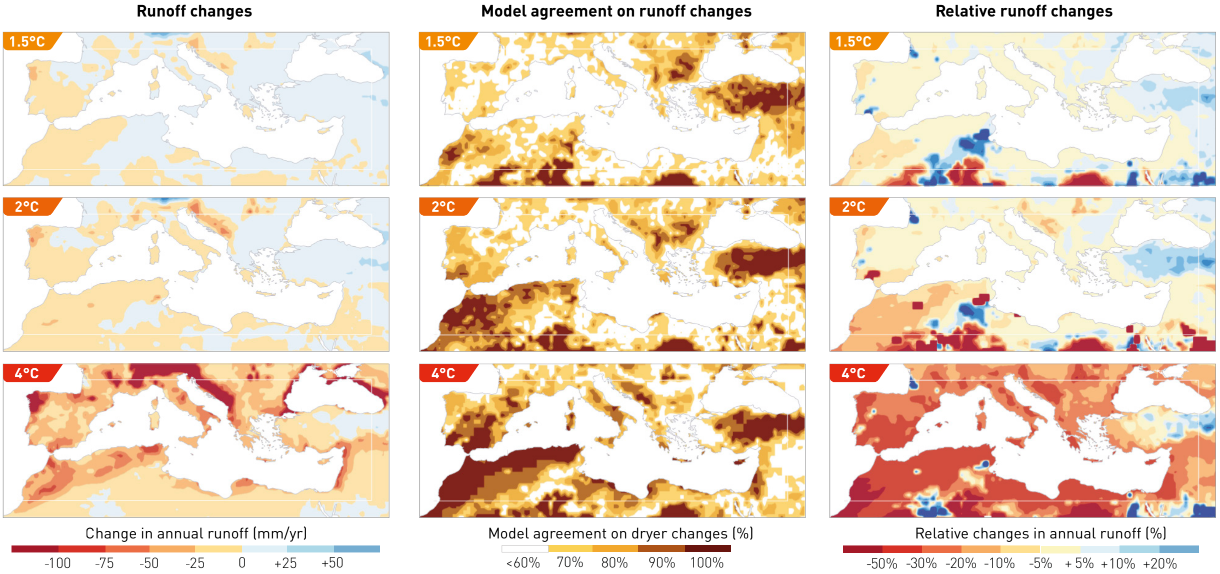

Figure 3.6 | Regional patterns of changes in multi-model mean simulated annual runoff (in millimetres of rain equivalent – left panel, and relative values [%] – right panel) at different warming levels (1.5°C, 2°C and 4°C relative to pre-industrial) relative to the 1981-2010 mean runoff states. The corresponding degree of agreement towards drier conditions in a set of high-resolution climate projections is shown in the middle panel (Papadimitriou et al. 2016; Wyser et al. 2016; Betts et al. 2018; Koutroulis et al. 2018).

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spatially averaged values over the Mediterranean SREX domain.

With global warming level of 4°C above pre-industrial conditions, these high-resolution projections project precipitation to be reduced by a median of 10.4% relative to 1981-2010 (-6.0% to +21.1% between ensemble members). With these precipitation changes, and combined with rising temperatures and thus higher evaporation demand, runoff is expected to be 7.4% less (-4.4% to -21.1% between ensemble members) *(Table 3.6)*. There are large local uncertainties in hydrological impacts, but in most locations, hydrological response indicates drier conditions at 4°C, with an increasing level of agreement between ensemble models.

The severe drying is particularly apparent over the southern Mediterranean, southern and western Iberian Peninsula and France, Italy and south Greece and the Levant, with relative changes

	PRECIPITATION CHANGE						RUNOFF CHANGE					
	[mm]			[%]			[mm]			[%]		
	Median	Max	Min	Median	Max	Min	Median	Max	Min	Median	Max	Min
1.5°C	-2.9	26.4	-37.80	-0.6%	5.5%	-7.8%	1.6	13.4	-11.1	1.3%	10.4%	-8.6%
2°C	-20.1	14.3	-44.69	-4.2%	3.0%	-9.3%	-4.6	11.5	-12.5	-3.6%	8.9%	-9.7%
4°C	-50.1	-28.9	-101.56	-10.4%	-6.0%	-21.1%	-9.8	5.6	-27.3	-7.6%	4.4%	-21.1%

Table 3.6 | Simulated changes in spatially averaged multi-model mean annual runoff (in millimeters of rain equivalent and relative values) at different warming levels (1.5°C, 2°C and 4°C relative to pre-industrial) relative to the 1981-2010 mean precipitation and runoff states. Percent changes are calculated based on the spatially averaged values over the Mediterranean SREX domain (Papadimitriou et al. 2016; Wyser et al. 2016; Betts et al. 2018; Koutroulis et al. 2018).

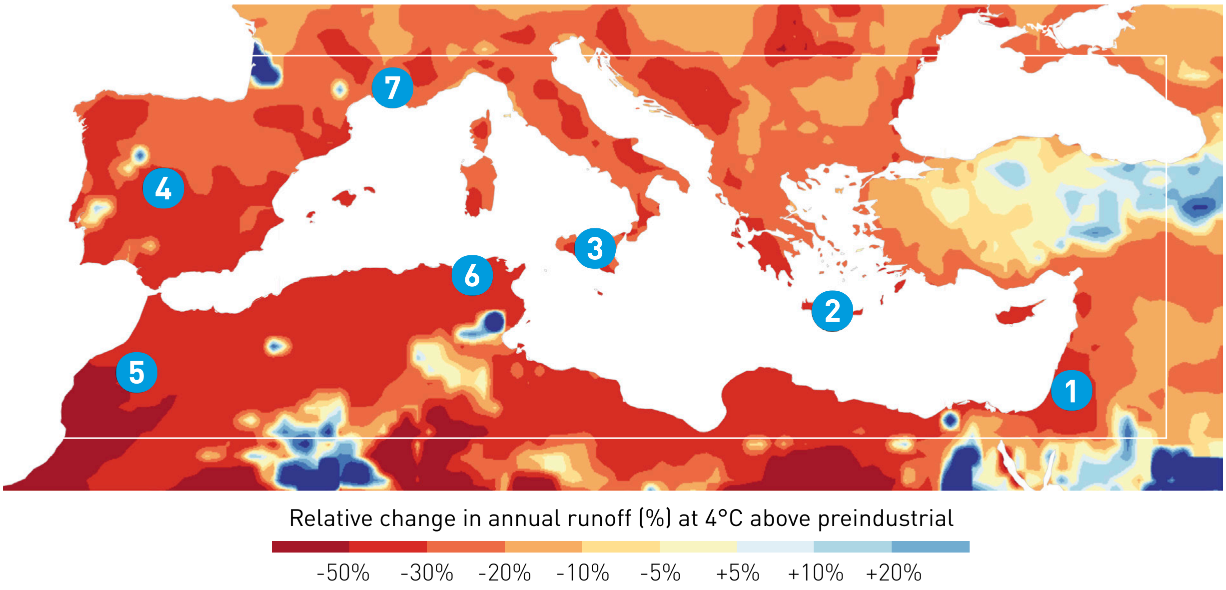

Figure 3.7 | Same as *Fig. 3.6* for the relative changes in multi-model mean simulated annual runoff at 4°C above pre-industrial with the locations of selected basin scale assessments. Source: see *Table 3.7*.

in mean annual runoff up to -50%. Global and regional scale studies show consistent patterns toward a drier Mediterranean, even if different in magnitude. Gaps in the spatial scale of these assessments are covered by a wealth of local and watershed scale studies on the simulated impacts of climate change on runoff and streamflow. Gosling et al. (2017) compared global hydrological simulations with catchment level models for the Tagus Basin and found consistency in the median values and spread of mean runoff between the two ensembles. For 3°C global warming, mean runoff is projected, by both ensembles, to decline by approx. 40% relative to 1980-2010. For high flows (Q5) the projected median decrease is also similar, 28% and 32% between the global and the basin scale multi-model ensembles, respectively. On the other hand, for low flows (Q95) the median decrease is considerably lower (35% vs 50%) as projected by the catchment hydrological model ensemble compared to the global hydrological model ensemble.

Ref. N° Fig. 3.7	Country	Watershed /Region	Size (km^2)	Future/baseline period of reported changes	No of climate models	Relative changes			Reference
						Mean	Max	Min	
1	Israel	Lake Kinneret watershed	800	2050-2079/ 1979-2005	15	-35%	-9%	-51%	*(Givati et al. 2019)*
2	Greece	Crete	8,320	2047-2076/ 1990–2011	5	-27%	-37%	-3%	*(Koutroulis et al. 2016)*
3	Italy	Imera Meridionale river basin	1,782	2080-2100/ 1990-2010	32	-50%	-25%	-80%	*(Viola et al. 2016)*
4	Spain	Tagus	80,000	2071-2100/ 1971-2000	5	-60%	-50%	-75%	*(Lobanova et al. 2016)*
5	Morocco	Rheraya catchment (high Atlas)	225	1979-2005/ 2049-2065	5	-50%	-35%	-65%	*(Marchane et al. 2017)*
6	Tunisia	North Tunisia (5 catchments)	81-315	1970-2000/ 2070-2100	8	-50%	-37%	-57%	*(Dakhlaoui et al. 2019a, 2019b, 2020)*
7	France	Rhône at Beaucaire	98,000	1970-2000/ 2070-2100	8	-17%	-30%	-5%	*(Dayon et al. 2018)*

Table 3.7 | Characteristics and relative changes in runoff and discharge under high-end climate change as reported by a number of recent basin scale assessments. The ref. no is a cross-reference with *Fig. 3.7*.

Basin scale assessments include local scale information and thus can provide detailed impact projections not only in terms of spatial scale but also on plausible developments of local socioeconomic and environmental conditions (i.e., land use changes and human management). A number of recent such studies, listed in *Table 3.7*, project runoff reduction across the Mediterranean, with regionally variable magnitude. The mean and the range of the relative projected changes *(Table 3.7)* are largely comparable with the regional changes simulated by the higher resolution hydrological projections (*Fig. 3.6* and *3.7*).

Extreme events

Floods

Global projections of river flood risk at a 4°C warming indicate that countries representing 70% of the world population and GDP will likely face an increase in flood impact above 500% (Alfieri et al. 2017). Countries of the northern Mediterranean like Italy, France and Portugal belong to this list. For southern Mediterranean countries projections rather indicate an average decrease in impacted population and expected damage at a 4°C above preindustrial levels. In a pan-European study based on Lisflood model simulations of Euro-CORDEX projections, Alfieri et al. (2015) found a general increase in 100-year daily peak flow and in average frequency of peak flow events for the majority of the northern Mediterranean river network, but the projected changes had large uncertainties under high-end climate change. An opposite (decreasing) signal was found for southern Spain caused by an overall reduction in the components contributing to river runoff. Using both socioeconomic and heavy precipitation scenarios for 1.5°C, 2°C and 3°C, Cortès et al. (2019) have demonstrated an increase in the probability of damaging events due to flash floods in the eastern part of the Spanish Mediterranean region that can arrive to be above 60% for an increase of 3°C.

Droughts

Regarding the evolution of drought occurrence, progressively drier conditions may be expected, based on outputs from a variety of studies, from the catchment to the global scale (Orlowsky and Seneviratne 2013; Prudhomme et al. 2014). For the RCP8.5 emission scenario, a significant increase in frequency of droughts is projected by the end of the 21st century for the Mediterranean Basin, where droughts are projected to happen 5 to 10 times more frequently not only for a global warming of 3°C, especially in Northern Africa (Naumann et al. 2018).

Groundwater

The assessment of changes in rainfall recharge in the more pessimistic emission scenarios shows reductions even higher than 55%. The heterogeneity described for the 1.5-2°C global warming scenarios, is expected to increase in higher end warming scenarios (Pulido-Velazquez et al. 2015).

Water quality

Climate change may affect water quality, through changing precipitation, temperature variability, frequency and occurrence of extreme events. For example, floods may result in the contamination of water sources (receiving media) with wastewater and solid waste leachate. Droughts can also affect water quality because lower water flows reduce dilution of pollutants (e.g., organic matter, heavy metals) and increase contamination of remaining water sources (Wilk and Wittgren 2009). Floods, for example, may magnify the risk of contamination in case sewerage network is composed of combined sewers collecting also rainwater. These systems are designed generally with overflow chambers to provide the security of the sewerage network by discharging the surplus water mixed with sewage into the receiving media (e.g., river, lake, sea). Leachate generated at solid waste dumping areas may contaminate water resources with hazardous pollutants disposed in such areas.

Surface waters are threatened by various kinds of point source pollution including municipal sewage discharges, industrial wastewater loads, and nonpoint source pollution from agriculture, inducing a metallic, nutrient and organic pollution, particularly cytotoxic emerging micropollutants, in river waters that can even be used for drinking purposes at a large scale (Etteieb et al. 2016; Khaled-Khodja et al. 2018) *(Section 2.3.3).*

Vulnerabilities and risks in the water-food-energy nexus

Global sustainability is intertwined with freshwater security. The combined dynamics of climate and socio-economic changes suggest that although there is an important potential for adaptation to reduce freshwater vulnerability, climate change exposure cannot be totally and uniformly counterbalanced. In many regions, socio-economic developments will have greater impact on water availability compared to climate-induced changes. However, under a global warming level of 4°C, freshwater vulnerability in the Mediterranean is expected to increase, regardless of the level of adaptation potential as formulated by the different Shared Socio-Economic Pathways (SSPs) *(Section 2.7)*.

Changes in hydrological variables affect the functioning of all economic sectors, especially the food and the energy sector (Fader et al. 2018). For example, reduced river flows lead to large (>15%) declines in hydropower potential as projected for southeastern Europe (Balkan countries) (van Vliet et al. 2015). This, combined with strong increases in water temperature, makes the use of water for cooling purposes more difficult and challenging *(Section 3.3)*.

The agricultural sector will also be severely affected by reduced water availability and increased drought under high-end climate change (van Vliet et al. 2015). Agricultural expansion in the Mediterranean region will be limited by the generally lower levels of productivity and water resources. More frequent and prolonged droughts in combination with heat stress is estimated to be the major limiting factor in crop yields, causing increased crop stress and failure in parts of central and southern Europe, especially in the European Mediterranean (Berry et al. 2017). Policy support will be increasingly important to maintain rural agricultural employment in southern Europe as increasing water scarcity and decreasing land suitability impact production and profitability (van Vliet et al. 2015). The water scarcity pressures are not homogeneous across Mediterranean and local management at the basin level is of crucial importance, but the potential benefits depend on the appropriate multi-institutional and multi-stakeholder coordination (Iglesias et al. 2007) *(Section 3.2.3)*.

3.1.5 Water management and adaptation

Risk, vulnerability and impacts of climate change and other anthropogenic interventions on water resources are not static variables depending only on the strength and characteristics of human interventions. Robust design, construction and operation of infrastructure can alleviate climate-driven hazards (e.g., appropriate location of landfill sites equipped with liner and well-operating on-site leachate drainage system can reduce possible flood-induced contamination of water resources as explained in the above paragraph). This approach can be a no-regret measure for climate change adaptation.

Regulatory frameworks for water quality management vary between and within countries, also in degrees of efficiency. Few legal and regulatory texts directly consider the impacts on water quality (Cross and Latorre 2015). Understanding that different uses require different water qualities provides an opportunity to increase water use efficiency (WUE) by developing an integrated framework regulating water qualities 'fit for purpose', drawing from the wide range of water quality standards and guidelines currently available (UN-Water 2015). Through (water, landscape, land use, etc.) management and adaptation measures, impacts, vulnerabilities and risks may be potentially reduced. This section shortly analyses strategies for management and adaptation in the water domain, divided into two subsections: (i) Integrated Water Resources Management and (ii) adaptation measures (supply and demand-side).

3.1.5.1 Integrated Water Resources Management (IWRM)

Definition, components and link to climate change adaptation

Integrated Water Resources Management (IWRM) has been defined as a "process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment" (Global Water Partnership 2011). The three main principles of IWRM are economic efficiency, equity and environmental sustainability. Based on them, three pillars should be developed: developing management instruments for institutions and stakeholders, establishing an enabling environment that supports IWRM implementation, and putting in place an institutional framework needed for the implementation of policies, strategies and legislation (Hassing et al. 2009). Through management of the resource at the most adequate level, the organization of participation in management practices and policy development, and assuring that the most vulnerable groups are considered, IWRM instruments directly assist communities to cope with climate variability.

There are similarities and differences between IWRM and adaptation to climate change. The main difference between the two is the focus on current and historic issues of IWRM compared to the (long-term) future focus of adaptation. Water management systems design has been based on historical climate and hydrological data assuming stationarity of systems behavior (Ludwig et al. 2014). However, future changes in the climate system no longer allow for such assumptions and historical data are no longer sufficient as the only source of information to plan for variability and extremes (Milly et al. 2008; Ludwig et al. 2009). Thus, climate change impacts will require new approaches to guarantee sufficient water resources and also to ensure that current investments will not become obsolete. In the Mediterranean Basin, where water distribution is uneven in time and in space and some regions suffer from structural drought, appropriate planning and management considering climate change impacts is the key issue. IWRM is increasingly viewed as comprising the best available framework for building the resilience needed to adapt to climate change. Any deficiency in pertinent decision-making process may result in severe shortfalls in the water management system, which may have adverse impacts on resource availability, including water supply.

Uncertainty management is crucial for the water sector given the marked inertia, which prevails as a result of the predominance of the long-term sectoral planning timeframes and in the lifespan of investments (de Perthuis et al. 2010). Many decisions relating to water, including adaptation, are sensitive to uncertainty and imply a particularly high risk of "maladaptation" when certain solutions are excessively structured or proven rather rigid (Plan Bleu 2011). However, the uncertainty surrounding impact and risk assessment should not be seen as hampering action. On the contrary, it should encourage the emergence of a dual approach: "no regret" actions and adaptation.

A challenge for implementing IWRM or adaptation measures is assuring the coverage of investment costs and long-term funding for functioning. Public-private partnerships (PPPs) can be an adequate approach for the implementation of some of the measures. This financial approach can be applied for example for local and targeted projects (IPEMED 2018), and for the construction and operation of "centralized" wastewater treatment plants (WWTP), that require a significant technical and financial support (e.g., the As-Samra WWTP that was built according to the Build-Operate-Transfer model over 25 years in Morocco). Although PPPs are developing, they remain marginal in medium-sized cities and almost non-existent in peri-urban and rural areas, especially in southeastern Mediterranean countries.

3.1.5.2 Adaptation measures

The existence of uncertainties in the evaluation of future climate change impacts (Pulido-Velazquez et al. 2018b) should not be an excuse for delay or inaction in the analysis and implementation of adaptation measures, especially in the Mediterranean region, which has been identified as one of the most vulnerable areas (Milano et al. 2013). However, due to these uncertainties, adaptation must be flexible, and adopt a comprehensive approach, considering not only climate change, but also other potential socioeconomic and environmental changes (UN 2009). The impacts will affect the private (for example irrigation communities), and the public (e.g., environmental impact, quality, and supply reliability) context. For this reason, the market for technologies for adaptation to climate change grows rapidly, given that "the cost of repairing damages is estimated to be 6 times greater than adaptation costs" (H2020WATER-2014/2015, Part 12 - Page 23 of 76).

Different approaches are applied to define adaptation scenarios. In a "top-down" approach, adaptation scenarios are developed based on expert criteria that considering the assessment of potential physical vulnerability obtained by simulating/propagating future potential scenarios within a modeling framework. Examples of application of this procedure can be found in many Mediterranean systems. Pulido-Velazquez et al. (2011) and Escriva-Bou et al. (2017) show that the systems are vulnerable to future climate change scenarios and suggest different adaptation strategies, for example, demand management alternatives or the introduction of complementary resources (additional pumping or water transfer), which can save important quantity of money (3-65 million € yr^{-1} in the Jucar Basin). "Bottom-up" approaches include definition of scenarios through participatory processes assessing social vulnerability (Culley et al. 2016). In this case, seminars are designed to involve the main stakeholders in the process of defining the adaptation scenarios. There are also combinations of both approaches (Brown et al. 2012; Girard et al. 2015), integrating the advantages of both of them (Serra-Llobet et al. 2016).

Adaptation measures can also be classified in measures on the demand side and on the supply side of water resources. The first group has the aim of control water demand and use through for example efficiency management, modernization in irrigation (Sanchis-Ibor et al. 2017), and application of economic instruments (prices policies, markets and subsidies) to reduce demand. In the group of measures on the supply side, we observe measures oriented to obtain complementary resources (water reuse, desalination, water transfers, etc.), measures to improve allocation and availability of water resources (for example building new small dams or channels), and conjunctive strategies, including Management Aquifer Recharge techniques.

Supply-side adaptation measures

In this section we include a short introduction to desalination, wastewater treatment and reuse, artificial recharge of groundwater, inter-basin transfer, dams and virtual water trade.

Desalination

The conversion of seawater or saline groundwater into drinking water increasingly provides a source of potable water in almost all Mediterranean countries, particularly in the eastern basin, the Arabian Peninsula and North Africa. Of the currently almost 16,000 operational desalination plants that are found in 177 countries, about half are located in the Middle East and North Africa region (Jones et al. 2019). In the Mediterranean Basin, desalination capacity has increased over the last few decades and the production of desalinated seawater in the MENA region is projected to be thirteen times higher in 2040 than 2014, the most advanced countries being presently Algeria, Egypt, Israel, Italy and Spain (UNEP/MAP and Plan Bleu 2020). Given the anticipated increase in demand as a result of growing population pressures in most Mediterranean countries on the one hand and diminishing supply resulting from precipitation decreases due to climate change, seawater desalination as an alternative source of (drinking) water will grow in importance for the region.

Desalination technologies fall into two basic groups and involve either (Younos and Tulou 2005):

- a phase change process of the water-salt mixture through the boiling of feed water; the evolving steam is subsequently cooled and condensed, leaving salts, minerals and pollutants in a highly enriched brine solution, which is separated from the clean condensed water; or
- the employment of semi-permeable membranes to separate the solvent or solutes from the water by including pressure, electric potential, and concentration to overcome natural osmotic pressures and effectively force water through the membrane, leaving all substances other than water behind.

For each group a number of different technologies have been developed (Miller 2003; Younos and Tulou 2005; Khawaji et al. 2008). Common to all of these technologies are a number of challenges. Most of them are relatively energy intensive, which is mainly due to the need for extensive pretreatment and post-treatment steps, implying a strong correlation between electricity prices and the price for the water produced (Semiat 2008; Elimelech and Phillip 2011). Utilizing conventional, hydrocarbon sources for electricity production results in the emission of air pollutants and greenhouse gases that further exacerbate climate change (Elimelech and Phillip 2011). The impingement and entrainment of marine organisms associated with the seawater intake of a desalination plant represents a further disadvantage (Elimelech and Phillip 2011). The discharge of high-salinity brines as well as of the chemicals used in the pretreatment and membrane-cleaning protocols into the sea adjacent to a desalination plant adversely affects near coastal marine ecosystems and represents an environmental problem that is increasingly recognized (Lattemann and Höpner 2008; Elimelech and Phillip 2011; Missimer and Maliva 2018; Jones et al. 2019).

Addressing particularly the first two challenges, there have been numerous efforts to improve existing technologies (Khawaji et al. 2008; Shannon et al. 2008; Elimelech and Phillip 2011; Subramani and Jacangelo 2015). More experiments and field monitoring are needed to assess adverse impacts of brine discharge from desalination into the ocean (Elimelech and Phillip 2011).

New solutions have been proposed, particularly with regard to the high demand for energy for desalination (Papanicolas 2010; Lange 2013, 2019; Georgiou et al. 2016). In this regard, utilizing renewable energies for desalination appear to be particularly promising. Given the environmental conditions in the Mediterranean Basin, solar energy appears to be the most suitable alternative related to other renewables (Li et al. 2013). Solar desalination can be achieved either directly by coupling a solar collector with a distilling mechanism through a one-stage cycle (García-Rodríguez 2003; Kalogirou 2004; Qiblawey and Banat 2008) or indirectly by connecting a conventional distillation plant to a solar thermal system (Eltawil et al. 2009; Li et al. 2013). It is also possible to combine electricity production with seawater desalination by utilizing concentrated solar power (CSP) (El-Nashar 2001; Trieb and Müller-Steinhagen 2008; Papanicolas et al. 2016). While these technologies offer the advantage of providing "clean" electricity and potable water from one plant by utilizing cost-free solar energy in regions were solar radiation is plentiful and water availability is scarce, there are a number of significant challenges including the requirement to improve existing technologies, the relatively high capital cost to build such plants, the need to build CSP plants close to the sea, where prices for land are usually particularly high, adding to the aforementioned capital cost, and the risk of enhanced corrosion of the plant's technical installations through sea spray and relatively high dust loads that reduce the efficiency of the CSP mirrors.

Despite these challenges, solar technologies in general and the co-generation of electricity and potable water in integrated CSP plants, in particular, appear as a viable alternative to conventionally driven seawater desalination (Lange 2013; Georgiou et al. 2016; Papanicolas et al. 2016; Bonanos et al. 2017). Seawater desalination thus clearly represents an adaptation measure to reduce (potable) water scarcity in arid and semi-arid Mediterranean countries. Desalination capacity in the Mediterranean is increasing. While promising new (solar) technologies are being developed, they still have their drawbacks and need to prove their economic feasibility. Importantly, operators will have to deal with the environmental repercussions of desalination and significant adverse impacts on near-coastal marine ecosystems (Missimer and Maliva 2018; Jones et al. 2019).

Wastewater treatment and reuse

The volume of wastewater produced in southern and eastern Mediterranean countries (SEMCs) was estimated at 8,134 km³ (with the exception of Israel), which makes it a valuable source with regard to its quantity (IPEMED 2018). In order to reuse wastewater, the first requirement is to have access to sewerage network connected to wastewater treatment plants (WWTPs) and network for reuse complying with the corresponding standards (IPEMED 2018). Not all effluent qualities match with the required reuse. According to the World Bank (2019)[10], 90 and 97% of Mediterranean populations (south-east and European Mediterranean, respectively) had improved access to sanitation services in 2015. However, these figures do not mean that there is available treated effluent for reuse. The situation is complex with regard to efficient interception of the sewage and treatment. Although in coastal urban areas, sewerage network is satisfactory, in general, in inland areas, less developed settlements have poor sanitation networks, with often leaking septic tanks, combined sewer system with overflow structure, illegal connection to streams etc. (EPA 2001; IPEMED 2018).

Fig. 3.8 shows the sectors in which treated wastewater can be reused (Lautze et al. 2014). Agricultural, industrial and watering activities present together approx. 70% water reuse potential. The heterogeneity of goals connected to reuse of wastewater shows that the quality of the treated water may differ for end-users accordingly. Most importantly, reclaimed water use practices are finding more users as a reliable alternative and low-cost resource in line with improved treatment technologies and standards in parallel with awareness raising campaigns with regard to cultural and social acceptance. Israel and Jordan have a leading role in SEMCs with a reuse rate of over 85% of their collected wastewater. Cyprus and Malta have high levels with 90% and 60%, respectively, of their treated wastewater re-used.

Wastewater reuse should be considered not only as a reduction of losses, but also as an improvement of water quality and a change in water fluxes inside a watershed, in accordance with the principles of circular economy. For example, grey water reuse, as partial recycling inside the buildings comprises flushing water for toilets from recirculated wastewater that has been treated. Introducing this system is recommended in newly constructed, smart buildings in Istanbul (Turkey). Some research work is being carried out in residences in order to work out the conversion of grey water into water source for flushing in some new buildings at planning level.

Artificial recharge of groundwater

Groundwater, which underlies most of earth's surface, represents one of the most important sources of freshwater. It is protected from evaporation by the overlying soil cover and is naturally replenished/recharged by percolation of surface water and during precipitation events. Percolation through the soil reduces impurities and thus improves water quality (Racz et al. 2012). Being protected from evaporation, groundwater resources are also less sensitive to annual and inter-annual rainfall fluctuations than surface water (Giordano 2009). For these reasons, aquifers with high mean residence time can play a significant role as buffer values to reduce the impacts of meteorological droughts (Foster et al. 2017).

Many groundwater aquifers in the Mediterranean, particularly in the eastern basin, are overexploited by groundwater extraction that exceeds surface water extraction (FAO 2016a; Jódar-Abellán et al. 2017). Satellite observations confirm these trends

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[10] https://donnees.banquemondiale.org/indicateur/SH.STA.BASS.ZS

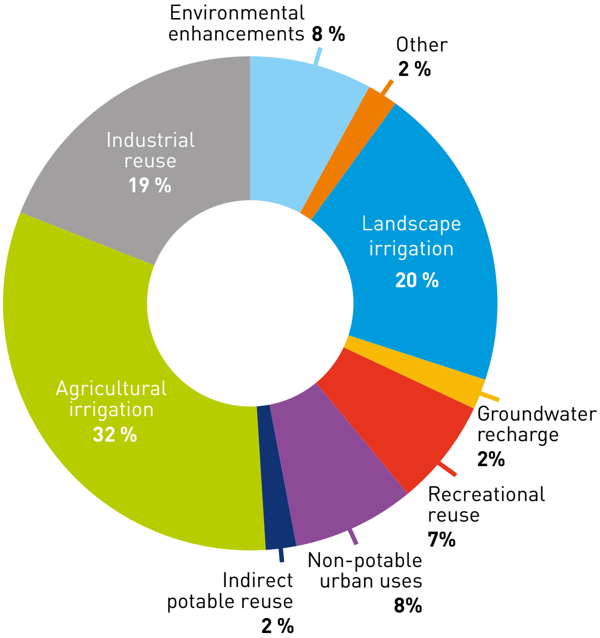


Figure 3.8 | Potential wastewater reuse per sector (Lautze et al. 2014).

(Voss et al. 2013; Rodell et al. 2018). In order to mitigate groundwater depletion, artificial recharge of aquifers has been used worldwide since the 1960s and 1970s (de Giglio et al. 2018). For this purpose, surface water has been pumped underground in order to re-fill the aquifer. More recently, more efficient techniques have been developed, referred to as Managed Aquifer Recharge (MAR) (de Giglio et al. 2018). These techniques include the use of treated waste water or saline water for aquifer storage and recovery (Foster and Chilton 2004; Koussis et al. 2010; Maliva et al. 2011; Djuma et al. 2016), building underground dams (Nilsson 1988; Onder and Yilmaz 2005; Chezgi et al. 2016), using groundwater in combination with other sources to minimize its usage and implementing water saving technologies (Giordano 2009), and groundwater recharge by check dams (Hashemi et al. 2015; Steinel et al. 2016).

The recharge of groundwater aquifers with treated wastewater is often seen critical because of potential water quality problems. Application of this technique is therefore often restricted by regulatory authorities and lacks public acceptance (Kazner et al. 2012). Nevertheless, it is used to counter seawater intrusion in order to maintain heavily exploited coastal aquifers (Koussis et al. 2010). For example, in Tunisia a Treated Waste Water (TWW) recharge in the aquifer in order to counter its salinization due to seawater intrusion and pollution due to agricultural activities has shown a reduction in groundwater salinity. Contamination by nitrate and bacteria remained a major problem of the aquifer (Cherif et al. 2013). In Israel a tertiary treated wastewater was used for the recharge of an aquifer during a 300 days experiment. The resulting water met irrigation standards with unrestricted use since no bacteriological contamination was found in the aquifer (Idelovitch 1978). This technique not only allows the exploitation of a high amount of non-conventional water resource that is TWW, but also enables the remediation of over-exploited aquifers by increasing the water table level, and its relative quality.

A less frequently applied technology is the use of underground or subsurface dams, which are claimed to enable management of groundwater in a more sustainable manner (Onder and Yilmaz 2005). Underground dams represent subsurface barriers across a stream and can be compared to check dams or sand-storage dams (Nilsson 1988; Onder and Yilmaz 2005). The construction of subsurface dams restricts the natural groundwater flow of the system and enables the storage of water below the surface. Such dams can contribute to meet demands during droughts or heavy irrigation periods (Nilsson 1988). This is often used in near-coastal situations, where groundwater would otherwise be discharged into the sea and lost for utilization. Similarly, subsurface dams are being employed in restricting saltwater intrusion into coastal aquifers.

Recharge check- or sand-storage dams represent barriers that are placed across a river or channel to slow the movement of water, encouraging groundwater recharge (Djuma et al. 2017a). Various materials have been used to build the barrier (Onder and Yilmaz 2005). Recharge behind the check dam depends on the build-up of sediment. More specifically, a growing layer of sediment reduces the volume of stored water that eventually recharges underground aquifers. Sediment accumulation is a result of riverbank erosion or erosion in the upstream watershed area. This is affected by land use, climate, topography and soils (Abedini et al. 2012; García Lorenzo et al. 2013; Djuma et al. 2017a, 2017b). Only few studies quantify the groundwater recharge efficiency of check dams. Djuma et al. (2017b) applied a water-balance approach for the Peristerona, an ephemeral river located on the northeastern hill slopes of the Troodos Mountains, Cyprus. They found that check dams can be valuable structures for increasing groundwater resources in semi-arid regions.

Inter-basin transfers

The movement of water through artificial conveyance schemes between river basins is called inter-basin transfer (IBT). IBT is mainly employed in order to ease water shortages in the receiving basin and can be traced back to ancient times (Shiklomanov 1999; Gupta and van der Zaag 2008; Pittock et al. 2009; Boddu et al. 2011). Ever since dams have been built during the last half of the 1900s more than 364 large-scale inter-basin water transfer schemes have been established (Pittock et al. 2009). These IBTs transfer around 400 km^3 of water per year (Shiklomanov 1999) and are considered viable solutions to meeting escalating water demands in water scarce regions. Pittock et al. (2009) estimate that the total number of large-scale water transfer schemes may rise to between 760 and 1240 by 2020 and will transfer up to 800 km^3 of water per year (Shiklomanov 1999).

While potentially solving water supply issues in regions of water shortage, IBTs have significant social and environmental costs usually for both the river basin providing and the river basin receiving the water (Pittock et al. 2009). The large scale of most IBTs usually renders them expensive and thus economically risky. From an environmental point of view, IBTs interrupt the connectivity of river systems and therefore disrupt fish spawning and migration. Natural flow regimes are usually altered, sometimes with great ecological cost to threatened aquatic species or protected areas. IBTs often also modify river morphology and contribute to salinization. Finally, IBTs may also enable the transfer of invasive alien species between river basins. Short, medium and longer-term impacts of moving water from one community (the donor basin) and providing it to another (the recipient basin) are often overlooked in IBT development (Pittock et al. 2009). This may lead to controversies and conflict.

In the Mediterranean Basin, Spain has a long history of water transfers and one of the largest systems of IBTs. Despite general agreement among the main water decision-makers and stakeholders on projects and plans regarding water distribution and management, several factors have thrown this old system into crisis (Hernández-Mora et al. 2014). The Ebro inter-basin transfer, which was the main project of the Spanish National Hydrological Plan, was initiated because of pervasive pressures, scarcity, and degradation of southeastern basins in Spain (Albiac et al. 2006). The project caused heated political debates, and ultimately failed due to difficulties in achieving a sustainable management of water resources, which was caused by conflicting interests of stakeholders and regions. Hernández-Mora et al. (2014) conclude that currently no technical, territorial, political, or social agreement exists on how to allocate water in Spain despite significant public and private investments in water supply infrastructure. These challenges, while depicted for Spain, are of a more general nature and can be seen in other countries of the Mediterranean Basin as well (Donta et al. 2008). They include increasing interregional conflicts and water allocation demands, the appearance of new water users who challenge the long-term privileges of large historic water holders, and a lack of understanding of water scarcity as a risk to be managed, not as a geophysical imbalance or a structural hydrological deficit (Hernández-Mora et al. 2014).

Water transfer projects have also played a major role in Turkey (Karakaya et al. 2014). The 25 main watersheds of Turkey have distinct characteristics regarding their water potential, their economy, culture, and demography. Since some of them do meet growing, but also conflicting water demands, inter-basin water transfer projects have been planned and implemented. IBTs in Turkey primarily supply water to watersheds that contain big cities, major industries, and significant agricultural activities (Karakaya et al. 2014). While water resources in Turkey are considered state property, their utilization is guaranteed for any user. Conflicts nevertheless arise between different donor/source and receiver/user basins as well as between various water consumer groups. Economic costs in the source basins have partly been met through financial compensations, and/or transfer of wealth associated with use of water resources from the user basins to the source basins. In order to address short- and long-term socio-economic implications of inter-basin water transfers, integrated assessments and specific studies are needed (Karakaya et al. 2014).

In Cyprus, groundwater was the main source of water supply for both drinking and irrigation until the 1970s. This resulted in almost all aquifers being significantly depleted because of overpumping. Seawater intrusion was observed in most of the coastal aquifers. Population increase, as well as rising numbers of tourist arrivals on the island exacerbated this problem. Already in the early 1960s, Cyprus engaged in a program to build dams to enable the collection of rainwater in surface reservoirs (see next subsection). While this somewhat eased the supply shortage of irrigation water to the agricultural sector, the gradient in precipitation values from relatively copious amounts in the central and western part of the island versus

Figure 3.9 | Example for a large-scale IBT project is the Southern Conveyor Project on the island of Cyprus (Water Development Department Cyprus 2000).

the eastern regions of Cyprus required additional measures (Nikolakis 2008). This led to the implementation of the Southern Conveyor Project, which was seen as a necessity and a basic prerequisite for the further agricultural and economic development of the island (Water Development Department Cyprus 2000). The Southern Conveyor Project is the largest water development project ever undertaken by the Government of Cyprus *(Fig. 3.9)*. Its main objective is to collect and store surplus water flowing to the sea and convey it to areas of demand. Major components of the project, aside from the pipeline transporting the water to the east, are the Kouris Dam in south-central Cyprus, river diversions and underground tunnels. The project aims at the agricultural development of the coastal region between Limassol and Famagusta, as well as to meet the domestic water demand of Limassol, Larnaca, Famagusta, Nicosia, a number of villages and the tourist and industrial demand of the southern, eastern and central areas of the island (Water Development Department Cyprus 2009). The project area extends along the southern coast, between the Dhiarizos River in the west and the Kokkinokhoria irrigation area in the east *(Fig. 3.9)*.

Large-scale IBTs are often seen as a technical solution to restore perceived imbalances in water distribution between neighboring basins. However, the disadvantages and pitfalls that often accompany such infrastructures cast doubts on the ultimate usefulness of IBT (Pittock et al. 2009). While providing irrigation water to agriculture, IBT can also be considered to promote unsustainable and subsidized cropping practices. In planning, implementing and constructing IBTs, alternatives to the IBT that may mean delaying, deferring or avoiding the costs (in every sense) of an IBT are often overlooked or omitted. In addition, poor to non-existent consultation with affected stakeholders frequently characterizes IBT development. Finally, sufficient and adequate consideration to the environmental, social and cultural impacts of the IBT, in both the donor and recipient basins are often neglected.

Dams

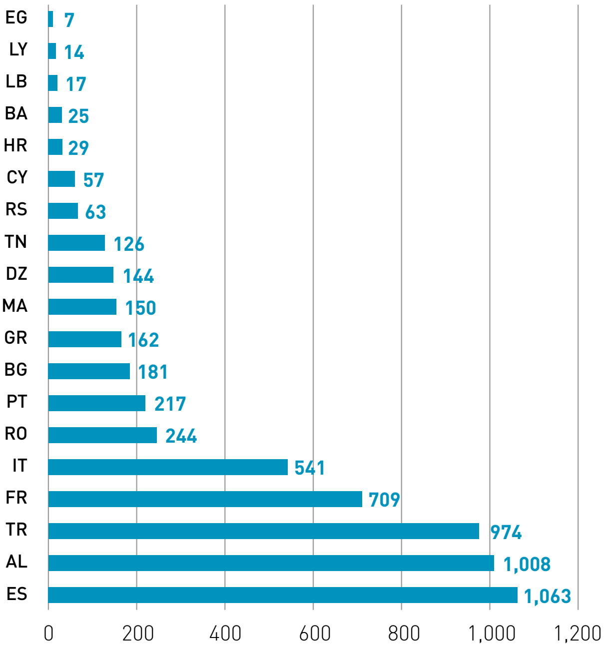
Freshwater flowing into the sea is “water lost” to arid and semi-arid countries. Reservoirs and dams play a crucial role in water resources management, but also in flood abatement, mitigating the adverse effects downriver from these structures (Sordo-Ward et al. 2012, 2013). Dams are thus built to store water, but also to divert rivers so that the bulk of their water can be used by various consumers. Dams also serve as major elements of hydropower generation in several large Mediterranean rivers.

The first evidence for dam building dates back to the early and middle Bronze Age (2,500–1,600 BC). One of the oldest records of dam building are found in the ruins of the Saad el Kafara dam near Cairo indicating that it was built in around 3,000 BC (Water Development Department Cyprus 2009). Roman dams were the first that were used to create reservoirs of fresh water to secure a permanent drinking water supply for urban settlements over the dry season, and also the first to introduce dam-construction types that are being used until today (Schnitter 1978, 1987; Hodge 2000). Throughout the following millennia, relatively little progress was made and it was not until the 19th century when engineering skills and construction materials available were capable of building the first large-scale arch dams. The era of building large dams was initiated by the construction of the Aswan Low Dam in Egypt in 1902 by the British.

The abatement capacity of a dam depends on the hydrologic load, the dam and reservoir characteristics, the existing operational rules, the volume to abate and other foreseen uses related with socioeconomic activities, which in some cases may lead to conflicts. Those conflicts are particularly important in those dams that are multipurpose, usually involving flood control and other purposes such as hydropower, ecological discharges, water supply or irrigation, which may be in conflict (Labadie 2004; Dittmann et al. 2009; Bianucci et al. 2013). To reduce conflicts, the decision-making process can be improved by applying a combined approach, including simulation of predefined rules (modeling without considering any inflow forecast) and optimization programming (i.e., from stochastically generated floods or flood forecasting), taking into account the different purposes through indices such as minimizing the expected deficit of water availability (for a certain purpose), or maximizing the reliability of satisfying downstream requirements (Bianucci et al. 2015). In all cases, to minimize the conflict between consumptive demands and flood abatement, the participation of users is crucial (Martín Carrasco et al. 2007). A final consideration refers to the use of meteorological forecasting to improve dam management in Mediterranean context. As the flood events are relatively short (fast response basin) and are usually due to heavy precipitation, short-term forecasting facilitated by the combination of mesoscale models and radar imagery is needed, while to manage droughts or water resources for irrigation, seasonal forecast gives substantial added value (Marcos et al. 2017).

Large dams are defined to be of at least 15 m in height, impounding more than 3 million m^3 of water (ICOLD 2019). In the Mediterranean Basin, the World Register on Dams lists 5,731 dams (ICOLD 2018), both single- and multi-purpose dams. In both, the single- and the multi-purpose dams, irrigation stands out as the most frequent purpose for dam building (50% and 24%, respectively), followed by hydropower *(Fig. 3.10)*.

Many North African countries, particularly Algeria, Egypt, Libya and Morocco, but also other Mediterranean countries including Cyprus, rely on dams and reservoirs to provide irrigation water (AQUASTAT Programme 2007; Water Development Department Cyprus 2009). While the importance and benefits of dams for the provision of water and hydroelectric power for many of the Mediterranean countries is obvious, there are a number of adverse impacts that need to be considered (Scudder 2006; Tortajada et al. 2012).



(Country code: Appendix D)

Figure 3.10 | Number of large dams in Mediterranean countries (ICOLD 2018).

The reservoirs created by a dam affect many ecological aspects of a river. The impacts of large dams on ecosystems, biodiversity and downstream livelihoods have been debated for many year and include the loss of forests and wildlife species and habitats, due to inundation, and the loss of aquatic biodiversity of upstream and downstream fisheries, amongst others (World Commission on Dams 2000).

On balance, the ecosystem impacts of practically all dams are considered more negative than positive, but enhancements of ecosystem values through the creation of new wetland habitat and the fishing and recreational opportunities provided by new reservoirs have also been observed. Most efforts to counter the ecosystem impacts of large dams have had limited success. This has led to increased attention to legislation aimed to avoid or minimize ecological impacts. This includes setting aside particular river segments or basins in their natural state and the selection of alternative projects, sites or designs (World Commission on Dams 2000).

The impacts of dam building on people are also significant (Scudder 2006; Tortajada et al. 2012). In many cases, dam construction requires the state to displace individual households or entire communities in the name of the common good, leading to hardships and conflicts. In some cases, these negative effects have not been assessed nor accounted for by the relevant authorities. In addition, large dams frequently cause significant adverse effects on cultural heritage through the loss of cultural resources of local communities and the submergence and degradation of plant and animal remains, burial sites and archaeological monuments. The World Commission on Dams (2000) concludes that the poor, other vulnerable groups and future generations are likely to bear a disproportionate share of the social and environmental costs of large dam projects without gaining a commensurate share of the economic benefits. Nevertheless, if this report is cited in the context of negative impacts, Schulz and Adams (2019) conclude that neither the impacts nor the controversy over large dams have ended.

Virtual water trade

Water (or any other resource) scarcity produced through an imbalance between demand and supply, leads to price increases or negative consequences for the sectors and stakeholders that need that resource. This, in turn, typically induces several societal adaptation mechanisms, such as increased efficiency through technological development, and the opportunity to import water-intensive products from other markets. More difficult is the import of the large water volumes required for local food production due to its weight and bulkiness. The strategy of trading the commodities that would be produced with the lacking water is called "virtual water trade" and can be considered an adaptation option. "Virtual water" (VW), as defined by Allan (1998), is the volume of water used to produce a good in the various steps of the production chain. Agricultural commodities require large amounts of water from rainfall (green water) or from freshwater resources (rivers, lakes, reservoirs, canals, etc.) (blue water) (Fader et al. 2011). The third main component of the anthropogenic water cycle is grey water, defined as water released from those activities, generated in households or office buildings from streams without fecal contamination, i.e., all streams except for the wastewater from toilets affected by the consequent degree of pollution. The trade of any commodity, but in particular of agricultural ones, is associated with a virtual transport of the green and blue water used and the grey water generated for their production (Hoekstra and Chapagain 2008). Water footprints (WFs) are the other side of the medal, indicating how much water (virtual or real) a country needs to produce the products consumed by its population.

Virtual water trade, even if widely disputed as it neglects fundamental strategic and national security issues (Fader et al. 2013), supports global food security (Merett 2003). Not only the trade of water embedded in agricultural products has gained the attention of scholars and media, but also the phenomena of "appropriation" of resources across the globe has emerged under the label of "land grabbing", i.e., large-scale acquisition of farmland in developing countries by international investors (privates of sovereign funds). Scarcity of water, food and biofuels may partially drive the international trade of commodities, or otherwise stimulate the direct acquisition of resources where they are with a phenomenon, which is currently in the order of tens of million hectares (Land Matrix Initiative)[11]. It has been argued that this phenomenon should be better named as water grabbing, since water is the resource that lacks and drives the acquisitions, more than land (Johansson et al. 2016).

Hoekstra and Mekonnen (2012) calculated and mapped the green, blue and grey water footprints. They assessed both national footprints and the international virtual water flows deriving from trade of agricultural and industrial commodities. According to their analysis, most countries of the Mediterranean Basin and the Middle East are hotspots of virtual water imports *(Fig. 3.11)*. Countries such as Portugal, Spain, Italy, Greece, Israel and Turkey are among those with the highest WF of national consumption (above 2,000 m^3 yr^{-1} $capita^{-1}$) (not shown). Hoekstra and Mekonnen (2012) also found that cereal products have the largest contribution to the WF of the average consumer (27%), followed by meat (22%) and milk products (7%).

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[11] https://landmatrix.org/

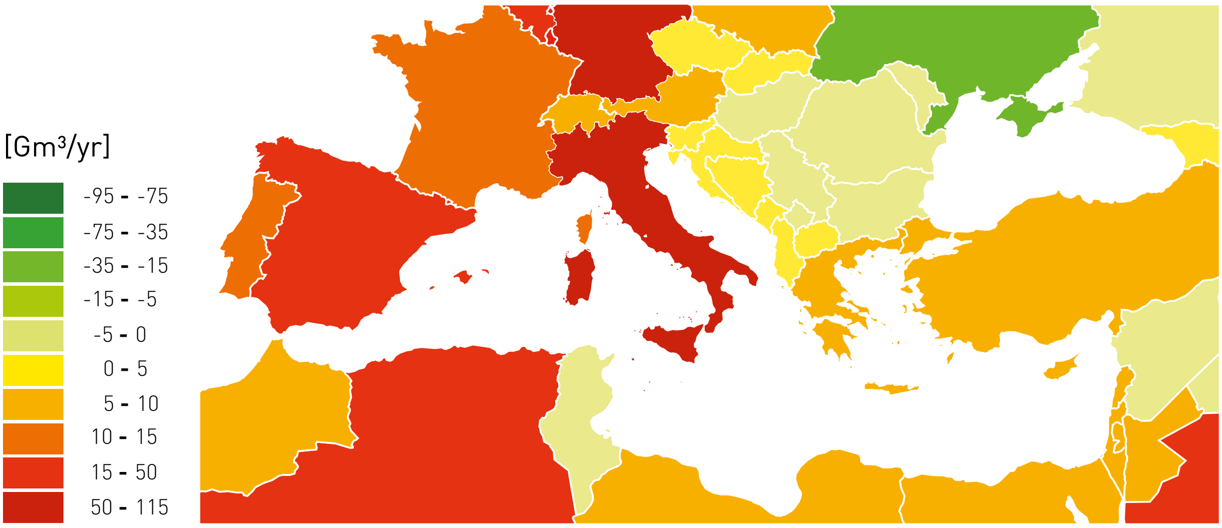

Figure 3.11 | Net virtual water imports of countries, after Fig. 2 of Hoekstra and Mekonnen (2012).

Antonelli et al. (2012) focus on 11 Mediterranean countries, critique earlier approaches for virtual water "flow" calculations, and propose an input-output approach to account for both direct and indirect (e.g., irrigation schemes providing water to households and livestock) consumption of blue and green water. In their calculations, consideration of indirect water consumptions increases the values calculated for national WF, with remarkable differences in results for countries like France (higher WF and higher estimated VW imports), ending up with consideration that focus should be on blue water and on the economic potential for re-allocating water from agriculture (low marginal value) to other uses (households, industry), where the marginal value is higher. They also affirm that, since "green water cannot be moved" there should be no interest in saving it. In their analyses countries like Morocco and Tunisia appear to be much less blue water intensive than Egypt, with the latter showing very high potential for blue water saving. Antonelli and Tamea (2015) calculated the average VW imports of the MENA countries as 601 m^3 capita^{-1} yr^{-1}. Sebri (2017) suggests that the Maghreb countries are already relying on non-conventional water sources, such as waste water reuse and desalination and that they should invest more and more on strategies focused on increasing virtual water trade and enhancing water desalination technologies with the use of renewable energy as a means for abating energy costs. The author affirms that those countries do not benefit enough from virtual water trade, but that it should be considered as an important policy instrument with great care, given the relevant strategic issues related to dependency on foreign countries for basic population needs.

Demand-side adaptation measures

Water demand management (WDM), seen as any method that saves water, or at least saves water of higher quality, is central to the reduction of water losses. WDM incorporates, (i) improving the efficiency of water used to achieve a specific task; (ii) adjusting the nature of the task or the way it is accomplished with less water or with lower quality; (iii) minimizing the loss in water quantity or quality as it flows from source through use to disposal; (iv) shifting the timing of use from peak to off-peak periods and (v) increasing the ability of the water system to continue to supply water to the users at times when water is in short supply (Brooks 2006). This embodies technical, economic, administrative, financial and/or social measures. This section assesses some demand-side measures aiming at reducing the demand for water, such as efficient water use in households and economic sector, agricultural management for water conservation, reduction of water losses, and returning or maintaining the Mediterranean diet.

Efficient water use in households and economic sectors

Water plays an important role in the context of the UN Sustainable Development Goals (SDGs, UN 2015) and is key in several SDG targets. While water for households is dealt by Target 6.1 (Achieve safe and affordable drinking water) and 6.2 (Achieve access to sanitation and hygiene and

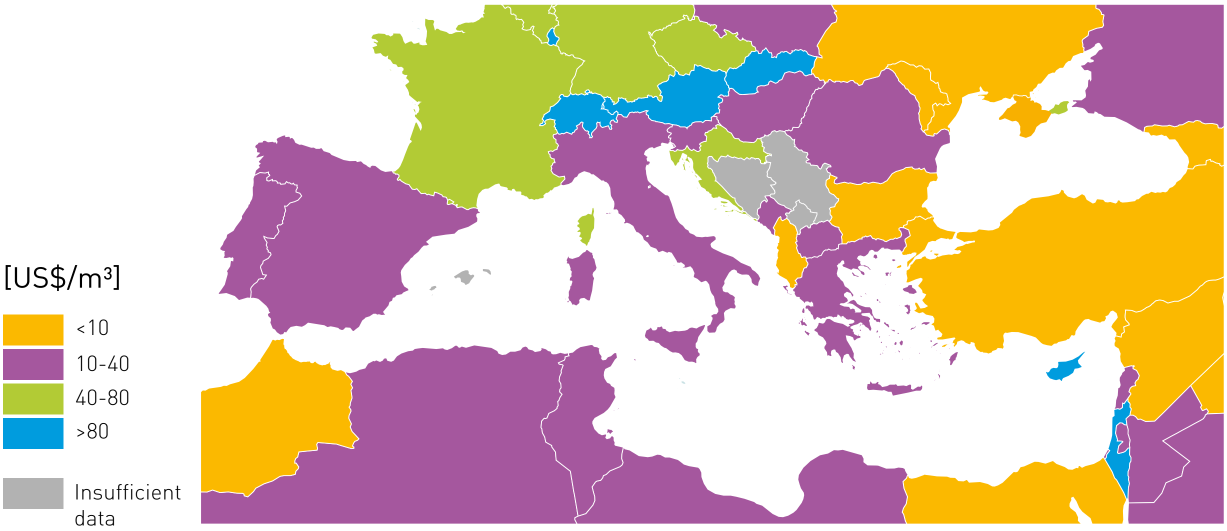

Figure 3.12 | Water-use efficiency per country (UN-Water 2018).

end open defecation), consideration of efficient use of water by different sectors means focusing on Target 6.4 (Increase water-use efficiency and ensure freshwater supplies), and in particular on Indicator 6.4.1 measuring water use efficiency (WUE) to address the economic component.

A recent report produced by UN Water (UN-Water 2018) provides a comprehensive assessment of the state of SDG 6 targets across countries. Concerning Target 6.1, the proportion of population using at least basic drinking water services in 2015 appears above 90% for all Mediterranean countries, with the exception of Morocco (75-90%), and almost the same happens for 6.2, regarding the proportion of population using at least basic sanitation services, with Morocco and Algeria being between 75 and 90%, with all the other countries being above 90%. Nevertheless, there is ample room for improvement of the current situation, by adopting both innovative technologies complemented by targeted education strategies.

On the technological side of possible solutions, Campisano et al. (2017) examine opportunities for improving household water management, with focus on the potential domestic Rain Water Harvesting (RWH) systems in multi-story buildings, demonstrating that in the case study of the old town of Lipari (Aeolian Islands) there is potential for yearly water savings between 30% and 50%. Regarding household behavior, Gul et al. (2017) point out that water consumption habits are quite similar across countries and that awareness campaigns and marketing policies could both contribute to more conscious tap water use in households.

The analysis of the situation of the productive sectors is more complicated, as it requires the quantification of the various components of WUE. As suggested by FAO (2017), the WUE is defined as the value added per unit of water withdrawn over time (showing the trend in water use efficiency over time) and is calculated in US$ m^{-3} of abstracted water as the sum of the three main sectors (agriculture, industry and services), weighted according to the proportion of water withdrawn by each sector over the total withdrawals. UN-Water (2018) provides a global map of WUE per country. Mediterranean countries appear grouped into three classes of WUE *(Fig. 3.12)*. Morocco, Syria Egypt and Albania show WUE below 10 US$ m^{-3}. On the contrary, France and Croatia have a WUE between 40 and 80 US$ m^{-3}, while all other countries are between 10 and 40 US$ m^{-3}.

Maximizing WUE means optimizing water allocation, in order to use the scarce resource for those uses that generate the highest value added. Wimmer et al. (2014) studied future scenarios of water allocation in Europe. Their results indicate that significant physical water shortages may result from climate and socio-economic change in many regions of Europe, particularly in the Mediterranean. Therefore, specific policies will be necessary in order to prevent conflicts among users and negative economic and social, but also environmental consequences. They also point out that cross-sectoral impacts can be limited if higher priority is assigned to the domestic or industry sectors, instead of to agriculture.

For Mediterranean tourism, Hadjikakou et al. (2013) examined five cases of holiday destinations in semi-arid eastern Mediterranean, and found that food tourists' consumption is by far the most significant contribution to the sector's water footprint, but they recommend also considering the links with energy use *(Section 3.3.4.1)*. Moresi (2014) explored environmental impacts of the food industry, with focus on the carbon footprint, pointing out that agricultural production appears as the hotspot in the life cycle of food products, but also that Mediterranean-type diet may have positive effects on both the environment and health. Hence, prioritizing increases water use efficiencies in the tourism and food sector may contribute substantially to the adaptation potential of the region.

Agricultural management for water conservation

Water saving in agriculture includes a set of different actions (technical, socio-economic, environmental and institutional) that should be governed and adopted at each specific location according to the effective needs, priorities and probability of success. Therefore, the solutions differ for different regions and consider both rainfed and irrigated agricultural systems. In marginal rural areas, which are usually among those most vulnerable to climate change, the overall objective beside durable improvement of the agricultural water management is the stabilization of yield and a broader socio-economic development. In this context, there is a need to integrate the traditional knowledge of cultivation with the modern technical achievements and application of new technologies. For example, the adoption of minimum-tillage in suitable soils and crops can be accompanied with a series of synchronized activities that include residue cover during the off-season, appropriate crop rotation program, adequate sowing machines, use of varieties tolerant to abiotic stresses, proper sowing, planting time and density, optimized water, nutrient inputs, weed and plant disease control, harvesting, yield storage and economic evaluation of the products.

In the ACLIMAS project (www.aclimas.eu), selected crop cultivars and best management practices were implemented in five Mediterranean countries (Lebanon, Jordan, Tunisia, Algeria and Morocco) at 109 farms over a total area of about 287 ha *(Section 3.2.3.1)*. Overall, yields increased by 19-33% compared to traditional cultivation and water saving and water rose by 20-50%. These results are in line with the findings obtained in small Mediterranean basins[12], where it has been shown that the increase of water use efficiency at basin level provide more water for all involved stakeholders, and also important economic, social and environmental benefits.

Traditional water harvesting techniques are already widely applied in the Mediterranean and they include interventions in micro and macro catchments, i.e., floodwater diversion to agricultural fields and construction of storage reservoirs, tanks, ponds and cisterns (FAO 2016b). Traditional techniques are assessed and designed by the application of modern technologies (GIS, digital land cover data, elevation models and satellite images) and implemented on the ground by new technologies for land preparation (Grum et al. 2016). Water saving and increase of water productivity can be achieved manipulating the microclimate of growing conditions by the application of different types of shelters (Ilić et al. 2012; Tanny 2013) and windbreaks (Lasco et al. 2014).

In the case of irrigated agriculture, the use of modern technologies, including remote sensing, for monitoring of crop water status and optimization of irrigation scheduling can contribute to more efficient use of water, nutrients and energy (El Ayni et al. 2012; Abi Saab et al. 2019) *(Section 3.2.3.1)*. Water conservation and water productivity enhancement can be achieved applying supplementary irrigation and deficit irrigation strategies as regulated deficit irrigation and partial root drying (Kang et al. 2017). Other water conservation solutions, still under investigation, include plant conditioners (Boari et al. 2015; Ćosić et al. 2015; Cantore et al. 2016; AbdAllah et al. 2018) like anti-transpirants, bio-stimulants and plant growth regulators, which regulate crop transpiration and mitigate the effects of abiotic stresses, and soil conditioners (Guilherme et al. 2015), which aim to improve soil physical properties.

Some techniques of sustainable intensification, such as mulching, zero tillage, etc. increase the water retention capacity of soils making them more capable of coping with dry spells and increasing the water amount accessible to plants (Kassam et al. 2012) (*Section 3.2.3.1* and *6.4*). Also, more efficient irrigation systems, shifts towards drought tolerant crops, adaptation of sowing dates, application of deficit irrigation schemes, land reclamation, and land management for carbon sequestration (Almagro et al. 2016; Funes et

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[12] http://medacc-life.eu/

al. 2019) may reduce water needs for agriculture and increase water use efficiency in terms of m³ per tons. For example, the yearly water withdrawal for irrigation in the Mediterranean region amounts to ~223 km³ (Fader et al. 2015), but there is a water saving potential of 35% through implementation of efficient irrigation systems (Fader et al. 2016). This would, however, increase the energy costs of farmers substantially (Rodríguez-Díaz et al. 2011), driving among others changes towards more profitable but more water-intensive crops such as citrus (Fernández García et al. 2014), and potentially increasing carbon emissions of energy generation. Also, the water saving effect of efficient irrigation systems may be counterbalanced by expansion of irrigated areas.

Another important factor under Mediterranean conditions relates to soil management *(Section 3.2.3.2)*. Water scarcity, soil disturbance and nutrient deficiencies limit net primary productivity in agriculture and consequently reduce soil organic carbon (SOC) stocks, since carbon inputs, such as litter, roots or crop residues, are limited. Soil carbon sequestration occurs if the balance between carbon inputs and outputs (through emissions from respiration and mineralization) is positive and finally leads to increased SOC stocks. Future increases in temperatures linked with a decrease in available soil water content, and the corresponding decrease in yields (Waha et al. 2017) may, hence, decrease soil carbon inputs. However, although it is widely known that warming increases microbial activity, soil moisture could act as the main driver of soil biomes in Mediterranean environments, limiting SOC losses by microbial mineralization. Also, agricultural management practices can significantly affect soil hydraulic properties and processes in space and time. These responses are coupled with the processes of infiltration, runoff, erosion, chemical movement, and crop growth (Green et al. 2003). All of them promote low soil water availability for crops. In all cases, water management (irrigation or soil water harvesting and storage) is critical to the feasibility of the agricultural sector in Mediterranean regions and the avoidance of SOC losses, since available water for crops increases biomass productivity, turnover of organic matter timing and humus formation (Funes et al. 2019). More information improved water management may be found in *Section 3.2.3.2.*

Reduction of water losses

Reduction of water losses in all sectors of water use is crucial for sustainable management and adaptation strategies by alleviating pressure on freshwater supplies and protecting quality. Increasing water efficiency by reducing physical losses, is the basic principle in urban water use. This measure requires adequate monitoring between supplied and consumed water in order to minimize the non-revenue water (NRW) ratio. NRW is composed of water produced but not consumed i.e., not metered, not billed (wasted), and non-physical portion (consumed) not metered, not billed which is unauthorized consumption *(Table 3.8)* (Alegre et al. 2006). This indicates the presence of illegal connections to the municipal water network.

The water use efficiency index indicates how to measure progress in water savings through demand management, by reducing losses and wasteful use during its transmission and distribution. It covers total and sectoral efficiency in domestic (municipal), agricultural and industrial water use (Blinda 2012). The municipal water use efficiency index is defined as the ratio of the 'total drinking water volume billed' to the 'total volume supplied (abstracted/treated and distributed)' to customers by the municipalities.

A good information basis about the sources of non-revenue water (NRW) is important for water demand management, avoiding both physical (real) and commercial/non-physical (apparent) losses. In Turkey, where municipal water use has significant NRW, comprehensive rehabilitation encompassing both physical/technical and administrative improvement has decreased NRW considerably. NRW losses have been reduced by measures including the installation of bulk water meters at source to precisely measure the volume of water supplied to the city; water balance calculations by reading source, bulk and customer meters regularly; preventing reservoir overflows; synchronizing district water supply and district meter readings (establishing controlled supply zones); conducting regular leak detection studies; replacing outdated pipes and repairing leaking house connections; detecting, correcting and preventing illegal connections; and others (Burak and Mat 2010). Eliminating illegal connections in itself will not directly conserve water because consumers will still require the water they previously acquired illegally. However, once legally connected, the consumer will be subject to tariffs, which in turn should reduce the previously unmetered levels of consumption. A further benefit of legalizing these connections will be that they are properly made: illegal connections are often sub-standard and lead to high losses.

System input volume (corrected for known errors) (Water Produced + Water Imported)	Authorized consumption	Billed authorized consumption	Billed metered consumption (including water exported)	Revenue water
			Billed unmetered consumption	
		Unbilled authorized consumption	Unbilled metered consumption	Non-Revenue Water (NRW)
			Unbilled unmetered consumption	
	Water losses	Apparent losses	Unauthorized consumption	
			Customer metering / billing inaccuracies	
		Real losses	Leakage on transmission and/or distribution mains	
			Leakage and overflows at utility's storage tanks	
			Leakage on service connections up to point of customer metering	

Table 3.8 | Water loss definitions and classifications (Alegre et al. 2006).

Water losses that could be recovered losses by improved network efficiency for drinking water and irrigation have been estimated to be 56 km³ for the whole Mediterranean region covering the northern, eastern and southern rims in 2005 (Margat and Blinda 2005). This estimate is based on improvement of drinking water (municipal) network efficiency raised to 85%, end-user (customer connection) efficiency to 90%, irrigation network efficiency increased to 90%, and plot efficiency increased to 80%. Although particularly the targeted irrigation efficiency seems to be ambitious, the correspond-

BOX 3.1.1

Impacts of structural aging and climate change on water infrastructure

Climate change and structural aging poses challenges for the functioning and security of water infrastructure, sometimes reducing water availability and quality. This subsection shortly summarizes this aspect with respect to dams and pipelines.

Dams

In the Mediterranean region, dams are important structures for the storage capacity of water for municipal and industrial use, irrigation purpose and energy production. Although they do not have environmental acceptance in recent years, these structures are also very important for water management in the Mediterranean Basin where available water quantity does not exist where and when required. Therefore, they are also key water structures for flood control and for maintaining water readily available for inter-basin transfer projects that have been widely implemented in several water-scarce regions in recent years (Gohari et al. 2013).

The security of dams in the face of climate change impacts is very important with respect their structural security due to increase in extreme conditions (heavy storms and flooding), changing runoff conditions (Alcocer-Yamanaka and Murillo-Fernandez 2016), and also any changes in storage capacity due to siltation (Burak and Margat 2016). It is estimated that actual capacities of dam reservoirs in Maghreb will decrease by 50% by 2100 due to siltation (Burak and Margat 2016). Permanent flow from upstream riparian countries (e.g., Turkey, Sudan) may not be ensured due to drought conditions (Margat 2011).

Pipelines

Pipelines are the closest infrastructure to the users; therefore, robust and well-operating water network pipelines are very important. It is quite common that water supply utilities face operational difficulties within their distribution network. Significant challenges are encountered for both rehabilitating and replacing aging infrastructure in response to growing population and new development patterns and/or shifting population (Grayman et al. 2009). In old systems, it is possible that asbestos cement pipelines (ACPs) exist even at present in some parts of the region. In Turkey, for instance, this material has been replaced in several municipal networks with ductile iron and/or high-density polyethylene (HDPE) pipes (e.g., Istanbul, Bursa and Adana) because they are low-standard pipes and because of their possible carcinogenic effect in the water network, even though there is no proven studies as stipulated by some researchers and by the WHO guidelines (Polissar et al. 1984; WHO 2003). Also, starting in 1990 in Istanbul and in other cities in the following years, investments for rehabilitation of existing water network in the new service area have been implemented in order to reduce physical losses (World Bank 2016). However, with regard to possible health risks generated by the use of ACP, practices vary from one country to another (Polissar et al. 1984).

BOX 3.1.2

Water use and the specific Mediterranean diet[13]

The choice of diets influences the amount of water needed to produce and process the corresponding food *(Section 3.2.1.2)*. Similarly, food waste is, at the same time, a waste of the water that was used to produce that food. Hence, influencing diet choices can be regarded as an adaptation option.

Countries like Spain are making significant efforts to reduce food loss and waste, reverse growing obesity trends, and promote the adoption of healthier food habits like the recommended and traditional Mediterranean diet. This is recognized as a key strategy to improve the population's health with locally grown, traditional, and seasonal products like fruits, vegetables, olive oil, and fish. Nevertheless, current Spanish consumption patterns (especially among younger generations, and urban and/or low-income citizens) appear to be shifting towards unhealthier diets. The largest share of the WF of current Spanish diet, as occurring with for example North American diet, is always linked to green water, which implies that the largest impact of dietary shifts is also linked to land use. Grey water in the US is 67% higher than in Spain. Only few products account for the largest share of the total WF of the two dietary options in both countries, being meat, fats, oil, and dairy products the food items with the largest WFs.

For the year 2014, the total WF of current consumption in Spain was equivalent to around 3,302 l per capita per day (of which 2,555 are green, and 400 blue WF). The products that account for the largest share in the total WF are once again meat, animal fats, and dairy products. Likewise, roughly 41% of the total WF linked to household diets is foreign, i.e., imported Virtual Water, and the main countries of origin are Tunisia, Portugal, and France. The Total WF of food waste at households' level is estimated at 131 l per capita per day (of which 97 are green and 19 blue WF), equivalent to 4% of the Total WF of current consumption. In addition, regarding nutritional analysis, the nutrients wasted (because of food waste) per capita year were 40,385 kcal, almost 7.5 kg of macronutrients (proteins, fats, and carbohydrates), 483 grams of fiber and almost 160 grams of micronutrients (vitamins and minerals).

Current Spanish household diet is shifting away from the recommended Mediterranean towards alternative diet containing three times more meat, dairy and sugar products, and 1/3 fewer fruits, vegetables and cereals. The Mediterranean diet is also less caloric, as it contains lesser amounts of proteins and fats, and is richer in fiber and micronutrients. Due to the high water content embedded in animal products, a shift towards a Mediterranean diet would reduce the consumptive water use by about 753 l per capita per day (of which 34 are blue WF). In addition, the Mediterranean diet has higher water-nutritional efficiency than current consumption: more energy, fiber, and macro- and micronutrients are made available per liter of consumptive water used. In conclusion, a shift back to a locally produced Mediterranean diet (in which fruits, fish and vegetables account for a larger share of the food intake) and lessening food waste, would deliver large water savings (753 and 116 liters of consumptive water per capita per day, respectively) and nutritional benefits.

ing saved water volume appears to deserve almost any affordable effort. An overall water use efficiency index of 74% was adopted for 2015 to be one of the desirable goals by the Mediterranean countries as part of the Mediterranean Water Strategy. In that spirit, Turkey government has decided that municipalities and water administrations had to reduce the rate of water loss, averaging 25% by 2023[14]. Tariff structures should seek to cover the operation and investment costs whilst at the same time trying to strike a balance with what is considered fair and socially acceptable.

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[13] This box is based on the PhD thesis and related research papers by Alejandro Blas (Blas et al. 2016, 2018).

[14] https://sustainabledevelopment.un.org/content/documents/23862Turkey_VNR_110719.pdf - page 75

Supplementary information

Country	Fresh surface water withdrawal	Fresh groundwater withdrawal	Total freshwater withdrawal	Direct use of treated municipal wastewater	Direct use of agricultural drainage water	Desalinated water produced
$(10^9\ m^3\ yr^{-1})$						
Albania	1.081	0.107	1.188	0.050		
Algeria	1.699	8.103	9.802			0.631
Bosnia and Herzegovina	0.107	0.294	0.401			
Croatia	0.248	0.425	0.673	0.015		
Cyprus	0.061	0.155	0.216	1.200		0.065
Egypt		6.500	64.400	0.411	11.9	0.2
France	20.930	5.506	26.440	0.104		0.0117
Greece	4.386	6.854	11.240	0.520		0.01
Israel	0.358	0.840	1.198	0.045		0.586
Italy			34.190	0.004		0.0973
Jordan	0.289	0.615	0.904	0.002		0.1363
Lebanon	0.396	0.700	1.812		0.028	0.0473
Libya	0.170	5.550	5.760	0.001		0.07
Malta	0.003	0.040	0.043			0.0202
Monaco			0.005			
Montenegro			0.161	0.070		
Morocco	8.251	2.322	10.350			0.007
North Macedonia	0.885	0.162	0.524	0.013		
Palestine	0.024	0.265	0.288	0.003		0.004
Portugal	4.352	4.794	9.146			0.0016
Serbia	4.917	0.460	5.377			
Slovenia	0.741	0.190	0.931			
Spain	24.830	6.394	31.220	0.592		0.364
Syrian Arab Republic			14.140	0.550	2.246	
Tunisia	1.151	2.066	4.768	0.042	0.01	0.055
Turkey	44.550	15.460	58.760	0.025		0.0082

Table S3.1 | Sources of water supply (FAO 2016a).

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2-FOOD

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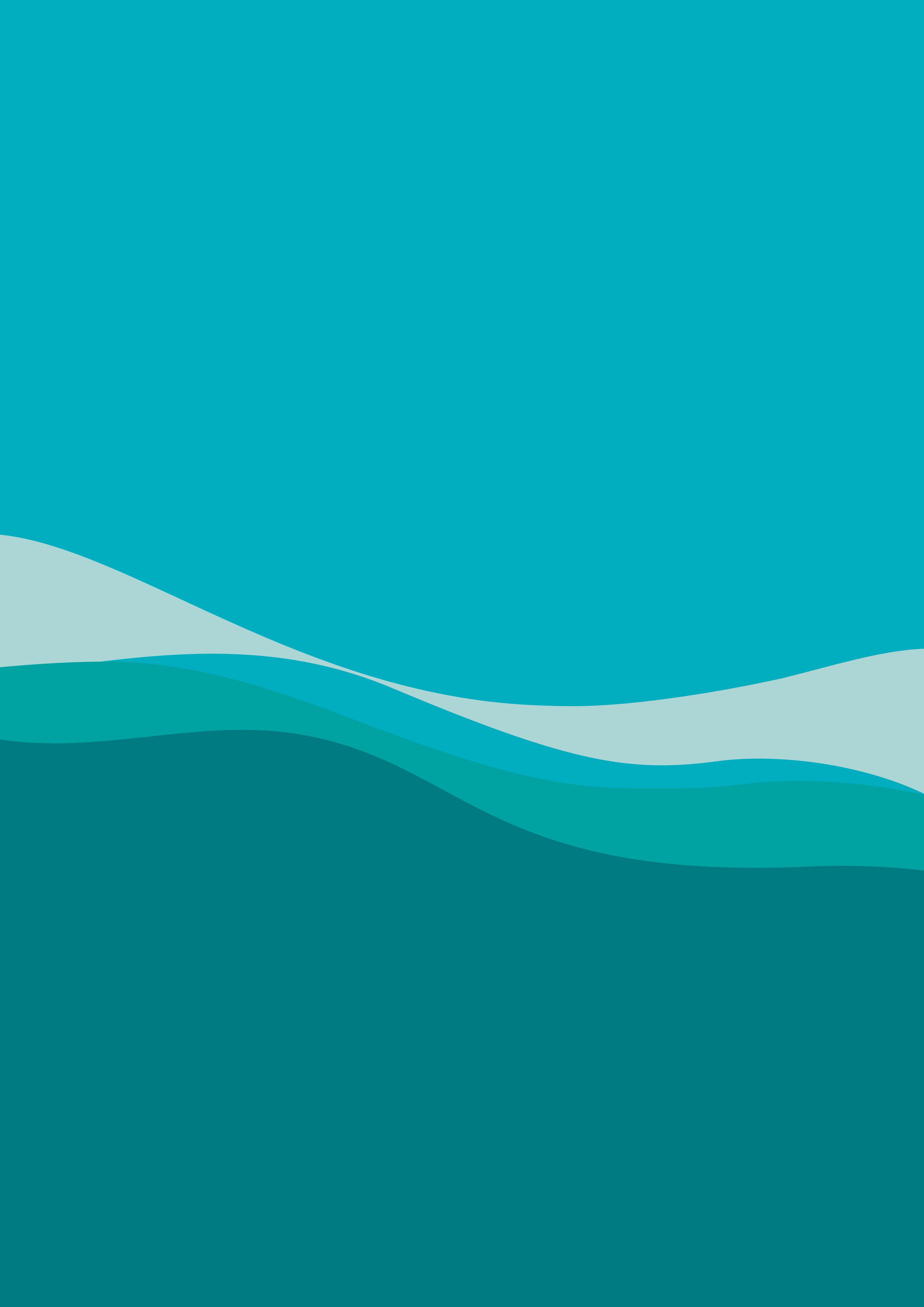
This chapter should be cited as: Mrabet R, Savé R, Toreti A, Caiola N, Chentouf M, Llasat MC, Mohamed AAA, Santeramo FG, Sanz-Cobena A, Tsikliras A 2020 Food. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. *First Mediterranean Assessment Report [Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 237-264, doi:10.5281/zenodo.7101080.*



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3.2 Food

Executive summary

Food production in the Mediterranean Basin, from both land and the sea, is impacted by climate change, more frequent and intense extreme events, jointly with land degradation, overfishing, ocean acidification and salinization of coastal soils. Climate extremes pose a threat to the entire agriculture sector. Extremes, such as heat stress, droughts but also floods, can cause crop yield losses/failures, crop quality reduction and impacts on livestock. Perturbations in the global agricultural markets may exacerbate the local impacts of climate change, especially because most Mediterranean countries are net importers of cereals and fodder/feeding products. Mostly due to unsustainable fishing, total fish landings in the Mediterranean Sea have declined by 28% from 1994 to 2017.

Climate projections show a decrease of water availability and an intensification of extremes in the Mediterranean region, and thus a higher risk for the agriculture sector. Crop yield reductions are projected for the next decades in most current areas of production and for most crops. The cultivation of some water demanding crops like maize or vegetables could become impossible in many Mediterranean regions if there will be no enough water for irrigation. This will potentially be worsened by emerging pests and pathogens, and perturbations in the global food markets due to environmental crises elsewhere.

Sea level rise will also negatively affect the agriculture sector by its direct impact on agricultural areas and associated increasing soil salinity, which could be multiplied by three. Rice production in Egypt and Spain could be the most affected.

Climate change is projected to heavily affect marine resources in the next decades. Warmer temperatures, acidification and water pollution will likely reduce marine productivity, affect species distribution and trigger local extinction of more than 20% of exploited fish and marine invertebrates around 2050.

In agriculture, there are large possibilities for adaptation consisting mostly in changing farming practices and application of more sustainable methods, including agroecological strategies. Successful strategies for sustainable development and enhanced resilience to environmental change are based on combining different approaches, i.e., reduced tillage, varieties, rotational patterns, and crop diversity or diversification of income. Sectorial co-designed climate services will represent a key asset to reduce the risk linked to unfavorable climate conditions and extremes.

Figure 3.13 | Total agricultural land in the Mediterranean countries in 2016 (% with respect to the total land at country scale). Source: World Bank (accessed February 2020).

Figure 3.14 | Total irrigated land in the Mediterranean countries (latest reported value in % with respect to the agricultural land at the country scale). Source of data: World Bank Data (accessed February 2020).

Sustainable intensification of farming systems offers greenhouse gas mitigation options by nitrogen fertilization optimization, improved water management, higher storage of soil organic carbon and carbon sequestration both in annual and perennial cropping systems, management of crop residues and agroindustry by-products.

3.2.1 Past trends and current situation

The ensemble of the Mediterranean countries has approximately 877 million ha of land, of which about 28% is devoted to agriculture *(Fig. 3.13)*. There is a pronounced spatial heterogeneity in the share of agricultural land, from 4% of Egypt to almost 76% of Syria *(Fig. 3.13)*. The agriculture sector is characterized by a variety of different farm structures and agro-management practices combined with pronounced differences in environmental conditions, rendering substantial variation in agricultural inputs (e.g., nutrients, pesticides, water for irrigation) and outputs (e.g., crop yields). Irrigation is practised only on 8% of the Mediterranean agricultural land area *(Fig. 3.14)*, however uncertainties characterize this value as data for several countries are neither available nor updated. Israel has the highest portion of agricultural land being irrigated (approx. 33%, *Fig. 3.14*).

The Mediterranean agriculture production is characterized by high spatial variability and differences *(Table 3.9)*. Annual crops include cereals (e.g., wheat, maize, barley and rice), and vegetables (e.g., potatoes and tomatoes). Together, wheat, maize, barley and rice cover, for almost all Mediterranean countries, more than 90% of the entire cereal production, with rice having a significant share (>3%) only in Egypt, Greece, North Macedonia, Portugal, Spain and Italy. Permanent crops consist of fruit, olives, grapes and dates. For cereals, France, Turkey, Egypt, Spain and Italy produce (2014-2018 average) about 66, 35, 23, 21, and 18 million t, respectively *(Table 3.9)*. As for fruit and vegetable production, the highest values (15-22 million t for fruit, and 13-24 million t for vegetables) come from Egypt, Italy, Spain and Turkey *(Table 3.9)*.

Although productivity has increased in recent decades, there are still large differences in the region, with for instance wheat yield ranging from approx. 1 to almost 7 t ha^{-1} (FAO 2017). These differences are also reflected in the estimated yield gap for wheat, maize and barley (e.g., Mueller et al. 2012; Schils et al. 2018). Improved agro-management practices can contribute to close the gap in regions where large differences exist between potential and farm yield. As an example, Pala et al. (2011) found that wheat yields can be increased 1.6–2.5 times in Morocco, 1.7–2.0 times in Syria and 1.5–3.0 times in Turkey.

Large spatial differences also characterize the livestock subsector, with meat (beef and buffalo) production varying from 0.1 to 143.9x10^4 t; while milk production varies from 0.4 to 262.7x10^5 t *(Table 3.9)*. Milk productivity also spans a vast range from

	Cereal	Fruit	Vegetables	Meat (beef & buffalo)	Milk
Albania	6.9	7.8	8.0	0.39	11.4
Algeria	40.4	67.6	63.4	1.57	35.8
Bosnia and Herzegovina	13.6	3.3	7.7	0.15	7.0
Bulgaria	92.5	4.9	4.6	0.18	11.3
Croatia	30.6	3.2	12.4	0.43	6.8
Cyprus	0.4	1.8	0.7	0.05	2.5
Egypt	229.7	150.8	158.2	7.89	51.6
France	662.6	92.2	52	14.39	262.7
Greece	38.5	40.5	25.2	0.43	19.4
Israel	2.9	13.8	14.9	1.29	15.4
Italy	175.8	175.3	125.9	7.75	119.3
Jordan	1.0	5.4	16.2	0.27	3.5
Lebanon	1.7	8.0	8.2	0.45	2.6
Libya	2.7	6.8	6.8	0.09	2.3
Malta	0.1	0.1	0.8	0.01	0.4
Montenegro	0.1	0.8	0.2	0.04	1.7
Morocco	84.7	57.3	40.3	2.61	23.9
North Macedonia	5.6	5.8	6.9	0.05	4.5
Palestine	0.5	1.2	6.4	0.08	1.6
Portugal	11.9	19.6	24.4	0.89	20.8
Serbia	95.2	16.5	8.5	0.69	16.0
Slovenia	6.2	2.1	0.9	0.34	6.4
Spain	211.6	192.7	128	6.32	80.2
Syria	31.4	25.1	17.9	0.70	22.3
Tunisia	17.8	20.9	30.3	0.59	13.8
Turkey	354.3	217.5	239.8	9.90	197.2
Kosovo	95.2	16.5	8.5	0.69	16.0

Table 3.9 | Production of cereals, fruit, vegetables, meat and milk in the Mediterranean countries, 2014-2018 average, 10^5 tonnes. Data source: FAOSTAT (accessed February 2020).

800 kg animal^{-1} in Libya to 5,500 kg animal^{-1} in Slovenia. Overall, Mediterranean countries of the MENA region have an average milk productivity of 700 kg animal^{-1}, compared to 1,800 kg animal^{-1} of the other countries and 2,300 kg animal^{-1} for the EU countries in the region.

3.2.1.1 Demand for agricultural products, consumption and trade

Agricultural demand in the Mediterranean region is influenced by changing dietary patterns and by the socio-economic and political situation of each country, including population growth and import/export flows. In 2013, the Mediterranean diet has been recognized by UNESCO as intangible cultural heritage of humanity, involving not only food production, processing and consumption but also social behaviour and community identity. Its low environmental impact and its importance for a sustainable future have been highlighted in many studies (Sofi et al. 2010; Capone et al. 2012; CIHEAM and FAO 2015). Recent studies indicate a diet transition affecting the Mediterranean countries and posing a threat for the preservation and enhancement of the Mediterranean diet (Bonaccio et al. 2012, 2014; CIHEAM and FAO 2015). These changes may further affect nutritional issues and human health in Mediterranean countries, where already malnutrition (characterized by the presence of significant percentage of overweight and underweight population) takes place.

The food system of the Mediterranean also contributes to the ecological deficit as estimated by Galli et al. (2015) and updated in the National Footprint Accounts 2019[15]. The amount and the

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[15] Global Footprint Network, http://data.footprintnetwork.org/

type of contribution are country dependent, and in some cases (e.g., Portugal, Greece, Spain, Malta, Croatia and Italy) characterized by a relevant component of meat, dairy and fish (Galli et al. 2017). Changes during the last decade (2000-2013) in meat consumption are not homogeneous in the Mediterranean region, with twelve countries showing a significant increase, six having characterized by a significant decrease and the others having a stationary pattern. For fish, fourteen countries show a significant increase, only two a significant decrease and all others have a stationary pattern *(Fig. 3.15)*.

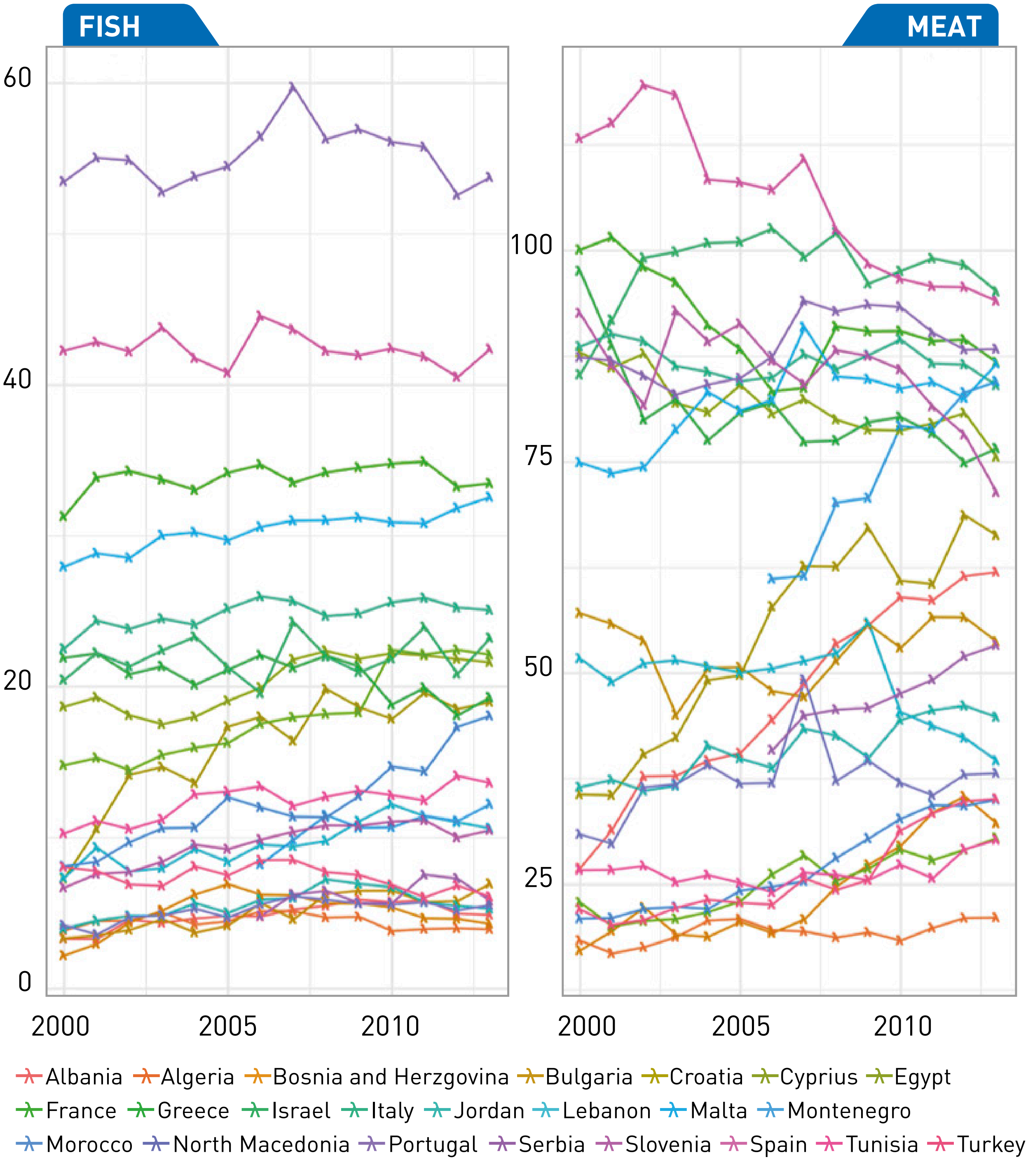


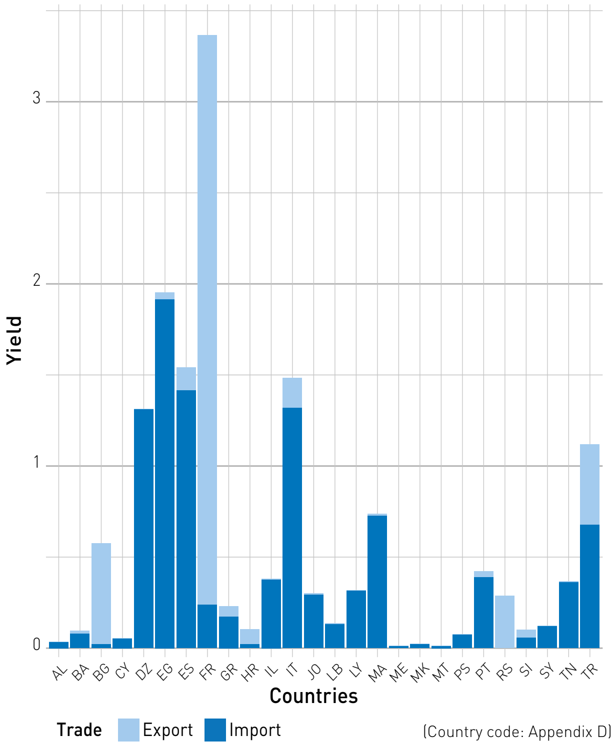
Figure 3.15 | Meat and fish consumption (kg capita^{-1} yr^{-1}) in Mediterranean countries from 2000 to 2013 (FAO 2017).

Trade patterns play a key role in the Mediterranean region, with most of the countries being net importer of cereal and fodder/feeding products (*Fig. 3.16* and *3.17*). Concerning cereal, four countries (Italy, Spain, Egypt, and Algeria) import 12-19 million t of cereal, while France exports about 29 million t *(Fig. 3.16)*. As for fodder and feeding products, five Mediterranean countries import more than one million t, with Turkey reaching about 4.3 million t *(Fig. 3.17)*. The current trade patterns have been reached by a profound transformation of the agricultural systems that has occurred in the last decades, often characterized by a decoupling of the crop and livestock producing systems (Lassaletta et al. 2014).

Overall, the Mediterranean region, in terms of nitrogen (N) import has moved towards a more unbalanced situation with most of the countries being net larger importer *(Fig. 3.18)* (Lassaletta et al. 2014; Sanz-Cobena et al. 2017). The decoupling of the crop and livestock producing systems caused a lower nutrient efficiency and issues associated with the lack of manure in cropping area and excessive manure in livestock farms (Lassaletta et al. 2012; Sanz-Cobena et al. 2017). The excessive manure production is difficult to manage, and over-application in areas close to high-density livestock systems can severely affect the environment. As a consequence, a high risk of catchment pollution has been estimated and reported in some studies (Lassaletta et al. 2012; Romero et al. 2016).

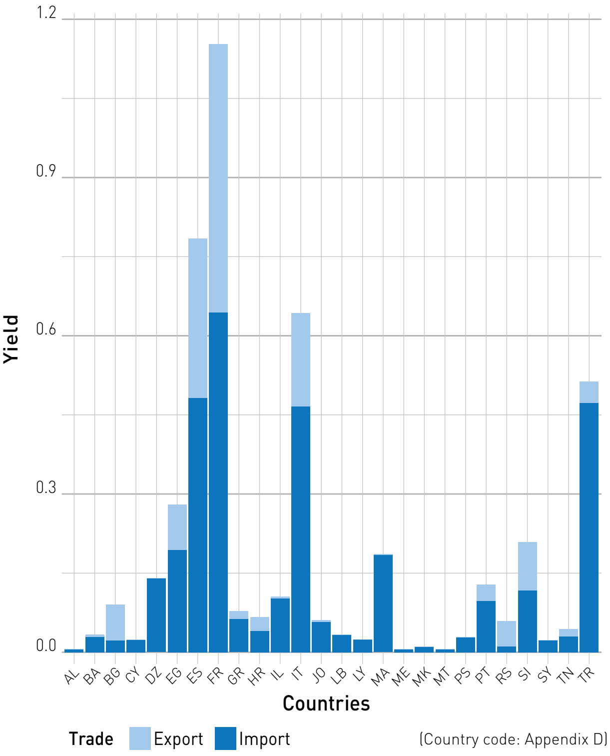
The Mediterranean is among the oldest examples of strongly coupled human-environment sys-tem that has undergone very profound land/landscape changes driven by activities such as the agriculture and by the human-water interaction (Barton et al. 2010, 2016) *(Section 4.3.1.1)*. Many factors have contributed to these changes in the Mediterranean, e.g., people's mobility towards the coast and the urban areas, tourism expansion, industrialization, agriculture intensi-fication (Bajocco et al. 2012; Niedertscheider and Erb 2014).

These changes have contributed to alter land quality, productivity and to degradation. Changes have not been homogeneous as very different



(Country code: Appendix D)

Figure 3.16 | Cereal trade patterns (average 2014-2017 values in tonnes x 10^7) in the Mediterranean countries: import (deep blue) and export (light blue) contribution for each Mediterranean country (identified by the ISO 3166-1 alpha-2 code) (FAO 2017).



(Country code: Appendix D)

Figure 3.17 | Trade patterns in fodder and feeding products (average 2014-2017 values in tonnes x 10^6) in the Mediterranean countries: import (deep blue) and export (light blue) contribution for each Mediterranean country (FAO 2017).

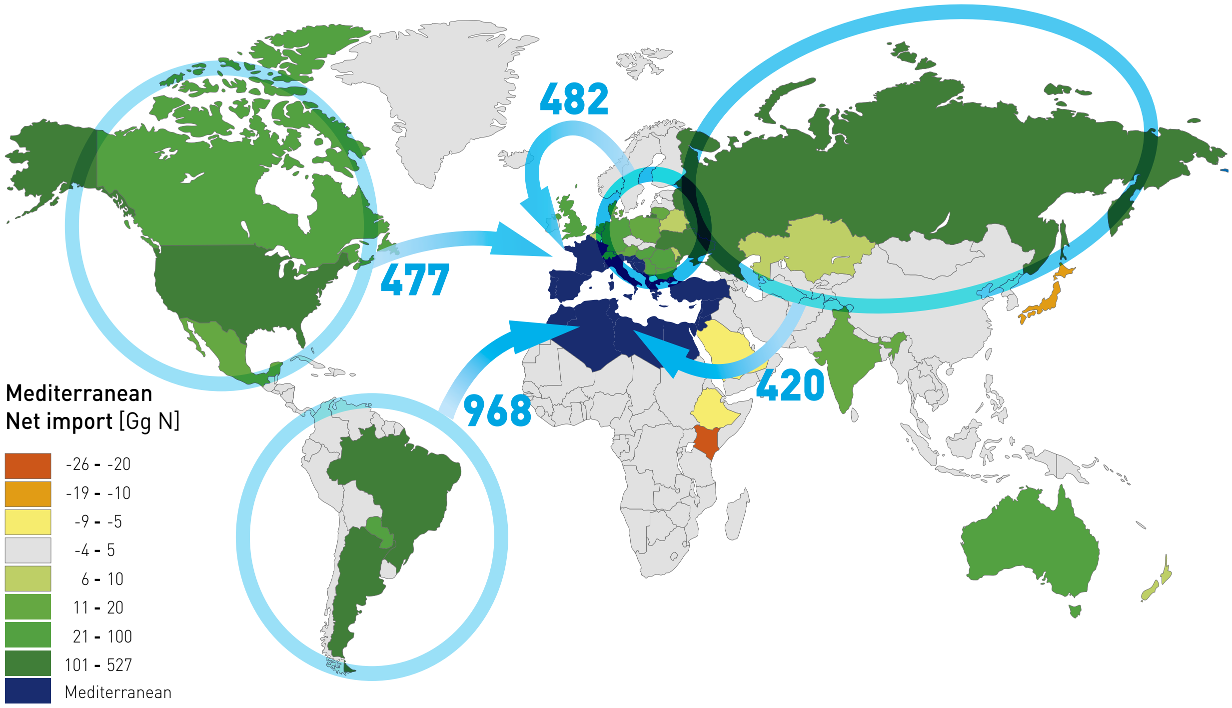


Figure 3.18 | Net protein fluxes (Gg N) of food and feed imported to the Mediterranean regions from the other countries in 2009. Green countries are net N exporters to the Mediterranean. Yellow/red countries are net N importing from the Mediterranean. Fluxes below 50 Gg N are not represented (adapted from Sanz-Cobena et al. 2017).

socio-economic conditions characterize the region as well as behavioural patterns in farming. For instance, in some areas of the western Mediterranean the abandonment of dryland farming, of farming activities in mountainous and/or re-mote regions, and the consequent afforestation modified the ecosystems and the services pro-vided (Kauppi et al. 2006; Falcucci et al. 2007; Padilla et al. 2010). Abandonment of agricultural terraces in mountainous regions has in some cases also favored erosion processes and loss of fertile soil (Arnaez et al. 2011). Land competition has also played a key role in some regions of southern Mediterranean, e.g., Morocco (Debolini et al. 2015). Mobility towards urban areas, evolving economic conditions, modified productivity in agricultural areas of Mediterranean countries also contributed to shifts in the cultivated crops. In Crete (Greece), for instance, a transition from cereal production towards olive cultivation characterized the 20th century (Karamesouti et al. 2015). In some countries, urbanization has forced agricultural expansion to-wards marginal areas requiring higher management levels in terms of irrigation and fertilization (Abd-Elmabod et al. 2019).

3.2.1.2 Marine food resources

Mediterranean total fishery landings have been declining in the last years *(Fig. 3.19)* (Tsikliras et al. 2015; FAO 2018) and so are the reconstructed catches that included discarded, illegal and unreported and recreational fisheries catch (Pauly and Zeller 2016). Total landings of the entire Mediterranean Basin exceeded 1.16 million t in 1994 and declined to around 842,000 t in 2017, i.e., a decrease of 28% *(Fig. 3.19)*.

While the peaks occurred relatively early in the central Mediterranean (~1985) and eastern Mediterranean (~1994), the landings peaked much later in the western Mediterranean (~2006) *(Fig. 3.20)*. In 2017, the landings were relatively low: from 161,000 t in eastern Mediterranean to 325,000 t in central Mediterranean *(Fig. 3.20)*. In 2017, the highest contribution to the total landings in the Mediterranean came from Italy (22%), followed by Algeria (12%), Tunisia (12%), and Spain (10%)[16].

Small pelagic fishes constitute the vast majority of landings across the entire Mediterranean Sea, with European anchovy *(Engraulis encrasicolus)* and

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[16] Data from FAO-GFCM, accessed March 2020. http://www.fao.org/gfcm/en/

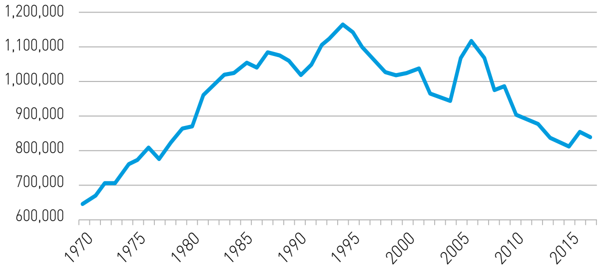

Figure 3.19 | Total fish landings (tonnes) in the Mediterranean Sea from 1970 to 2017. Data source: FAO-GFCM[16], accessed in March 2020.

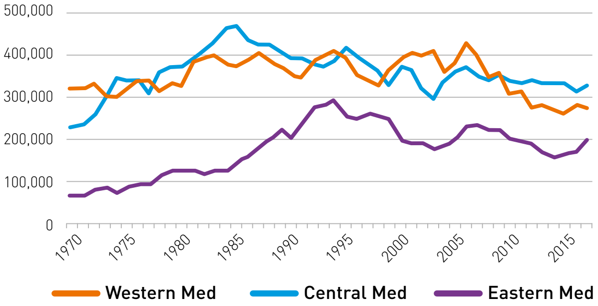

Figure 3.20 | Total landings (t) from 1970 to 2017 in the Mediterranean Sea. Data source: FAO-GFCM[16], accessed in March 2020.

European sardine *(Sardina pilchardus)* being the species with the most landings accounting for 34% of the 2014-2016 average annual landings (FAO 2018; Tsikliras et al. 2019). The main pelagic fish species landed in the western Mediterranean are European anchovy, European sardine and sardinella nei (*Sardinella* spp.) accounting for 46% of the total landings (FAO 2018). In the Ionian part of central Mediterranean, European sardine, sardinella nei, jack and horse mackerel nei (*Trachurus* spp.), and common Pandora *(Pagellus erythrinus)* account for 30% of the total landings (FAO 2018). While in the Adriatic part of Central Mediterranean, landings of European sardine and anchovy reach 61% (FAO 2018). Finally, in the eastern Mediterranean, European sardine, anchovy and European sardine are again the main species landed accounting for 33% of the total landings (FAO 2018) (*Sections 2.4.2, 4.1* and *4.2*).

3.2.1.3 Observed impacts of extreme weather and climate events on food production

Extreme weather and climate events (such as floods, droughts, storms, heat waves and cold spells) pose a threat for agricultural production (Lesk et al. 2016; Zampieri et al. 2017; FAO 2018). The impacts of heat stress occurring in critical phenological phases can induce serious crop yield losses and quality reduction. In Italy, for instance, early heat waves have been associated to durum wheat yield losses occurred in the last decades (Fontana et al. 2015; Zampieri et al. 2017). In Greece, recent trends in extreme temperatures reduced cereal yields by 1.8-7.1% per degree increase in maximum temperatures (Mavromatis 2015). Also milk production and quality are affected by heat stress (Bernabucci et al. 2010, 2015; Gantner et al. 2017) as well as livestock fertility (de Rensis et al. 2015). Temperature changes during important phenological stages such as blossoming may affect yields of maize, alfalfa, apples, almonds and other crops (Savé et al. 2012; Funes et al. 2016; Díez-Palet et al. 2019).

The entire agriculture sector in the region is also heavily affected by drought events (Blauhut et al. 2015; Zampieri et al. 2017). Severe socio-economic impacts triggered by drought events were reported on Moroccan agriculture (Verner et al. 2018), with the events of 2007 (Schilling et al. 2012) and 2015-16 that caused heavy losses on wheat, citrus and olive production, posing a threat for the livestock sector. Severe droughts can also modify the rural landscape, preventing the adoption of new crops and ultimately forcing farmers to emigrate (Ruaudel and Morrison-Métois 2017). The costs and the risks associated with climate extremes are not only related to direct losses, such as crop failures, but also to a wide range of indirect effects triggered by market reactions to events occurring in other producing regions of the world (Chatzopoulos et al. 2019).

The Mediterranean is also a high fire-risk region, where fires are the cause of severe agricultural, economic and environmental losses and even human casualties (San-Miguel-Ayanz et al. 2013; Moritz et al. 2014; Bowman et al. 2017). The abandonment of agricultural land leads to an increased risk of forest fires due to the occupation of what were agricultural lands by forest and the bushes, and increasing the biomass available for burning as well as its spatial continuity. Conversely, some forest fires may be triggered for the creation of more pastures for livestock or farmland.

3.2.1.4 Food policy and economics

Agriculture and the entire food system are generally influenced by socio-economic conditions, also in Mediterranean countries. The strong fluctuations in food markets are partly due to the characteristics of agricultural production itself (perishable products, climatic and health risks, seasonal production cycles, size of farms, distance from markets etc.), which, together with aspects of the overall economy, even of a geopolitical nature, can modify the food supply-demand balances (Reguant and Savé 2016). These conditions also endanger the capacity of Mediterranean countries to guarantee food security (Santeramo 2015). Among the Mediterranean countries, some in the southern and eastern shores have also suffered political instabilities and conflicts that have posed a challenge to the maintenance and development of the agriculture system (Tanyeri-Abur 2015; Petit and Le Grusse 2018).

The food system of the Mediterranean region in all its aspects (production, trade patterns, etc.) is under strong influence from the policies of high-income countries and, in particular, the European Union (Caracciolo et al. 2014). The tight links among Mediterranean countries imply that changes in the EU Common Agricultural Policy and in trade agreements may have important impacts on national agri-food sectors also outside the EU. For instance, the Euro-Mediterranean trade partnership between the EU and the southern and eastern Mediterranean non-EU countries (except for Syria and Libya, entered into force to promote trade and investments in the region) tends to influence market fundamentals in all Mediterranean countries. Furthermore, food quality standards and entry price mechanisms are very important for trade patterns (Cioffi et al. 2011; Santeramo and Cioffi 2012; Marquez-Ramos and Martinez-Gomez 2016; Bureau and Swinnen 2018).

Trade has prioritized the export of fruits and vegetables and has widened the production-consumption gap of cereals, which are the main food of the most vulnerable segments of the population in the southern and eastern parts of the region (Larson et al. 2002; Cioffi and Dell'Aquila 2004; García Martinez and Poole 2004). The vulnerability of the cereal sector has enhanced the impact of food price fluctuation on food security, which may have severe impacts (e.g., in terms of income level and income distribution) depending on the capacity of the countries to be self-sufficient (Caracciolo and Santeramo 2013).

Pasture based systems are becoming less competitive, due to the high labor costs (on-farm resources are being substituted with external inputs) promoting intensive livestock systems near urban areas (Malek et al. 2018). This has resulted in the increase in landless livestock systems in the Mediterranean region.

Mediterranean countries are vulnerable to price fluctuations on international markets due to their dependence on imports of basic foodstuffs. Worldwide phenomena (e.g., food crisis) have accentuated the structural weakness of the agricultural production model adopted by these countries, increasing social and political frustrations (Reguant and Savé 2016). In this context, it is worth to mention initiatives such as the Mediterranean Agricultural Market Information Network (MED-Amin)[17] and the MedAgri platform[18] from FAO, the European Bank and the World Bank. The drivers of price volatility are numerous and complex (Santeramo et al. 2018b), but it seems there is a consensus that arbitrage, and price discovery mechanisms tend to have a positive impact on price stabilization (Santeramo and Lamonaca 2019).

Access to agricultural technology is unequally distributed across countries of the Mediterranean area and is usually more accessible to farmers in the north-western part. It is also true that most developed countries tend to provide higher subsidies (at least in nominal terms) to their agricultural sector. The adoption of risk management strategies, and the access to credit are also very unequally distributed and generally lower in the developing countries of the Mediterranean area (Santeramo et al. 2014). These peculiarities allow to conclude that the less developed countries, among the Mediterranean ones are likely to be the most vulnerable to food security issues. On the other hand, investments on technology, on policies to promote the agri-food sector, and in particular to promote risk management strategies may prove effective mechanisms to enhance resilience to food security.

3.2.2 Projections, vulnerabilities and risks

3.2.2.1 Agricultural resources

Climate projections indicate significant warming and drying in the Mediterranean Basin, together with intensification of climate extremes such as

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[17] www.med-amin.org

[18] www.medagri.org

drought and heat waves (*Sections 2.2.5.2* and *2.2.4*). Thus, severe impacts on the agriculture sector are to be expected if no adaptation and mitigation will take place. These impacts include changes in phenology and growing cycle of many crops (Trnka et al. 2011; Funes et al. 2016), combined with higher water demands due to enhanced evaporation (Savé et al. 2012; Girard et al. 2015; Saadi et al. 2015; Valverde et al. 2015; Phogat et al. 2018). The wheat growing period in Tunisia is expected to be shortened by 16 days for 2.5°C and by 30 days for 4°C (Mougou et al. 2011). Additional constraints include water scarcity *(Section 3.1.4.1)* (Vicente-Serrano et al. 2017, 2018) and soil salinity (Lagacherie et al. 2018; Phogat et al. 2018).

As a consequence, potential yields of crops and livestock yields are projected to decline in many areas due to climatic and other stress factors without adaptation. Several regions of the Mediterranean might entirely lose their suitability for growing specific crops (Ceglar et al. 2019). Crop yields in MENA countries are expected to decline by approx. 30% with 1.5-2°C warming in Jordan (Al-Bakri et al. 2011) and similarly in North Africa (Drine 2011) and up to 60% with 3-4°C warming (Schilling et al. 2012). Maize is projected to be among the most affected crops (Webber et al. 2018; Zampieri et al. 2019; Feyen et al. 2020), with significant yield decline of, e.g., 10-17% in Italy, Bulgaria, and Greece by the mid-century (2021-2050, under the business as usual RCP8.5 scenario and assuming the current agro-management will still be in place). Wheat yield losses are projected for some European countries in the Mediterranean region (5%-22% in 2021-2050 under the RCP8.5 scenario with no adaptation) (Feyen et al. 2020) associated with higher inter-annual variability and decrease resilience of the production (Zampieri et al. 2020). Reductions in wheat yield in case of no adaption have been also reported for Algeria (Chourghal et al. 2016). However, reductions in water availability for maize irrigation could bring much bigger losses. Based on a meta-analysis of 16 studies available at the time, Waha et al. (2017) conclude that climate change constitutes a significant risk for crop yields across the MENA region *(Fig. 3.21)*.

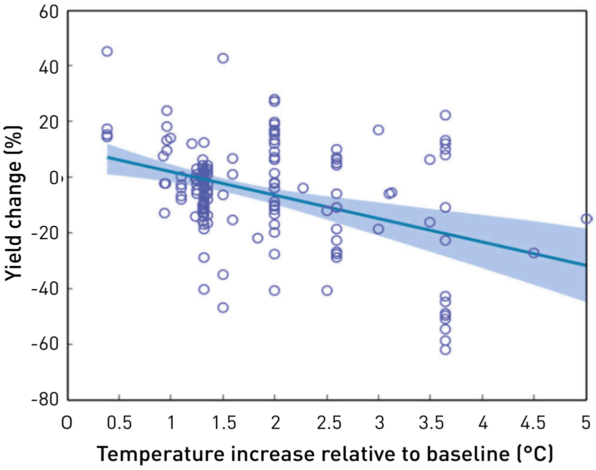

Figure 3.21 | Crop yield changes in the MENA region based on a meta-analysis of 16 different studies (Waha et al. 2017).

Soil and agro-management influence on the projected changes has also been reported for wheat yield in an Italian region, showing moderate yield increase as well as heavy decrease (63% in 2040-2070 under the A1B scenario, which is close to the relatively high scenario RCP6.0) (Bird et al. 2016) according to the soil type. While a strong dependence on water availability has been pointed out for tomato yield in Tunisia, where a 10% reduction in water for irrigation could make some productions not feasible (Bird et al. 2016). In Tunisia, wheat yields may increase in some producing areas (Annabi et al. 2018). However, recurrent drought events may induce losses of approximately -50% in olive production, and the increase in floods could lead to a decrease of -13% in rainfed cereal production (Requier-Desjardins 2010). The effects of changes in precipitation regimes on olive production in the entire Mediterranean region were investigated by Tanasijevic et al. (2014) that pointed to the likely absolute need of irrigation in future olive cultivation. Large climate impacts have been also estimated (assuming no adaptation) for agriculture in Egypt increasing over time and triggering exceptional food price increases (McCarl et al. 2015). Sea level rise will also pose a threat to agriculture in Egypt leading to area losses and affecting, for instance, rice production (Chen et al. 2012; Sušnik et al. 2015). Similarly, heavy impacts of sea level rise and associated increased soil salinity (estimated to be three times the current one) on rice production have been estimated at the end of the century in Spain (Genua-Olmedo et al. 2016).

The increase in the atmospheric concentration of CO_2 could bring beneficial effects in terms of yield under optimal growing conditions (especially for C_3 crops such as wheat and barley) and could buffer some days more under drought conditions (Kimball 2016) but may also bring new nutritional challenges (Uddling et al. 2018; Asseng et al. 2019). Results also highlight the limited beneficial contribution of elevated atmospheric CO_2 concentration under pronounced water-stress conditions. Reductions in wheat protein yield by 5-10% have been estimated at some south-western locations of the basin (2040-2069 under the RCP8.5 scenario) (Asseng et al. 2019).

Concurrent and recurrent extremes, not fully considered in the current impact assessments, may well pose the main threat to the stability and the resilience of the Mediterranean production systems. Climate extremes occurring in other regions of the world may also trigger impacts through increased market volatility and price spikes (Chatzopoulos et al. 2019; Toreti et al. 2019). New and re-emerging pest and pathogens, usually not fully considered in impact assessments, may contribute to larger than estimated losses (Bebber et al. 2013, 2014). Another threat to food security and quality may be represented by mycotoxigenic fungal pathogens and higher level of contamination (Medina et al. 2017). Agriculture in the region may be also affected by increased risk of large fires, with a 34 to 140% rise according to the location and the scenario *(Section 4.3.2.1)*.

3.2.2.2 Marine food resources

Projected climate change is also expected to heavily impact marine food resources, which are overexploited already. Ocean warming, acidification, water pollution and constrained migration possibilities to cooler areas (due to sea enclosure) may lead to local extinction of up to 50% of exploited fish and marine invertebrates around 2050, affecting also endemic fishes, including commercial ones (e.g., Cheung et al. 2016) (*Section 4.1.2.1)*. Pollution from anthropogenic activities also affects fish population, notably in the Nile delta, with potentially serious consequences on human food security.

Besides warming, marine ecosystems are also sensitive to increasing atmospheric CO_2 concentration due to its rapid dissolution in seawater, which causes alterations in the chemistry of inorganic carbon with a lower pH and higher concentration of carbonic ions (Doney et al. 2009). The carbonic ion is an essential element for organisms that depend on the deposition of calcium carbonate ($CaCO_3$) through biomineralization for the formation of calcareous structures, such as the mollusk shells. If the biomineralization process does not occur properly, organisms reduce their growth rate and may present morphological anomalies that cause, for example, the loss of capacity of fixation to the substrate and diminishes feeding activity.

The joint effects of ocean warming and acidification may also include a number of biological alterations such as decreased ocean productivity (Behrenfeld et al. 2006), reduced growth and survival of calcifying organisms (Hoegh-Guldberg et al. 2007), changes in species distributions, altered food dynamics (Vergés et al. 2014), and altered incidence of disease (Burge et al. 2014). These effects can be translated into a diminution of the abundance and, therefore, of the fisheries production. The affected activities would be both extractive fishing (shellfish, in this case) and aquaculture that is extensively used in coastal areas (Gazeau et al. 2014; Prado et al. 2016). The example of mollusks is perhaps the most quoted but we should not forget that other organisms are subject to biomineralization processes for the formation of the skeleton (e.g., fish), and thus, can also be negatively affected. The effects on habitats can also be quite important because at lower pH some plants can be affected directly or indirectly and even calcareous substrates of biological or mineral origin. All this has to be added to the benthic organisms with calcareous structures that are not commercial species but are the base of the food web for upper trophic groups.

To fully understand the potential effects of global change, it is important to focus on population bottlenecks, which are usually early developmental and reproductive stages (Thorson 1950). Survival of adult and juvenile bivalves shows little dependence on pCO_2 (Berge et al. 2006; Hendriks et al. 2010; Range et al. 2012), although increasing temperature may result in increasing mortality and metabolic rates (Basso et al. 2015). In contrast, gametes, embryos, and larvae are generally more sensitive to both temperature and elevated pCO_2 stress (Havenhand et al. 2008; Parker et al. 2009, 2010) because the deposition of $CaCO_3$ shells and skeletons begins in these stages (Kurihara et al. 2007). Yet, there is also a wide natural variability in pH ranges of seawater (7.5-8.5, with even lower values possible in semiconfined waters; Flecha et al. 2015) which may partly account for observed differences in the responses of calcifying organisms to acidification and complicates the generalization of patterns across species and ecosystems (Kurihara 2008).

3.2.3 Adaptation and mitigation

3.2.3.1 Adaptation of the food system to environmental change

The assessment of how climate change will affect crops is essential for policymakers, planners, farmers and all the other actors of the agriculture sector to develop, propose and implement adaptation and mitigation strategies at the local/regional scale to make agriculture more resilient to changes (Liebig et al. 2016). For instance, future water availability and water demands put the current management model in question, so adaptation choices have to be necessarily developed (Iglesias and Garrote 2015; Ronco et al. 2017). The projected water scarcity and increase of drought events will limit adaptation actions based on irrigation. Under some scenarios combining climate change and population growth, half of the Mediterranean countries (mainly in the southern and eastern shores) are projected to be unable to cover irrigation water demands by the end of the century (Fader et al. 2016) *(Section 3.1.5.2)*.

Crop distribution, diversity, varieties, rotation patterns, and agro-management represent key elements of adaptation strategies at the farm scale (Valverde et al. 2015; EEA 2019). Breeding and sowing new varieties water and heat stress tolerant (del Pozo et al. 2016, 2019; Hatfield and Dold 2019), adapting the crop calendar (Ronco et al. 2017), using optimal crop diversification (Lin 2011) could be all used as adaptation strategies. The inclusion or reintroduction of wild food plants, neglected and underutilized crops, also add to diversifying the agricultural portfolio of crops with potential resilience against climate change. North-south differences were estimated for the adaptive capacity in agriculture (Grasso and Feola 2012), mainly associated with soft factors (e.g., information) rather than with other more structural ones (such as technological and infrastructural perspective). Looking at the implemented adaptation strategies in the Mediterranean (Harmanny and Malek 2019), the most common ones are farming practices (diversify and change crop types, adjust crop rotation), water management (modify irrigation practices), and farm management (diversify source of income). The main drivers of such adaptation actions are water scarcity, environmental factors (climate change, soil degradation and erosion, sustainability), and socio-economic factors (Harmanny and Malek 2019).

Combining several actions can also lead to better results in terms of crop yield. Higher wheat yield under different water conditions in Lebanon were achieved by using a drought-tolerant variety, conservation tillage and precise irrigation during grain filling[19]. A higher degree of diversification, more varieties of the main crops, earlier sowing, and hedgerow planting were also identified as actions to increase the resilience in a pilot farm project in southern France[20]. Crop productivity (vines, corn, apples, lucerne) was increased using different agronomical practices to increase water availability by plants without increase water from irrigation in Spain[21]. Some strategies have also additional indirect benefits, such as soil organic carbon accrual due to agroforestry (Chatterjee et al. 2018), cover crops (Aguilera et al. 2013b; Vicente-Vicente et al. 2016), and local crop varieties with a higher residue and root biomass production (Carranza-Gallego et al. 2018) *(Section 6.4)*. Improved soil erosion control, increasing soil fertility, retaining soil moisture and resource efficiency are the dominant drivers for conservation agriculture, organic farming and agroforestry (Lagacherie et al. 2018). Conservation agriculture represents a relatively widely adopted management system that aims to sustain long-term crop productivity and system's sustainability (Kassam et al. 2012). The environmental and economic benefits of no-till implemented as its core principle combined with other practices have been pointed out in several studies (Peigné et al. 2007, 2015; Cooper et al. 2016; Vincent-Caboud et al. 2017). The use of sectorial climate services (Buontempo et al. 2020; Ceglar et al. 2020) at different spatio-temporal scales will also be a key adaptation measure to reduce the risks and alleviate the impacts of extreme events.

Advanced agricultural technologies may also influence the ability of the region to produce food (Asseng et al. 2019) and adapt to the changing climate and environment. Precision agriculture will make possible a targeted monitoring of plant growth and thus a more efficient use of resources (water, pesticides, nutrients) by combining technologies for data collection (e.g., in-field sensors, weather stations, imaging) with analytical tools, computer vision and artificial intelligence technologies (Bhakta et al. 2019). Precision agriculture has been already applied by some Mediterranean countries (e.g., Israel, Italy, Spain), in viticulture and other crops, and holds a significant technological innovation potential. At the same time, bio and nanotechnologies may help to ensure food security and increase productivity (King et al. 2018; Santeramo et al. 2018a). Cultured, plant-based and insect-based meat are emerging technologies for producing alternatives to meat-

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[19] Results from the SWIM-project ACLIMAS, www.aclimas.eu

[20] Results from the LIFE-project AGRI-ADAPT, www.agriadapt.eu

[21] Results from the LIFE-project MEDACC, http://medacc-life.eu/

derived proteins whose demand is growing. High costs and consumer reluctance appear to be be major obstacles to the implementation of these techniques (Santeramo et al. 2018a; Gómez-Luciano et al. 2019).

3.2.3.2 Mitigation of climate change drivers

Mediterranean climatic conditions host two main crop production systems, rain-fed and irrigated, largely differing in terms of management and, consequently, emissions of N_2O, a potent greenhouse gas. Rain-fed systems are usually characterized by periods with low soil moisture and cold temperatures, thus with decreased soil micro-biological activity and N_2O fluxes. Recent reviews have shown that N_2O emission factors (EF) from rain-fed Mediterranean cropping systems are much lower than the IPCC-default EF threshold of 1% (Aguilera et al. 2013b; Cayuela et al. 2017). Rain-fed crops in Mediterranean regions have lower EFs (EF: 0.27%) than irrigated crops (EF: 0.63%). Irrigated systems usually receive large amounts of water and nitrogen inputs, which create favorable soil conditions for N_2O emissions. Emission factors in these systems fluctuate greatly according to water management and the type and amount of fertilizer used (e.g., synthetic, solid or liquid manures). Sprinkler irrigated crops lead to N_2O emission factor of 0.91%; whereas, drip irrigated systems emit at a lower rate (EF:0.51%) (Cayuela et al. 2017).

Among the most relevant mitigation strategies, there are: nitrogen fertilization optimization; improved water management; better storage of soil organic carbon and carbon sequestration in soil and perennial wood structures of woody crops; management of crop residues and agroindustry by-products.

Nitrogen fertilization optimization

Optimized nitrogen fertilizer application (in terms of input rate and time of application), as well as the careful selection of the type of fertilizer used are crucial to improve crop productivity while reducing N_2O emissions (Sanz-Cobena et al. 2017). An additional effect could be achieved by applying already existing nitrogen (organic fertilizer) when possible or with the use of nitrification and urease inhibitors. Reduction of nitrogen application rates according to soil nitrogen availability and crop yield potential may decrease nitrogen surpluses and subsequent direct and indirect N_2O emissions, while saving energy and abating other greenhouse gas emissions (e.g., associated to manufacturing synthetic fertilizers). Significant effects of nitrogen application timing on N_2O emissions have been reported from cereal crops in Mediterranean countries such as Spain (Abalos et al. 2016). The estimated N_2O mitigation potential, through adjusted fertilization (rate and timing) in Mediterranean agro-ecosystems ranges between 30% and 50% compared to non-adjusted practices. Replacing mineral nitrogen with organic fertilization provides not only nitrogen, phosphorus, potassium (NPK) and micronutrients to the soil and crop, but also organic carbon when using solid fertilizers (i.e., solid manure, composts, etc.), which is highly beneficial in Mediterranean soils with low organic carbon contents (Aguilera et al. 2013a; Funes et al. 2019).

In areas were croplands co-exist with livestock farms, using a farm sub-product allows the reuse/recovery of farm products, thus decreasing the volume of waste that needs to be managed, and then avoiding the emission of greenhouse gases both in the management of such wastes and in the manufacturing of new synthetic fertilizers. In Mediterranean areas, the efficient use of manure of fertilizer should be encouraged, and this could be facilitated by increased cooperation between farmers´ unions. The use of organic sources of fertilizers may also decrease the need to import synthetic sources thus decreasing greenhouse gas emissions from the production and transport stages. Unfortunately, current intensive livestock production systems are often decoupled from agricultural systems (Sanz-Cobena et al. 2017).

The N_2O emission reduction at plot scale depends on the form of manure used. Solid manures have proved to significantly decrease N_2O emissions (ca. 23%) in Mediterranean systems (Aguilera et al. 2013b), although there is some contradictory information in the scientific literature (Webb et al. 2004; Thorman et al. 2007). For liquid manures (i.e., slurries), no significant differences have been observed when these substitute synthetic nitrogen sources. This seems to be a consequence of the strong similarities between available nitrogen, in the form of NH_4^+, in both fertilizer types (Meijide et al. 2009; Plaza-Bonilla et al. 2014).

Trade-offs in the form of NH_3 emissions, odors, enhanced denitrification rates due to coexistence of high soil water contents and organic carbon suitable for denitrifiers, must be considered together with the application technology used to fertilize with liquid manures. Nitrification and urease inhibitors (NI) are used in a wide range of agro-climatic regions (Akiyama et al. 2010; Gilsanz et al. 2016). In Mediterranean soils, NIs have shown high mitigation efficiency in rain-fed and irrigated fields, with a likely indirect effect on denitrification in the latter systems (Meijide et al. 2010). Soil texture may regulate mitigation efficiency (Barth et al. 2008) but to a limited extent, since soil texture has been shown to have a small influence on the inhibition of nitrification (Gilsanz et al. 2016).

Improved water management

The different soil conditions between irrigated and rain-fed crops affect soil microbial processes, which control the fluxes of carbon (carbon dioxide, CO_2; methane, CH_4; organic carbon) and nitrogen (nitrous oxide, N_2O; molecular nitrogen, N_2; nitrate, NO_3; ammonia, NH_3). Soil moisture is a key factor affecting N_2O losses (del Prado et al. 2006; García-Marco et al. 2014), hence the potential for N_2O mitigation linked to irrigation technologies is high, even above 50% (Sánchez-Martín et al. 2008, 2010; Guardia et al. 2016). The lower amounts of water applied in subsurface drip irrigation (SDI) or normal/superficial drip irrigation (DI) through more frequent irrigation events, generate "dry" and "wet" areas in the soil, lowering the overall soil moisture and favoring nitrification over denitrification (Sánchez-Martín et al. 2010), thus reducing N_2O emissions. Drip irrigation systems have shown an N_2O emission factor of only 0.18%, compared to 1% in sprinkler systems (SI), showing the mitigation potential of irrigation technologies in the Mediterranean region (Cayuela et al. 2017). Optimized irrigation techniques to decrease greenhouse gas emissions from Mediterranean regions are particularly used in perennial crops and intensive vegetable cropping systems and in paddy soils (water table management). Other strategies which have been shown to be effective increasing nitrogen use efficiency and reducing N_2O emissions are fertigation and sub-surface drip irrigation (Ayars et al. 2015).

Soil improvement

Most Mediterranean agricultural landscapes are subject to soil organic matter depletion, particularly in the southern and eastern parts of the basin (Ryan et al. 2006). In the northern part of the basin, the issue of low soil organic matter (SOM) is of particular concern for perennial systems such as orchards and vineyards (Meersmans et al. 2012). Maetens et al. (2012) showed that bare soils, vineyards and orchards in Europe are prone to high mean soil losses (10-20 t ha^{-1} yr^{-1}), while cropland and fallow show smaller values (6.5 and 5.8 t ha^{-1} y^{-1}) largely because the latter occupy land exhibiting little or no slope. SOM in the Mediterranean countries is somewhat affected by climate change, with land use types such as permanent pasture and cropland being more sensitive than forests (Fantappié et al. 2011). Large losses of SOM may also be caused by erosion caused by the torrential storms that frequently occur in Mediterranean regions (Lagacherie et al. 2018). Likewise, rainfall shortage limits net primary productivity and, in turn, soil carbon buildup. Low carbon inputs driven by limited soil moisture availability are exacerbated by the adoption of certain management practices. Crop residues competition for livestock feeding or the introduction of long fallowing in the crop rotation are two examples of typical management practices in the Mediterranean region that have contributed to the reduction of carbon inputs returned into the soil.

Besides decreases in carbon inputs, agricultural management may also cause soil organic carbon (SOC) losses. Reduction or complete cessation of tillage decreases the direct incorporation of fresh organic debris into deeper soil layers. The absence of tillage (NT) slows down aggregate turnover and increases the physical stabilization of SOC within soil aggregates (Álvaro-Fuentes et al. 2008; Mrabet 2008; Plaza-Bonilla et al. 2010). When tillage is avoided, an approximate annual increase of 1% in SOC can be observed in Mediterranean croplands (Aguilera et al. 2013a). These estimates are highly dependent on soil depth, since vertical SOC distribution in no tillage (NT) and conventional tillage (CT) systems are different (Cantero-Martínez et al. 2007). Further, the assumption of a steady and linear C sequestration may not hold true, because the annual carbon accumulation rate tends to decrease in the long-term (Álvaro-Fuentes et al. 2014).

Long crop rotations have been proposed in rain-fed Mediterranean systems to enhance carbon sequestration and restore soil fertility and structure (Benlhabib et al. 2014). The effect of crop rotations on carbon sequestration is highly dependent on time with no significant effect reported in short-term studies (Saber and Mrabet 2002; López-Bellido et al. 2010). Positive effects in long-term experiments (>15 years) could appear if crop biomass is properly managed after harvest (Masri and Ryan 2006; López-Bellido et al. 2010; Martiniello and Teixeira da Silva 2011). The effect of crop rotations on SOC stocks is also dependent on the type of crops included in the rotation (Triberti et al. 2016) and the management of crop residues. The introduction of perennial crops has shown benefits (di Bene et al. 2011; Pellegrino et al. 2011). The substitution of bare fallows by any crop has been associated with SOC stabilization in NT systems (Álvaro-Fuentes et al. 2009), and to reduced soil erosion (Boellstorff and Benito 2005). The effect of inclusion of grain legumes in rain-fed yearly rotations on carbon sequestration is uncertain, due to their low biomass production, although their conversion to stabilized soil organic matter could be more efficient than that of cereals (Carranca et al. 2009). Consequently, the highest potential of fallow and legumes for mitigating greenhouse gases from these types of cropping systems comes from the avoidance of fertilizer production emissions.

Estimating the greenhouse gas mitigation potential of using crop residues and organic by-products from agroindustry in Mediterranean areas implies accounting for: (i) soil amendments to improve SOM and enhance SOC sequestration (Aguilera et al. 2013a), (ii) feedstock for bioenergy production (di Giacomo and Taglieri 2009; Spinelli and Picchi 2010), (iii) co-substrate for composting (Santos et al. 2016), (iv) feed for livestock (Molina-Alcaide and Yáñez-Ruiz 2008) or (v) construction materials (e.g., animal beds, buildings). The potential to increase SOC levels by using agroindustry by-products, as in crop residues, depends on their composition and degradability. However, agroindustry by-products vary widely in their chemical composition and therefore in their degradation rates. For example, olive and mill waste as they have very low degradation rate in the soil have been found to be good amendments to increase SOC when applied to the soil (Saviozzi et al. 2001).

Besides the potential direct greenhouse gas reduction that any strategy involving the return of the crop residues and agroindustry by-products to the soil may cause (Kassam et al. 2012; Plaza-Bonilla et al. 2014), applying these materials, treated or untreated, as soil amendments can also deliver environmental co-benefits. These benefits include erosion reduction when raw products are used for mulching (Blavet et al. 2009; Jordán et al. 2010) or, in general, the closing the nutrient cycles, with associated potential reductions of fertilizer use and reductions in draught force and fuel consumption for soil tillage (Peltre et al. 2015). Trade-offs may occur with some of the strategies that may results in larger greenhouse gas mitigation potential. For example, the use of crop residues on the soil surface might pose a risk of fire in some Mediterranean areas and, sanitary, pollution and legal constraints may apply, especially if the by-product is applied to crops e.g., fresh vegetables without pre-treatment.

3.2.3.3 Synergies and trade-offs between adaptation and mitigation

Developing sectorial adaptation strategies requires considering also the mitigation needs and efforts (Sanz-Cobena et al. 2017). For N_2O mitigation and its links with adaptation measures, the pedoclimatic conditions for soil processes in Mediterranean cropping systems imply different N_2O emission patterns as compared to temperate soils (Aguilera et al. 2013b). Nitrification and nitrifier-denitrification, and not denitrification, are very often the main pathways leading to emissions of nitrogen oxides in rain-fed Mediterranean cropping systems (Sánchez-Martín et al. 2008; Kool et al. 2011; Aguilera et al. 2013b; Norton and Ouyang 2019). These two processes are favored by conditions of soil water content (i.e., water filled pore space, WFPS) under saturation (i.e., 40–60% WFPS). Denitrification may play a predominant role in anaerobic soil microsites in intensively managed and irrigated systems (Sanz-Cobena et al. 2012, 2014). Consequently, different cumulative N_2O emissions have been proposed for rainfed crops (0.7 kg N_2O-N ha^{-1} yr^{-1}) and for e.g., sprinkler irrigated crops in Mediterranean areas (4.4 kg N_2O-N ha^{-1} yr^{-1}) (Cayuela et al. 2017).

The importance and potential for N_2O mitigation and the best mitigation strategy differ greatly depending on the cropping system, being highly affected by adaptation strategies regarding to soil organic carbon and water management in cropping systems. In this sense, increasing the generally low carbon content of Mediterranean soils is an important greenhouse gas mitigation strategy (Robertson et al. 2000), and is also a priority for preventing erosion and improving soil quality. Soil organic carbon content of Mediterranean soils is typically lower than in temperate areas (Chiti et al. 2012), and degradation processes are present in many areas (Lahmar and Ruellan 2007), a trend that is expected to be exacerbated by climate change in the coming decades (Al-Adamat et al. 2007). However, SOC in Mediterranean croplands is also highly responsive to management changes such as organic amendments, cover crops and tillage reductions, and there is a high potential for SOC storage through land restoration. Significant carbon sequestration rates have been observed after the application of recommended management practices and organic management in Mediterranean cropping systems (Aguilera et al. 2013a). This high responsiveness is reflected in SOC storage rates nearly one order of magnitude higher than the 0.4% annual SOC increase proposed by the "4 per 1,000" initiative, as reported in a recent meta-analysis (Chabbi et al. 2017; Minasny et al. 2017) . This meta-analysis underlined the differences between herbaceous and woody crops regarding the carbon sequestration potential and the practices to be applied in each system. Thus, organic fertilizers, tillage reduction and residue retention are effective practices in herbaceous systems. Woody systems, in which the storage potential is higher, would greatly benefit from maintaining a soil cover and making use of agro-industry byproducts, such as composted olive mill waste, as a source of organic matter (Vicente-Vicente et al. 2016).

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3

RESOURCES
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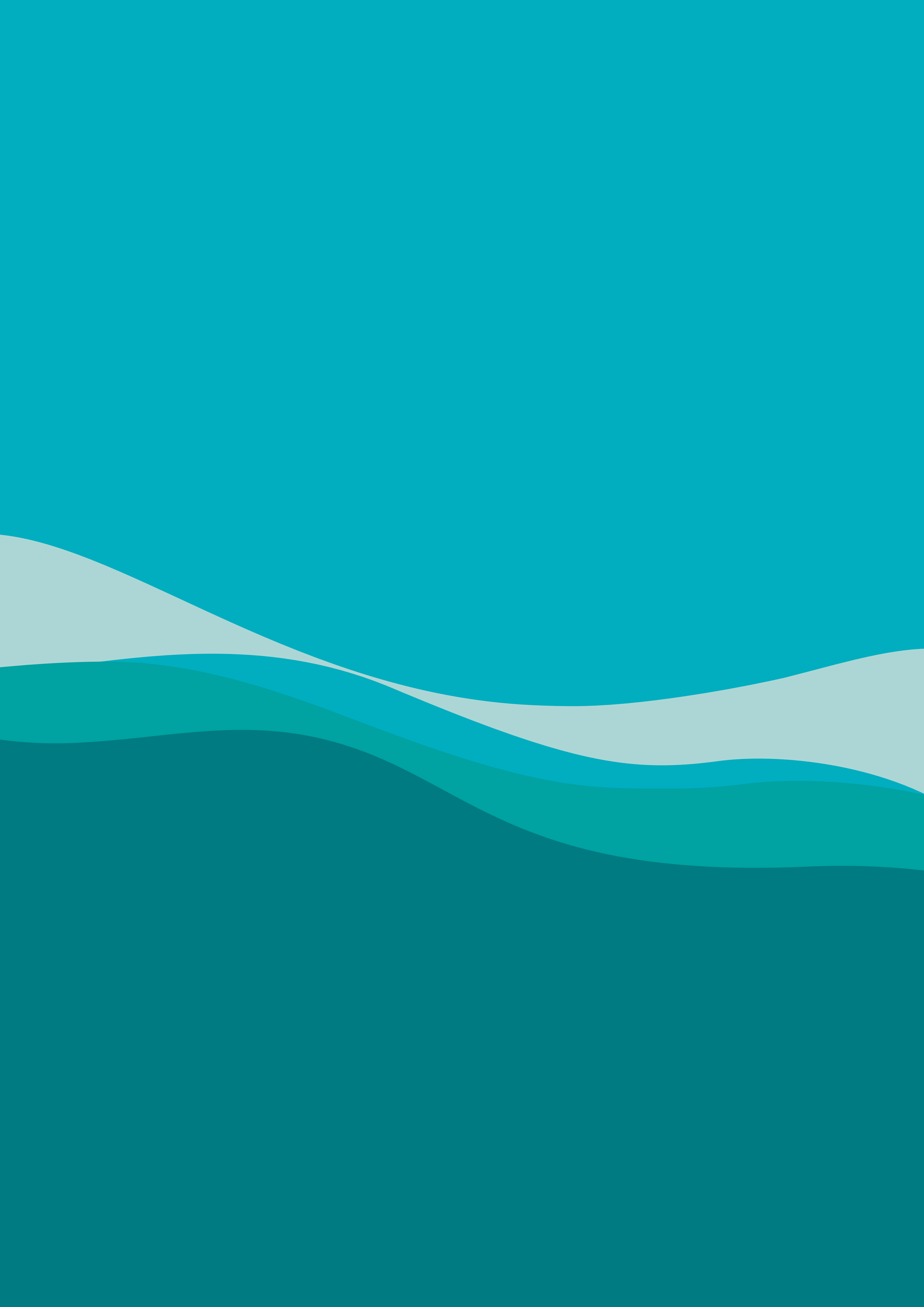
This chapter should be cited as: Drobinski P, Azzopardi B, Ben Janet Allal H, Bouchet V, Civel E, Creti A, Duic N, Fylaktos N, Mutale J, Pariente-David S, Ravetz J, Taliotis C, Vautard R 2020 Energy transition in the Mediterranean. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 265-322, doi:10.5281/zenodo.7101088.*



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3.3 Energy transition in the Mediterranean

Executive summary

Current Mediterranean greenhouse gas emissions amount to a relatively low level of 6% of the global emissions, a proportion close to its proportion of the world population (7.4%). The expected impacts of climate and environmental changes necessitate an accelerated energy transition in the countries of this region to enable a secure, sustainable and inclusive development. The primary energy consumption in the Mediterranean Basin from 1980 to 2016 has steadily increased by approximate 1.7% annually. This trend is mostly related to a steady increase in the consumption of oil, gas, nuclear and renewables and is caused by changes in demographic, socioeconomic (lifestyle and consumption) and climatic conditions in the region. While the northern rim countries advance in gradually diversifying their energy mix, improving energy efficiency and increasing the fraction of renewable energy sources, the eastern and southern rim countries (SEMCs) still lack behind in these developments. The Mediterranean Basin, especially the SEMCs, has large potential for renewable energy, terrestrial as well as marine, including wind, solar, hydro, geothermal, bioenergy, waves and currents. With the increase of the share of renewables, the electricity transmission system will be more exposed to weather variations and may be threatened by specific weather conditions that are usually not considered as extremes.

The projected energy demand trajectories for the next few decades in the Mediterranean Basin are significantly different for the northern versus the eastern and southern rim countries. The energy demand in the North has decreased by 4% since 2010, due to a moderate population growth and a decreasing gross domestic product, and expected to continue to decrease until 2040. The SEMCs have experienced sustained economic and population growth over the past years, which resulted in a growth in a 6% energy demand since 2010. Towards 2040, the energy demand is expected to continue to increase. Although fossil fuels are currently expected to remain the dominant component of the energy mix until 2040, renewables will become the second most used energy source in the Mediterranean Basin and triple until 2040.

A significant gap between energy supply and demand is expected, particularly in SEMCs. It is, therefore, more than necessary to move rapidly towards a restructuring of the energy sector, particularly the more pronounced integration of renewable energies. Mitigation of greenhouse gas emissions and adaptation to climate change will require investments from households, companies and governments. Regional energy market integration and cooperation are crucial to unleashing cost-effective climate change mitigation.

3.3.1 Introduction

Despite a relatively low share in global greenhouse gas emissions (6%), close to its proportion of the world population (7.4%), the Mediterranean region is severely hit by impacts of climate change *(Section 2.2)*. The nature and magnitude of current and future impacts of climate and environmental change in the Mediterranean region, and the associated vulnerability of people, are important imperatives to accelerate the energy transition in all countries of this region in order to enable them to secure a sustainable and inclusive development trajectory.

While the energy transition raises common issues for the region as a whole, the nature and extent of these issues are expressed differently between both shores of the Mediterranean. Northern countries have achieved at least two decades of reforms that enabled them to gradually diversify their energy mix and control to some extent their energy demand due to the deceleration of their demographic growth and the gains in terms of energy efficiency. With respect to the relatively high level of CO_2 emissions from these countries, their energy transition is bound by a rationale that is different from that of Southern and Eastern Mediterranean countries (SEMCs).

The energy transition issue in the SEMCs is closely linked to the sustainability of their development model. These countries face multiple challenges related among others to the fast population growth (607 to 659 million inhabitants, depending on the scenario, by 2050 against 534 million in 2015, *Section 2.7*) which would put additional pressure on energy demand to accompany the surge of urbanization and increasing needs of various sectors of the economy. Therefore, the energy demand in the south-east Mediterranean countries is expected to rise nearly 118% by 2040. The polarization of SEMCs' energy mix on fossil fuels, mainly oil and natural gas, is another important challenge, especially for the countries

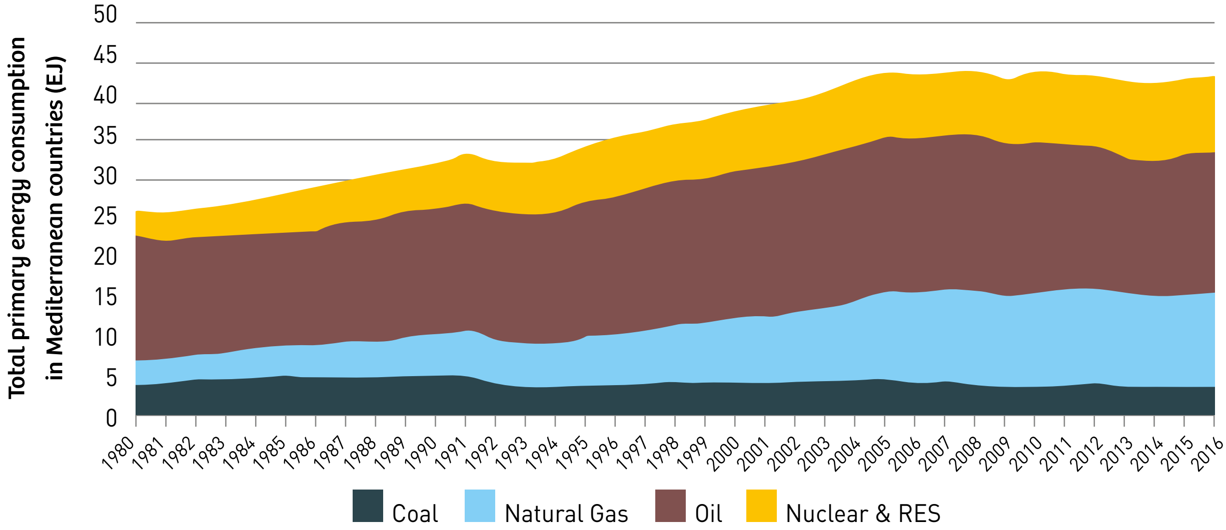

Figure 3.22 | Evolution of Primary Energy Consumption across the Mediterranean for the period 1980-2016, in exajoules EJ (10^{18} joules) RES - Renewable Energy Sources (EIA 2019).

where hydrocarbon export revenues play a central role in the macro-financial balance.

3.3.2 Past trends and current situation

3.3.2.1 Mediterranean energy situation

The Mediterranean region holds 5% of the world oil and gas reserves, of which 98% are in the countries of the southern rim (UNEP/MAP 2007; Plan Bleu 2008; UNEP/MAP-Plan Bleu 2009). There is also a significant potential of renewable energies, in particular, solar and wind energies. The Mediterranean region as a whole has been experiencing a steady increase in primary energy consumption, from about 26 exajoules (EJ) in 1980 to 34 EJ in 1995 to 43 EJ in 2016, representing an approximate annual growth rate of 1.7% as in *Fig. 3.22*. This trend concerns oil, gas, nuclear and renewables, combined with a small decline in the use of coal. In 2005 the combination of

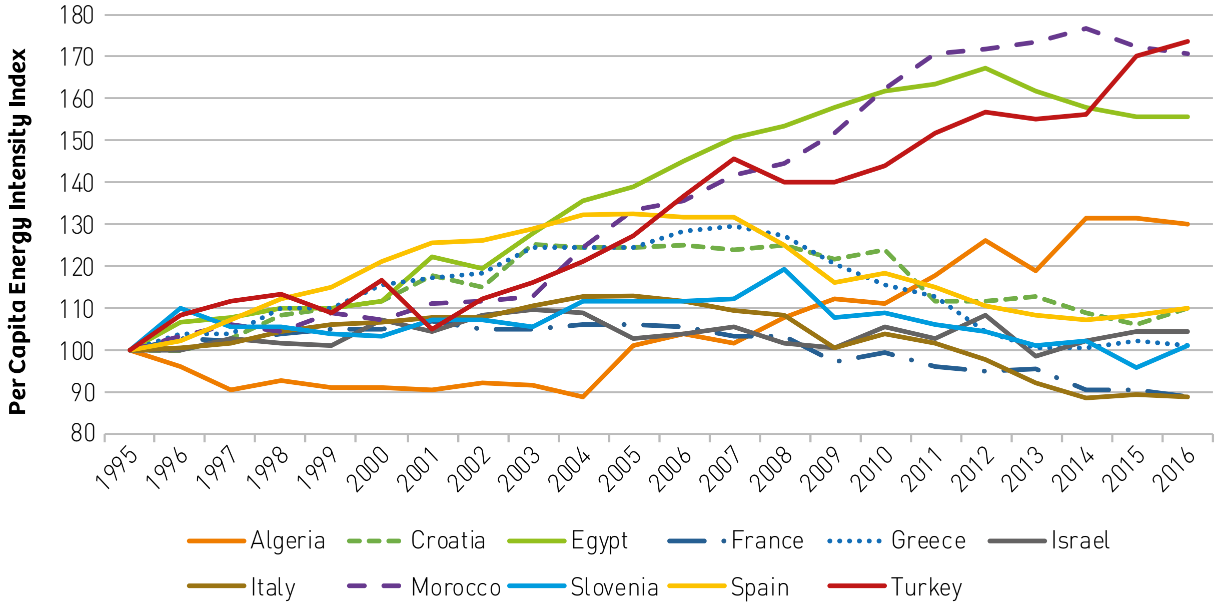

Figure 3.23 | Evolution of per capita Energy Intensity Index (energy divided by GPD) in selected Mediterranean countries; 1995 used as a year of reference (EIA 2019).

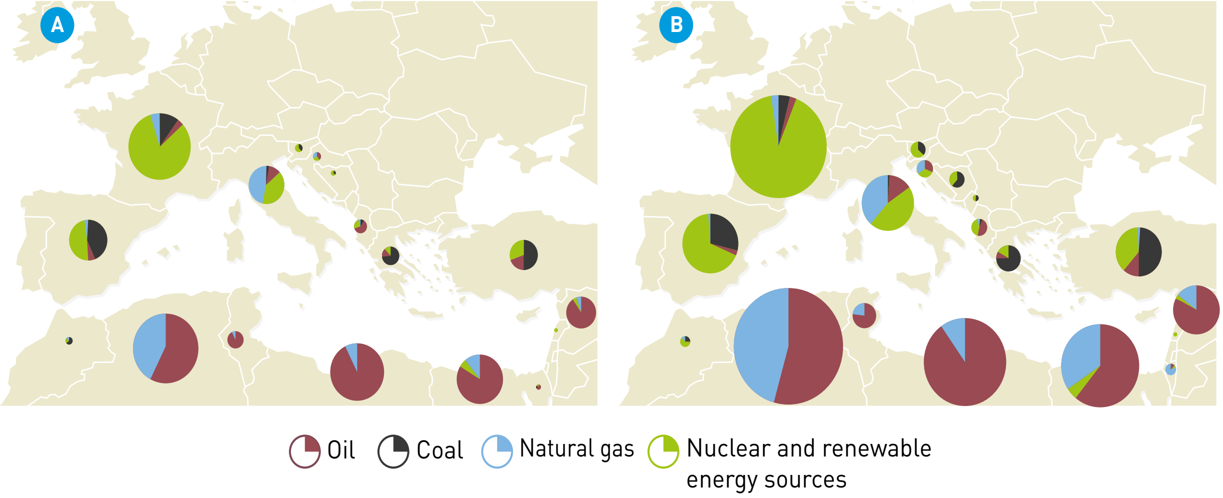

Figure 3.24 | Evolution of primary energy production across the Mediterranean between 1995 (A) and 2016 (B) (Data from the EIA 2019).

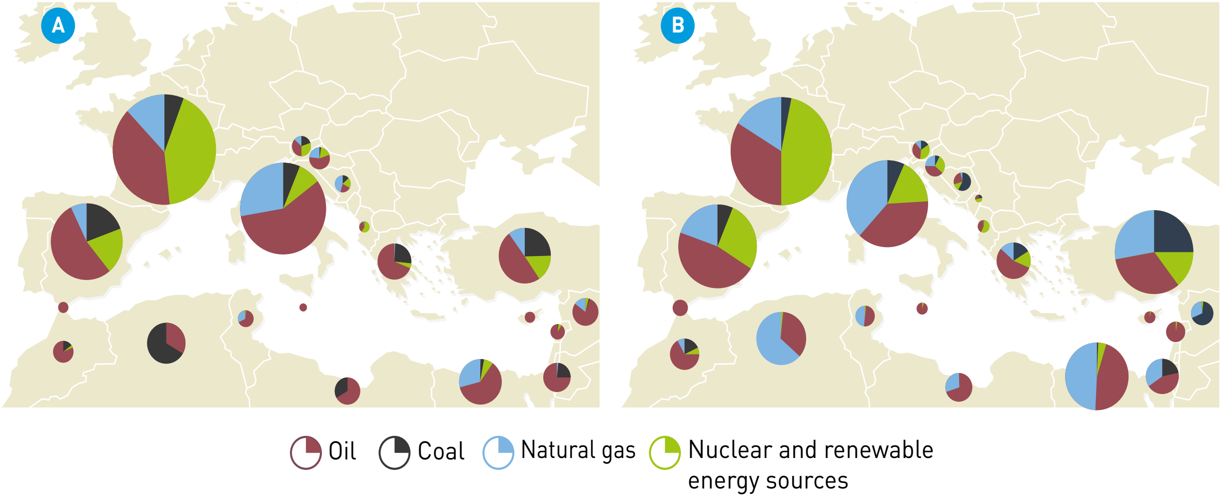

Figure 3.25 | Evolution of primary energy consumption across the Mediterranean between 1995 (A) and 2016 (B) (Data from the EIA 2019).

mechanisms that include reduced energy intensity by some large consumers, economic crises and political instability, and improved energy efficiency halted the increase in consumption.

Mediterranean countries differ in their patterns of energy use. The level of industrialization, sectoral energy profiles, prevailing climatic conditions and the level of economic growth is among the crucial aspects affecting the energy intensity of each economy. *Fig. 3.23* illustrates the evolution of the per capita energy intensity, expressed as units of energy per unit of GDP, in a selection of Mediterranean economies. Egypt, Morocco and Turkey show the highest increase in energy intensity during the period 1995-2016, driven by the economic growth. Partly hampered by the financial crisis and partly driven by energy efficiency measures, the French and Italian economies show the highest decline in energy intensity. Others, such as Greece and Spain, had experienced an increase until the mid-2000s but the subsequent financial crisis brought energy intensity back down and has stabilized in the period 2012-2016.

In terms of the energy mix, *Fig. 3.24* and *3.25* illustrate the recent evolution of primary energy production and consumption across the Mediterranean for the period 1995-2016 (EIA 2019). In absolute terms, during this period, the

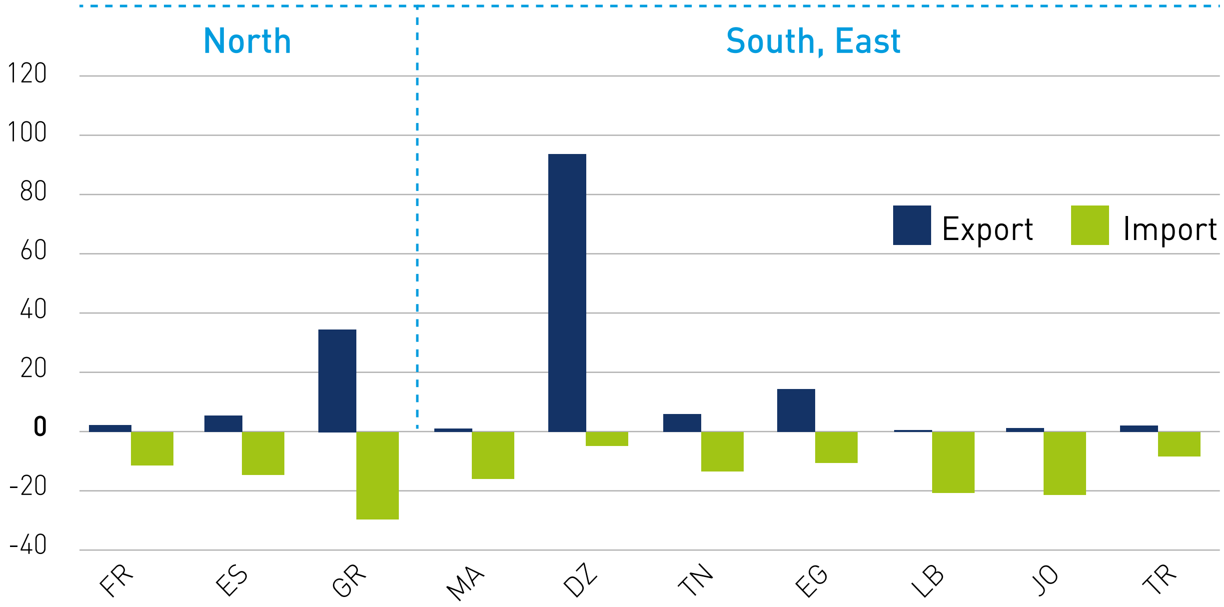

Figure 3.26 | Energy weight in trade balance (2017-2018) (MEF 2019). (Country code: Appendix D)

contribution of oil has remained stable at 17 EJ, while consumption of coal has experienced a mild gradual decrease from 4.1 to 3.7 EJ during the two reference years. Primary energy consumption of natural gas has doubled from 6 EJ in 1995 to 12 EJ in 2016, while nuclear and renewable energy sources contribution has risen from 7 to 10 EJ between 1995 and 2016.

On the national level, France has the largest energy-consuming economy in the Mediterranean. Its primary energy consumption has risen from 9.1 EJ in 1980 to 10.7 EJ in 1995, at which level it has returned by 2016 after peaking at 12.1 EJ in 2006. In both 1995 and 2016, roughly 50% of the primary energy consumed, was produced locally (EIA 2019); the vast majority of this relating to the large share of nuclear power in the country's energy mix (UN DESA 2016).

In 1995, the vast majority of Mediterranean nations were mostly dependent on oil, primarily imported, except for Algeria, Egypt, Libya, Tunisia and Syria *(Fig. 3.25)*. The importance of fossil fuels in the energy mix of most of the Mediterranean countries affects their trade balance negatively *(Fig. 3.26)* (MEF 2019). The SEMCs suffer more from this negative impact because most of them are net importers, and the energy imports can amount to, for some countries, up to 20% in the trade balance.

By 2016, oil dependence was reduced to a certain extent, as the share of natural gas and low carbon technologies has increased. Despite the increased shares of less carbon-intensive or carbon-neutral energy sources, increasing energy demand has continued to drive greenhouse gas emissions upwards in the region. An attempt to diversify and decarbonize the energy mix is underway, driven mainly by the deployment of renewable energy technologies, as well as substitution of carbon-intensive coal and oil with natural gas. The energy mix is still heavily dependent on fossil fuels.

The shift in energy carriers is a consequence of costs, constraints, regulations and new technologies, among others. The services that make use of these energy sources are, again, disparate and in various states of growth or decline depending on the country. *Fig. 3.27* shows the change in energy use in various sectors of the economy for selected Mediterranean countries. The selected countries provide a good representation of the situation in the Mediterranean as a whole, as they are the region's most significant energy users.

There are some clear-cut sectoral trends worthy of note, and some which are not easily explainable by raw data alone. All examined countries exhibit consistent growth in the transportation sector. This is in line with increases in both passenger-km and increased economic activity. This trend is mostly following an increased uptake of private vehicles in the South such as in Turkey, Israel, Egypt, Algeria and Morocco, which is also partially the case for countries in the North Mediterranean such as France, Italy, Spain and Greece, but for those countries, final consumption

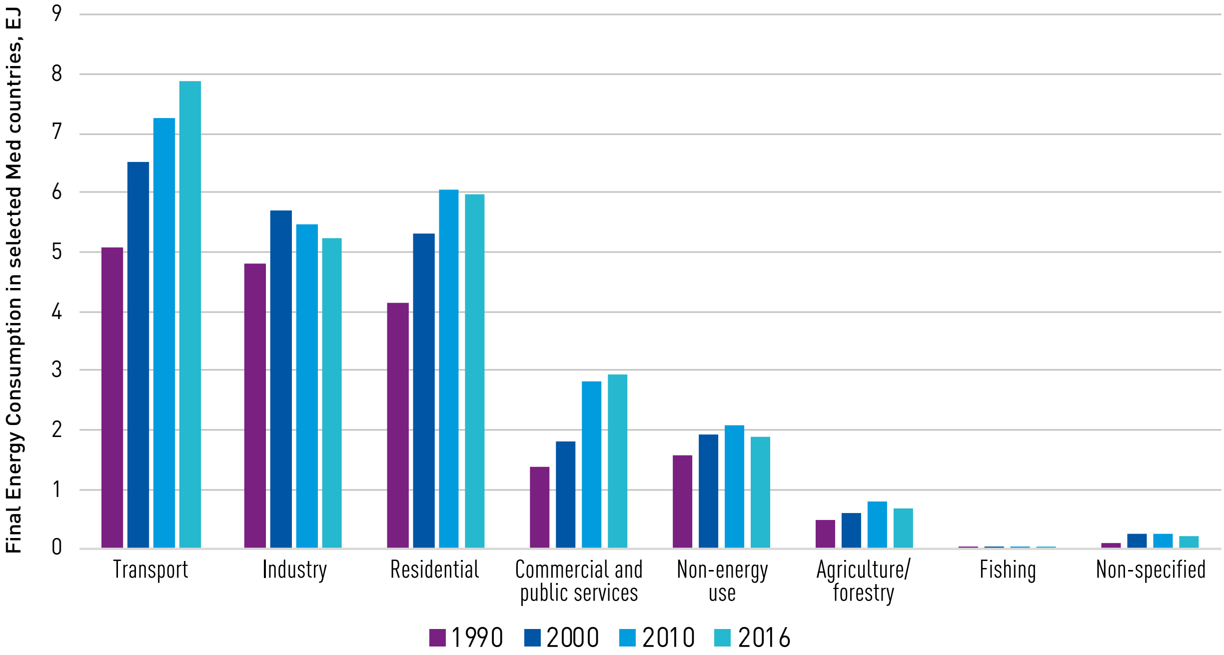

Figure 3.27 | Energy consumption in selected Mediterranean countries 1990-2016. Data for France, Italy, Spain, Greece, Turkey, Israel, Egypt, Algeria and Morocco (IEA 2018).

in transportation has been declining since 2010. This decline is attributable to a modal shift, policies and regulations that target energy savings in transportation, economic recession, increased use of more efficient vehicles and gradual electrification of transport. These characteristics are not yet strongly apparent in the countries of the South. There is evidence, that energy consumption in transportation will fall, with wider adoption of some (or all) of the above measures across the Mediterranean (OME/MEDENER 2016).

Residential energy use follows a similar upward trajectory in both North and South Mediterranean countries up to 2010, after which final energy consumption in the North is decreasing. The partial decline shown in *Fig. 3.27* is attributable to lower consumption in the four EU countries of this set. There are numerous challenges and opportunities for reducing energy demand. Improved energy efficiency measures and technologies will allow buildings to lower their energy demand per m^2, but the proliferation of air-conditioning due to higher living standards and increased demand due to climate change-induced higher ambient temperatures may also intensify demand in the region (OME/MEDENER 2016).

Energy use in industry differs significantly between northern and southern Mediterranean countries *(Fig. 3.27)*. While the countries of the north experience a decline due to structural change in the economy, with a shift to services and transformation industry that are less carbon-intensive (from primary industries that are more carbon-intensive), fuel switching and technical efficiency measures, the countries in the south exhibit the reverse, mainly due to new investments in industrial infrastructure and growing economies. Commercial and public service energy use is growing across all the countries examined, but at a much higher rate in the south, where the sector's registered energy use was limited in 1990. Growth in this sector's energy use reflects the changing dynamics in the economies of all countries involved.

Overall the energy consumption in the Mediterranean is increasing but tapering-off of overall consumption. There are multiple sectoral dynamics and a distinct North-South differentiation in the energy use patterns. While the total use seems to be levelling off, there are significant challenges on the horizon about increased demand for industry and services, especially in the south. The projected increase in cooling of living and working places, as caused by climate-change-induced temperature increases, represents the most significant increase in projected energy consumption in the region. The rapid growth in electricity demand is contributing most to the energy demand increase. Between 1971 and 2006 the Mediterranean region saw a fourfold increase in electricity consumption.

Transport continues to be the primary consumer compared with the other sectors in the Mediterranean. Transport electrification is set to shift the resource mix towards low carbon forms of energy but does not reduce overall energy consumption.

3.3.2.2 Renewable energy resources

The Mediterranean Basin benefits from a temperate climate with mild winters and warm and sunny summers, with a large potential for energy production from terrestrial renewable energies, as well as for the development of marine energy (Soukissian et al. 2017). These include energies drawn from wind, solar, hydro, bioenergy (crops and forests), waves and currents. Geothermal is an additional key renewable energy source in Europe that can provide low-carbon base-load power. Capacity factors of new geothermal power plants can reach 95% (Chamorro et al. 2014). In the early 2010s, a resurgent interest in geothermal power was observed after nearly a decade of only small development. A substantial number of projects have been developed throughout Europe, and geothermal energy is on its way to becoming a key player in the European energy market (Bertani 2017).

The assessment of resources for wind and solar is generally based on in-situ measurements. Long-term datasets including seasonal, yearly and decadal variability are required. These are usually available from in-situ or remote sensed measurements and gridded re-analyses. These tools have various limitations. In-situ measurements are local and may not have large measurement footprints, and homogeneity of long time series is not granted. At regional scales re-analyses are generally used but have biases, which require specific bias correction methods (Staffell and Pfenninger 2016). Remote-sensed data sets have large spatial coverage but are often short, even though several datasets are currently used for solar radiation estimate (e.g., Müller et al. 2015). Renewable energy resources should be assessed using a variety of tools combined together (Pfenninger and Staffell 2016).

Wind power

Wind power is essentially affected by wind speed in the lower part of the atmosphere, at the altitude of the hubs of wind turbines (from 50 to 150 m). Wind power production is a highly nonlinear function of hub-height wind speed, with no electricity generation below wind speeds of a few m s^{-1}, a rapid growth and a saturation at nominal wind speed (typically 10-15 m s^{-1}). To protect turbines, production is usually cut beyond a threshold of about 25 m s^{-1}. Therefore, production is extremely sensitive to low wind-speed changes as well as extreme stormy winds. Wind power production is also marginally sensitive to air density, the denser the air, the larger the production. It is sensitive to turbulence as it decreases efficiency.

A number of studies have currently assessed both the wind power potential in Europe and in Mediterranean areas, as part of the enhanced effort to develop prospective energy mix scenarios including intensive share of renewable energy sources. Beyond national assessments of wind resources in many countries, a New European Wind Atlas (NEWA)[22] (Petersen et al. 2014) is currently being developed, combining wind observations with model results. The offshore component of this atlas includes Mediterranean areas and presents regional climate model results calibrated with satellite scatterometer observations (Karagali et al. 2018).

Over the Mediterranean Sea, larger wind potentials are found in the northwestern part (the Gulf of Lions), in the Alboran Sea and in the Aegean Sea, as indicated by satellite datasets and regional climate modeling (Balog et al. 2016; Onea et al. 2016; Omrani et al. 2017; Soukissian et al. 2017; Rusu and Rusu 2019) *(Section 2.2.2.4)*. Offshore installations can theoretically extract much more kinetic energy from the lower atmosphere than onshore installation in large-scale wind farms (Possner and Caldeira 2017). Currently most installed power lies onshore, with reported installed power provided in *Table 3.10*. More than 80 gigawatts (GW) are currently installed in Mediterranean countries, but the potential is much higher. Near the shorelines, wind power also benefits from regular and generally predictable land/sea breezes.

Observed near-surface winds have long-term trends (i.e., multidecadal). In Europe in general, winds have been declining for several decades (McVicar et al. 2012), a more general phenomenon called "wind stilling" (Vautard et al. 2010). In the Mediterranean region this trend was less clear. Recent observations show that the wind-stilling trend is recovering on a global scale (Zeng et al. 2019).

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[22] http://www.neweuropeanwindatlas.eu/

	Installed wind power (MW)	Installed solar PV power (MWpeak) 2018
Albania	150	
Algeria	10	
Bulgaria	644	1,036 (1)
Croatia	529	61 (1)
Cyprus	188	113 (1)
Egypt	1,375	1,800 (2)
Greece	8,256	2,652 (1)
France	19,668	9,466 (4)
Israel	123	1,450 (5)
Italy	11,175	20,107 (1)
Libya	20	
Malta		131 (6)
Montenegro	118	
Morocco	1,343	
North Macedonia	37	
Portugal	5,567	671 (1)
Spain	24,664	4,751 (1)
Tunisia	242	
Turkey	9,384	5,063 (3)
Total	**83,165**	**47,170**

Table 3.10 | Reported installed wind and solar (photovoltaic, PV) power in Mediterranean countries in 2019. References are given in the footnote.

For wind power, see:

https://www.thewindpower.net/

For solar power, see:

(1) https://en.wikipedia.org/wiki/Solar_energy_in_the_European_Union

(2) https://spectrum.ieee.org/energywise/energy/renewables/egypts-massive-18gw-benban-solar-park-nears-completion

(3) https://en.wikipedia.org/wiki/Solar_power_in_Turkey

(4) https://en.wikipedia.org/wiki/Solar_power_in_France

(5) https://en.wikipedia.org/wiki/Solar_power_in_Israel

(6) https://solarfeeds.com/wiki/solar-energy-in-eu/

Solar power

Solar power production (concentrated solar power, CSP, or photovoltaic, PV) is mostly influenced by surface solar radiation *(Section 2.2.3.1)*, whose variations depend mostly on atmospheric composition (aerosols, water vapor) and clouds. The importance of aerosols has been noted in several studies for Mediterranean areas (e.g., Gutiérrez et al. 2018). Solar production is extremely sensitive to clouds and cloud types. For PV, panels efficiency also largely depends on cell temperature, which itself depends on air temperature, radiation and near-surface wind speed. Solar panels may also be sensitive to the presence of snow and ice cover or particulate matter potentially covering panels. Solar resources are of particular interest in Mediterranean countries due to the high mean solar irradiance in the region (Hadjipanayi et al. 2016). Solar radiation increases from North to South in the Mediterranean Basin, with typical yearly mean values of 150-250 W m^{-2}, and 1,300 to 2,000 kWh m^{-2} yr^{-1}.[23] On the European side weather disturbances make the resource variability higher than on the southern side.

Solar radiation has undergone varying trends in past decades, due to cloud changes and the "dimming and brightening" phenomena linked to changing aerosols atmospheric composition (Wild et al. 2005) *(Section 2.2.3.1)*. In Europe an increase of solar radiation of 2 W m^{-2} decade^{-1} was observed from 1983 to 2010 (Sánchez-Lorenzo et al. 2017), with higher values in the Mediterranean regions found in a set of ground stations (about 5 W m^{-2} decade^{-1}) (Pfeifroth et al. 2018). These trends are probably mostly attributable to changes in cloudiness but aerosol variations also affect mean solar radiation in a significant manner (Philipona et al. 2009; Nabat et al. 2015) *(Fig. 2.4)*. Such changes are also likely to affect summer temperatures. Dong et al. (2017) found that aerosols decline explain about half of the rapid rise of summertime extreme temperatures.

Hydropower and thermoelectric power

Hydropower relies on the availability of water in large reservoirs, or the streamflow intensity for run-off-the-river production. Production is sensitive to precipitation and snowpack melt, allowing to feed the reservoirs. Droughts and associated low flows are limiting the production. Bioenergy, just as agriculture and forestry, is largely dependent on climate conditions in many ways (seasonality of temperature, radiation, precipitation). Marine energies depend on currents, which have a low frequency variability, and on waves, themselves influenced by wind speed conditions.

Addressing impacts of climate variability and change on water resources, electricity supply and energy infracstructure vulnerability and resilience relies on a global hydrological-electricity coupled modelling framework. It consists of a physically based hydrological (Liang et al. 1994) and water temperature model (Yearsley 2009; van Vliet et al.

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[23] https://globalsolaratlas.info/

2012a), which are linked to hydropower and thermoelectric power models (Koch and Vögele 2009; van Vliet et al. 2012b). *Fig. 3.28* shows simulated hydropower utilization rates and utilisation rates of thermoelectric power over the period 1981-2010 in the form of boxplots with the distributions of utilisation rates of all plants for the Mediterranean (van Vliet et al. 2016a). The utilization rates are fairly constant, but they may be reduced in severe drought years. During such years, hydropower utilisation rates were on average reduced by 5.2%, and thermoelectric power by 3.8% (worldwide average). This corresponds to severe streamflow drought years for hydropower and to streamflow drought and high water temperature for thermoelectric power. Overall utilisation rates of thermoelectric plants are lower than for hydropower, since usable thermoelectric power capacity may be limited by more factors (i.e., streamflow drought and high water temperature) and benefits less from storage of water in reservoirs during low flow conditions than conventional hydropower plants (van Vliet et al. 2016a).

Marine energy

The energy resource in the ocean comes from five distinct sources, each with different origins and requiring different technologies for conversion, including, (1) tidal currents that extract kinetic energy from tidal flow, (2) tidal range which captures the potential energy created by the difference in sea level between high and low tides, (3) waves which convert kinetic energy transmitted by the wind to the upper surface of the ocean, (4) ocean thermal energy conversion which exploits the temperature difference between deep and surface ocean layers, and (5) salinity gradients which exploit the chemical potential due to salinity gradients in water bodies. These resources are not uniformly distributed on the globe. Also, the degree of maturity of the technology necessary to their exploitation is different. In the Mediterranean Sea, the two ocean energy sources with the highest potential are tidal currents and waves.

The Mediterranean coastal areas experience two high tides and two low tides per day. Tidal currents are generated by horizontal movements of water, modified by seabed bathymetry, particularly near coasts or other constrictions (e.g., islands). Tidal current flows result from the rise and fall of the tide; although short-term weather fluctuations can slightly influence these flows, their timing and magnitude are highly predictable and largely insensitive to climate change influences (Lewis et al. 2011). In the Mediterranean Basin, there is no commercial development of the tidal energy sector. As tidal turbines need a stream speed of at least 1.5-2 m s^{-1} to operate effectively, the tidal energy potential of the basin sets specific constraints. Given the minimal flow needs provided above, some Mediterranean sites could be of particular interest. The Straits of Gibraltar, and particularly the Strait of Messina (where tidal stream energy resource presents its highest values in the Mediterranean) have been under consideration (Soukissian et al. 2017). The Strait of Messina is characterized by high-energy tidal currents with maximum velocities at spring peak tides ranging

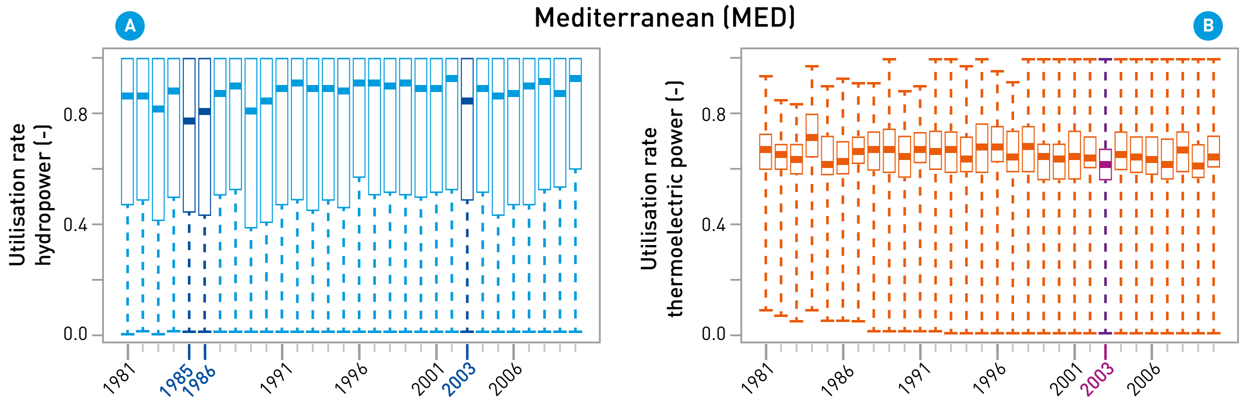


Figure 3.28 | Impacts of streamflow drought and high water temperature on utilisation rates of hydropower (A) and thermoelectric power (B) for 1981–2010. Boxplots with distributions of utilisation rates of hydropower and for thermoelectric power are presented with the largest number of plants and installed capacity. Values of 1 indicate that a power plant works at full capacity (no constraints) while for instance a value of 0.8 indicate that the plant works at 80% of the maximum capacity. Highlighted years indicate that utilisation rates were reduced significantly compared to the average over 1981–2010 (van Vliet et al. 2016a).

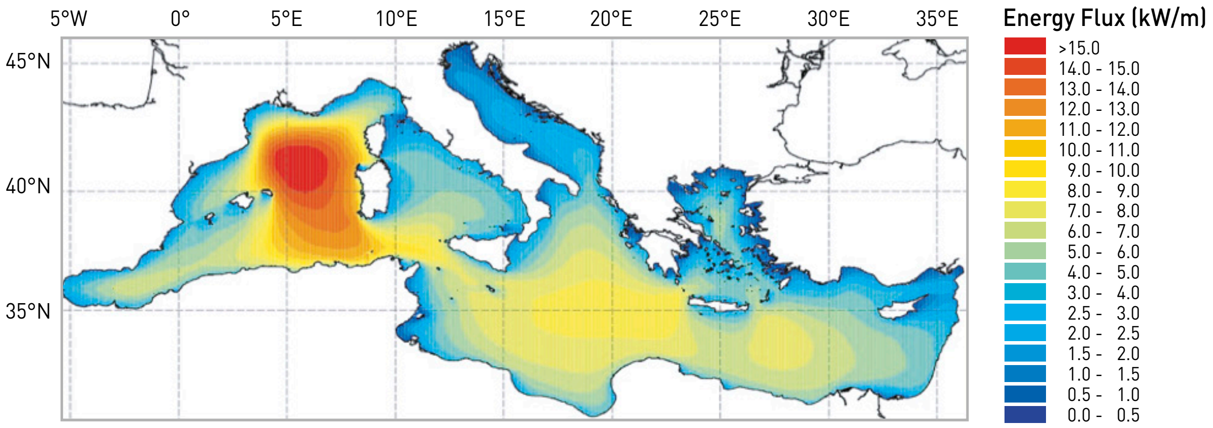
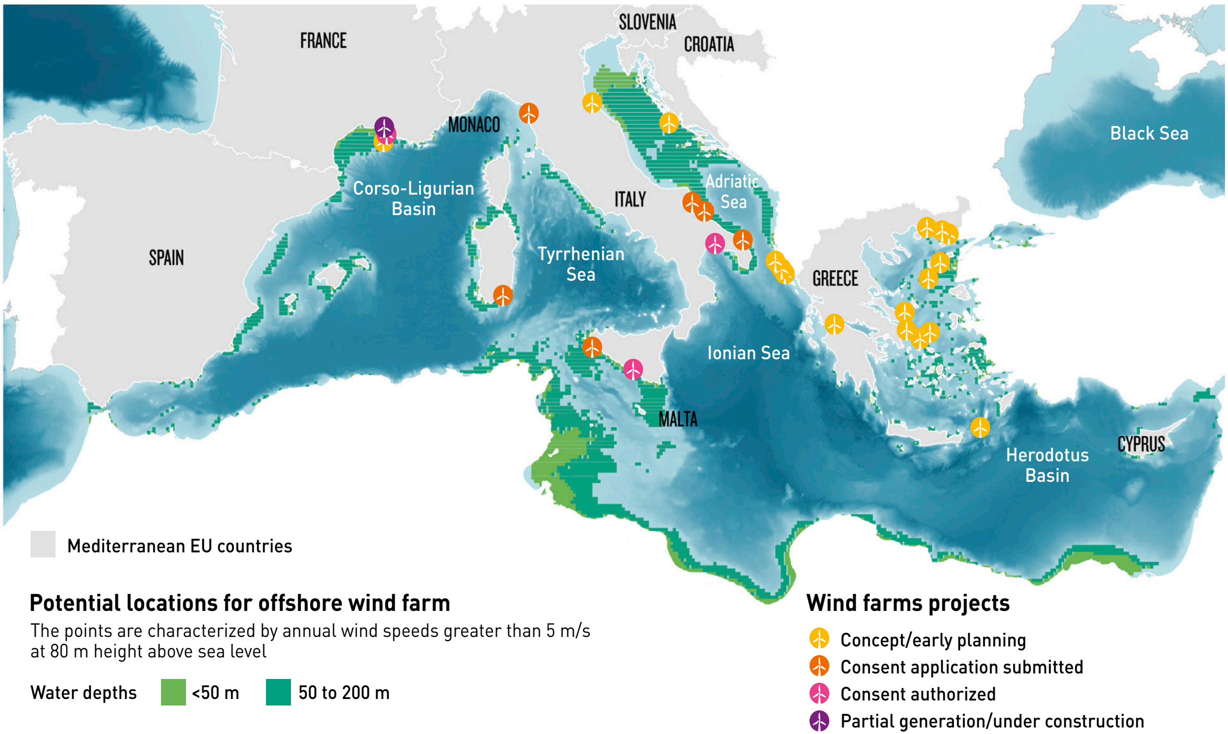


Figure 3.29 | Distribution of wave energy flux in kW m^{-1} averaged over the period 2001-2010 in the Mediterranean Sea. The energy resource was evaluated through of a numerical simulation performed using an ocean wave model. The model was forced with six-hourly wind fields obtained from European Center for Medium-Range Weather Forecast (ECMWF) operational analysis at 1/4° spatial resolution (Liberti et al. 2013).



Source: FP7 Collaborative project - Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential (CoCoNET 2015)

Source: Offshore4C (2014)

Figure 3.30 | Potential locations for offshore wind farms (Piante and Ody 2015).

from 1.8 m s^{-1} to more than 3 m s^{-1}, proving the suitability of the site for tidal energy harnessing (El-Geziry et al. 2009; Coiro et al. 2013). An estimation of the marine current energy fluxes in the Gibraltar Strait has been provided in Calero Quesada et al. (2014), revealing the suitability of two main sills (Camarinall in the middle of the Strait, and Espartell at the wester entrance of the Strait) for a power plant installation, with computed averaged fluxes in these areas that can exceed 1.8 kW m^{-2}.

Ocean wave energy is energy that has been transferred from the wind to the ocean. As the wind blows over the ocean, air-sea interaction transfers some of the wind energy to the water, forming waves, which store this energy as potential and kinetic energy. The size and period of the resulting waves depend on the amount of transferred energy, which is a function of the wind speed, the length of time the wind blows (order of days) and the length of ocean over which the wind blows (fetch). Energy availability is certainly a major factor affecting wave energy production but high energy potential usually implies exceptional wave conditions during extreme events. Such conditions pose serious engineering challenges to the design and deployment of wave energy converters increasing the costs of development, production, installation, maintenance and insurance of these devices. On the other hand, in calmer and semi-enclosed seas such as the Mediterranean, where lower amounts of wave energy are available, many technical issues related to extreme sea climate could be more easily solved, possibly making wave energy production still economically viable. From this point of view, wave energy production in the Mediterranean is particularly appealing *(Fig. 3.29)* (Liberti et al. 2013).

Offshore wind is likely the aspect of the energy transition of the Mediterranean region with the most important development potential, particularly in SEMCs. It has been introduced in other parts of the world, as it is less environmentally disturbing than on-shore alternatives (Piante and Ody 2015). So far, there is no offshore wind farm in the Mediterranean, although offshore wind production could be highly profitable *(Fig. 3.30)* (Gaudiosi and Borri 2010).

	Installed wind power (MW)	Installed solar PV power (MWpeak) 2018
Albania	150	
Algeria	10	
Bulgaria	644	1,036 (1)
Croatia	529	61 (1)
Cyprus	188	113 (1)
Egypt	1,375	1,800 (2)
Greece	8,256	2,652 (1)
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Malta		131 (6)
Montenegro	118	
Morocco	1,343	
North Macedonia	37	
Portugal	5,567	671 (1)
Spain	24,664	4,751 (1)
Tunisia	242	
Turkey	9,384	5,063 (3)
Total	**83,165**	**47,170**

Table 3.11 | Levels of primary solid biofuels (in terajoules (10^{12} joules, TJ) from domestic supply in Mediterranean countries for which information is available for 2017. Data downloaded from https://www.iea.org/data-and-statistics.

Bioenergy

Bioenergy is an important source of renewable energy in the Mediterranean, with an annual output from solid biofuels that dominates by far the production of electricity from solar or wind sources (*Table 3.10* and *3.11*; Bryden et al. 2013; IEA Bioenergy 2016). Traditional biomass remains a major source of renewable energy on the south side, given the low development of renewable energy in this part of the region *(Table 3.11)*. Biomass is the least promising sector for electric energy production and it is rather reserved for the production of heat or fuel. This stems from the fact that bioenergy encompasses a broad range of value-chains and end-uses, providing heat, electricity, and transportation fuels from a variety of biomass sources and conversion pathways (Sansilvestri et al. 2020).

In the Mediterranean region, the importance of bioenergy is highly variable across countries as it depends on the available biomass from forests, agriculture and organic waste. Bioenergy is difficult to characterize as it also has the advantage of producing fertilizers after the organic matter has been digested. In terms of technology, it is common to separate traditional biomass, which predominates in developing countries and involves the burning of wood fuels and agricultural residues for heating and cooking, from modern forms of bioenergy production relying on somewhat more complex biomass processing systems (Chum et al. 2011). Those include liquid biofuels for transport (e.g., bioethanol from sugar crops), pellets from forest residues or agricultural biomass, or electricity generated by dedicated power plants. Anaerobic digestion of organic waste (from cattle, agro-industry or municipal sources) to produce biogas has been growing lately throughout the Mediterranean area. Traditional biomass and modern uses of biomass are both present in the Mediterranean region, although the latter is more difficult to quantify due to a lack of statistics.

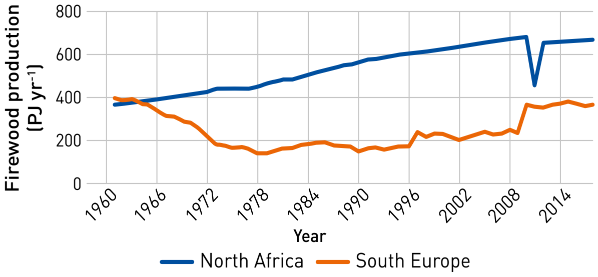

Figure 3.31 | Firewood production in the southern and northern parts of the Mediterranean Basin (FAO 2017).

Overall production of energy from solid biomass in the Mediterranean region amounts to at least 1.56 PW according to the statistics published for 2017 by the International Energy Agency[24]. Energy, including heat production from biomass, varies significantly from one country to another, being concentrated in northern Mediterranean countries *(Fig. 3.31)*. The consumption of wood, as reported by FAOSTAT includes traditional and modern usages of the biomass, presumably with a large proportion of the former when compared to other statistics available on modern value-chains relying on this feedstock. The production of firewood has increased by about 90% in North Africa over the last 60 years while it is back to its 1960's level in southern Europe after a large dip from 1973 to 2009 *(Fig. 3.32)*. The increased demand for firewood in North Africa arises from rising demographic pressure, especially in the rural areas (Schilling et al. 2012). The pressure on wood resources may be alleviated by improving the efficiency of cook stoves (thereby reduce health damages associated with open-hearth indoor fires), or switching to alternative renewable energy sources (Chum et al. 2011). In northern Europe, the competition with other end-uses for wood (e.g., for building, furniture-making or pulp and paper) explains the temporary decrease in firewood consumption.

The availability of biomass from forests is highly asymmetric between northern and southern Mediterranean countries *(Fig. 3.32)*. Considering its large area of forests, the Mediterranean Basin represents a good candidate to develop wood biomass energy for the renewable energy sector development (Gómez et al. 2010). Wood biomass

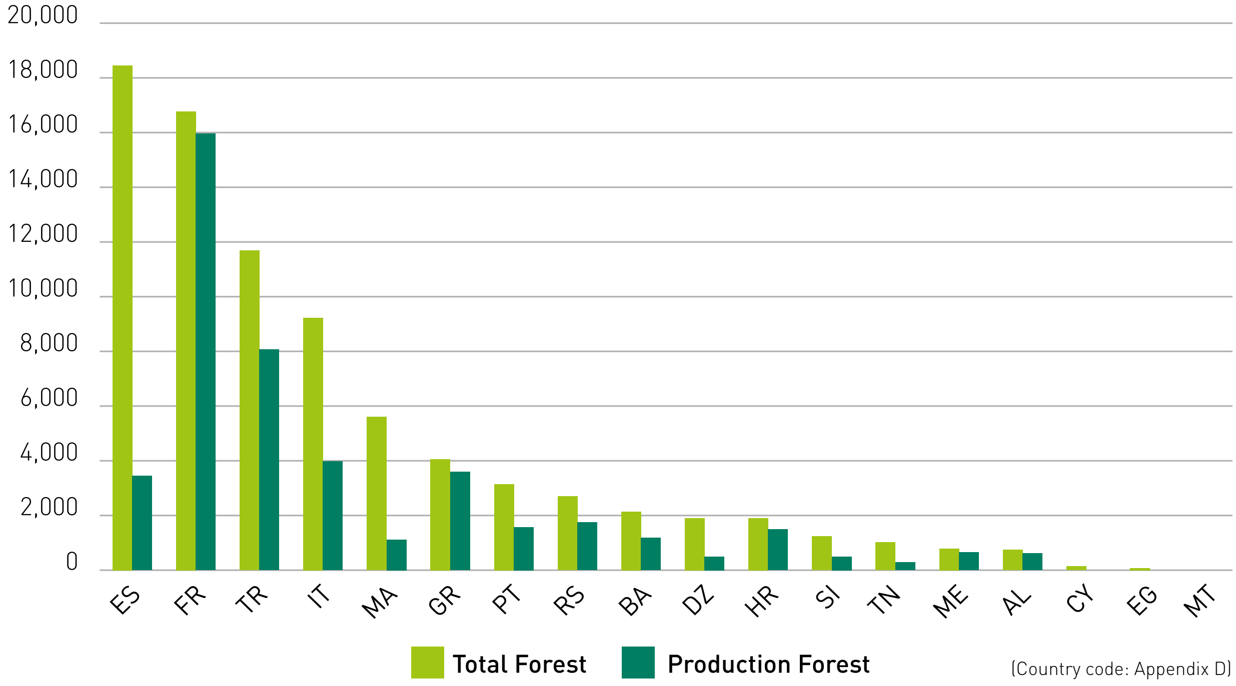

Figure 3.32 | Forest area and production forests available for industrial use including biomass for energy purposes. Values correspond to 1,000 hectares. Data obtained from the 2015 FAO Global forest Assessment[25]. Data for France obtained from official reports[26], whose classification of production forests may vary with respect to FAO guidelines.

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[24] https://www.iea.org/data-and-statistics

[25] http://www.fao.org/forest-resources-assessment/en/

[26] https://inventaire-forestier.ign.fr/

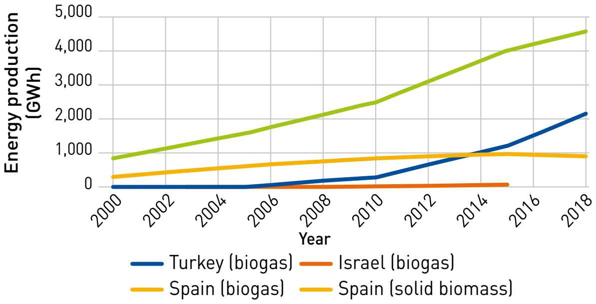

Figure 3.33 | Electricity production from biogas and solid biomass in Turkey, Israel and Spain (IEA 2018).

has low energy density and it is highly spread, two problems that increase harvesting and transportation costs (Caputo et al. 2005; Yoon et al. 2012). While forest surface may be increasing on northern Mediterranean countries, a continuous decline in northern African countries is currently occurring (see FAO forest Global Assessment[27]). Forest fragility is exacerbated in the Mediterranean area where forests have low productivity and agriculture is difficult considering regional climate conditions (González et al. 2015).

Large bioenergy facilities may constitute threats to the biodiversity and forest cover in any region, this also in the Mediterranean. Bioenergy must be ecologically sustainable, environmentally acceptable for the public, and the delivery costs need to be lower than for fossil fuels (Bilgen et al. 2015), but this is often not the case. An example can be found in the Mediterranean zone of France where the conversion of a carbon-based electric central to wood biomass-fueled power plant in 2016 caused conflict between citizens, the forestry sector and regional authorities (Sansilvestri et al. 2020). In contrast, small sized boilers using wastewood resources do not raise the same levels of concern to citizens and are more accepted.

Important efforts exist in Algeria and Morocco to scale up renewable energy sources. For instance, the Renewable Energy Development Centre in Algeria[28] has programs on the whole array of renewable energy including biomass and solar. Clearly, North African countries and other Mediterranean countries will rely more on non-forest biomass as long as there are agricultural or domestic waste as the forest biofuel supply is limited in this region.

Spain uses mainly biofuels for transports and more recently solid biomass for heating network installations (Paredes-Sánchez et al. 2016) In France, the number of heat boilers and networks increased from 30 in 2003 to 284 in 2016 (Neumuller 2015; OFME 2015). The main bioenergy potential in Portugal is domestic wastes (Ferreira et al. 2017). For Morocco wood biomass represents a real economic market with the heat demand for hammam and domestic cooking, causing continuous loss of forest surface (Zouiri and Elmessaoudi 2018).

While firewood is mostly used for heating and cooking, the recent development of more refined bioenergy systems may be captured by statistics on biogas production for the co-generation of heat and electricity in Turkey, Israel or Spain *(Fig. 3.33)*. Power plants running on solid biomass (from forestry or agriculture) are operating in Spain, Italy and Portugal, with similar outputs (2,600 - 43,000 GWh range in 2018) (IEA 2018). No estimates were found for northern Africa, but some programme targeting small-scale household digestion systems have been reported in Morocco and Tunisia (Mulinda et al. 2013). Biogas and bioelectricity production use mostly residues as feedstocks, but statistics on the amount of biomass hereby mobilized are not available. Overall, the contribution of biomass to the national energy mixes is variable in the transport sector (from 0% in the SEMCs to 9% in France), usually larger in the heating sector, and small but growing in the electricity sector.

The production of liquid biofuels (which currently relies on food crops as feedstocks) has only been reported in three southern Europe countries (France, Italy and Spain), as a result of the changes in the Common Agricultural Policy of the EU in the 1990's, and of a series of policies such as the renewable energy directive of the EU. The latter mentioned a 10% target for the share of renewables in the transport sector in 2020, most of which would be achieved with biofuels. Specific rules will be applicable for bioenergy produced from food and feed crops with a target of no more than 7%. The contribution of biofuels with a high risk of indirect land use change (i.e., mainly imported biomass such as palm oil) will be gradually reduced to 0% by 2030.

Unlike other renewables, biomass and biofuels in general may be traded across countries and con-

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[27] http://www.fao.org/3/a-i4808e.pdf

[28] https://www.cder.dz/

tinents. In 2017 for instance, Italy imported large amounts of wood pellets from North America (totalling 1.8 M tons or about 32.4 PJ of energy content). This means that the lack of local biomass production potential in the Mediterranean Basin may be compensated for by imports, although its consequences in terms of overall pressure on land resources should be carefully assessed (Searchinger et al. 2008).

In general, agriculture and forestry in the Mediterranean countries are faced with a growing array of challenges (IPCC 2014): the net primary production of managed ecosystems is constrained by limited water resources, the low availability of land on which to grow crops, and soil degradation (in general from erosion, salinity or desertification in the southern Mediterranean) (Olsson et al. 2019). This clearly hinders the development of purpose-grown plants (whether biofuel crops, lignocellulosic plants such as miscanthus, or short rotation coppice), which make up a large part of biomass supply in bioenergy expansion scenarios, e.g., in the 1.5°C warming scenarios of the IPCC SR1.5 (IPCC 2018). Also, regarding agricultural land management, the emphasis in the SEMCs is primarily on food production since all countries rely on imports to meet the needs of their inhabitants. The food constraint is such that in the study of biomass potentials by Beringer et al. (2011), no bioenergy plantations are projected in the SEMCs area by 2050, and to a very limited extent in the northern part of the basin *(Fig. 3.34).*

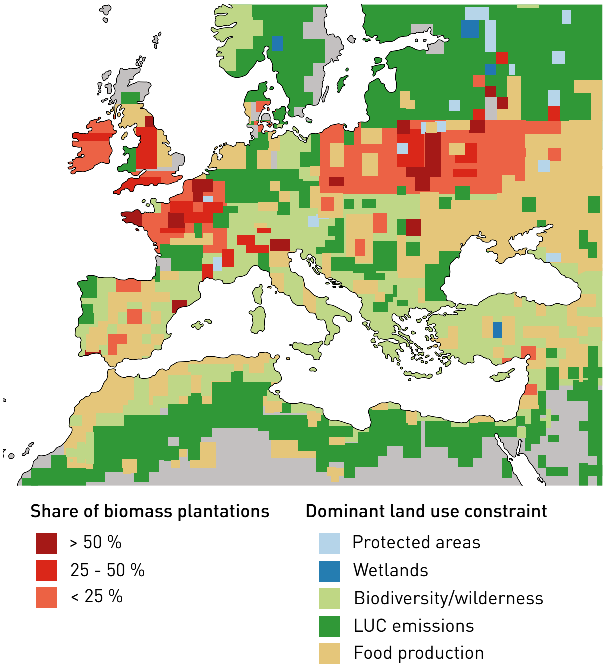

Figure 3.34 | Projected constraints to the establishment of bioenergy plantations by 2050. The "LUC emission" constraint corresponds to a loss of soil C upon converstion to bioenergy crops, which could not be paid back in less than 10 years. Adapted from Beringer et al. (2011).

Since biomass availability is the primary constraint to the development of bioenergy and is limited by a range of physical and economic factors (e.g., land availability, competition with other uses, productivity), many studies have attempted an assessment of "biomass potentials" given a set of assumptions and limitations. Sustainability has also become a major issue with bioenergy systems, arising in particular from the consequences of developing biofuels on the use of land worldwide, and the possibility that these may negate the climate benefits of substituting biofuels (Searchinger et al. 2008; El Akkari et al. 2018). In principle, "sustainable biomass potentials" would provide the most useful guidance, but are not easy to determine because the multifaceted nature of sustainability is difficult to factor in Chum et al. (2011). The trade-offs with soil quality when exporting agricultural or forest residues for bioenergy purposes can be evaluated (Saffih-Hdadi and Mary 2008). It results in a drastic reduction of removal rates (by two thirds in France, for instance).

Regarding the use of land for bioenergy plantations, an option to mitigate the competition between food production and bioenergy markets would consist in growing these plants on marginal land, i.e., land which is unsuitable for other purposes (Fritsche et al. 2017). There is still considerable debate as to the actual amount of such land worldwide, and whether it would be economically feasible to grow biomass plants on these lands. Current estimates range from 350 to 6,000 Mha worldwide (compared to a global cropland area of 1,700 Mha), and a recent study estimated an area of 69 Mha in Europe, among which 43 Mha are located in the northern Mediterranean area (Elbersen et al. 2018). Assuming an energy yield of about 60 GJ ha^{-1} on marginal land (Gelfand et al. 2013), this would translate as an output of 2,600 PJ yr^{-1} for the northern Mediterranean. This is a large amount compared to the current use of biomass in this area (for instance biomass produces 73 PJ of heat yr^{-1} in France and Italy (IEA 2018), with wood as the main feedstock). Aside from this potential opportunity on marginal land, avenues to increase biomass outputs in Europe include an intensification of forestry, the development of purpose-grown plants, which only occupy a marginal fraction of land so far (Don et al. 2011), and an increased valorization of residues and waste streams (for biogas, heat and power). Regarding energy crops, a study factoring in sustainability constraints estimated that the Northern Mediterranean countries could produce 630 PJ yr^{-1} in 2030 from less than 10 PJ yr^{-1} in 2010 (Don et al. 2011; Elbersen et al. 2012).

Regarding the SEMCs, Stecher et al. (2013) reviewed the biomass potential studies and their numbers for the African continent, concluding that the potential for energy crops could range from 0-13,900 PJ yr^{-1}, 0-5,400 PJ yr^{-1} for forestry biomass and 10-5,254 PJ yr^{-1} for residues and waste by 2020. While those numbers could not be disaggregated across regions in Africa, they point to significant potential for all three feedstock categories. From a sustainability perspective, as suggested in Chum et al. (2011), residues are particuliraly efficient at reducing GHG emissions. Their use was prioritized in the strategic energy plan of Morocco for 2030, which emphasizes the use of organic waste, agricultural residues, and algae – a medium-term technology unlikely to be commercialized before 2040 (Chum et al. 2011; Royaume du Maroc 2017).

3.3.2.3 Energy system vulnerability to climate extremes

There are a number of ways extreme weather events affect energy resources and energy systems. Individual events may threaten localized installations but large-scale events such as cold spells may threaten the electricity load balancing at a large scale. Also, with the increase of the share of renewables, the electricity transmission system will be more exposed to weather variations and may be threatened by specific weather conditions that are usually not considered as extreme.

Heat waves increase energy demand for cooling and increase rivers temperature. Long heat waves are generally associated with low flows (see bellow). Increased river temperatures reduce the permissible temperature increase in power plants, thereby inhibiting cooling the cooling water capacity and inducing plant production (Koch and Vögele 2009; van Vliet et al. 2016a). Permissible temperature increase is in particular bounded by critical biological threshold for freshwater species and strongly regulated. Excessive heat also affects power lines capacity to dissipate heat and reduces transmission capacity (Bartos et al. 2016). Heat also reduces the efficiency of solar panels and long-term thermal stress deteriorates PV cells (Chow 2010).

Long-lasting droughts may induce low flows in rivers, reducing production of run-of-the-river hydropower and stock in reservoirs for hydropower (van Vliet et al. 2016a). Droughts also increase the sensitivity of river temperature to air temperature, so that low flows combined with a heat wave can lead to a large warming of river temperatures with consequences on thermal production. The 2003 heatwave and associated drought impacted production in 30 nuclear power plants (Schewe et al. 2019). During the drought, warm year of 2003 simulated hydropower utilisation in Europe was significantly reduced by 6.6% and thermoelectric power by 4.7% compared to the average of 1981–2010 with a smaller impact in the Mediterranean than in northern Europe as Mediterranean power plants are hampered by water constraints on a more

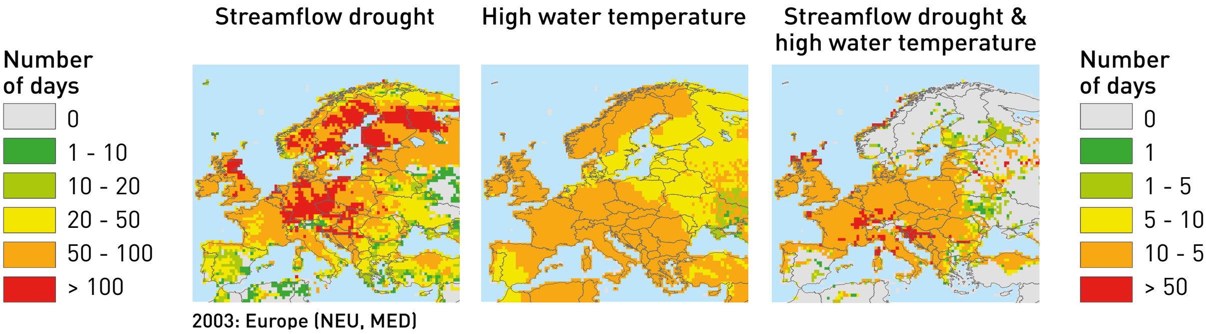

Figure 3.35 | Mediterranean patterns with number of days in the given year with streamflow drought (left), **high water temperature** (middle), **and that both events coincide** (right). Results are presented for year 2003 with both streamflow drought and high water temperature. Scale for right figure panels (streamflow drought and high water temperature) differs from the scale of the left (streamflow drought) and middle (high water temperature) panels (van Vliet et al. 2016a).

regular basis, resulting in lower absolute values of plant utilisation rates and smaller relative changes in usable capacity for 2003 compared to the long-term average for 1981–2010. In 2003, northern Europe and the Mediterranean region display large regions with streamflow drought for more than 100 days and high water temperature for more than 50 days (*Fig. 3.35*; van Vliet et al. 2016a).

Cold spells are exacerbating energy demand, due to increased heating (Thornton et al. 2016). Cold spells generally cover a large geographical extent (typically 1,000-2,000 km²) and may induce challenging conditions for the transmission system. Floods threaten all infrastructures and power devices. Storms and wind gusts also threaten infrastructures, in particular power lines, which may be damaged by falling trees. Solar panels are sensitive to several sorts of extreme weather events (floods, storms), which may threaten the infrastructure. Storms also induce halting of wind turbines for their protection. Storm surges threaten coastal infrastructures. By contrast, low winds induce a loss in wind power production. There are also a number of other hazards, which affect energy systems such as icing on wind turbines, freezing rain and heavy snowfalls endangering power lines, landslides affecting infrastructures.

3.3.3 Projections, vulnerabilities and risks

By improving energy efficiency and deploying renewables on a large scale, the Mediterranean region would enhance energy security for all countries, improve export potential for exporting ones and reduce energy costs and environmental

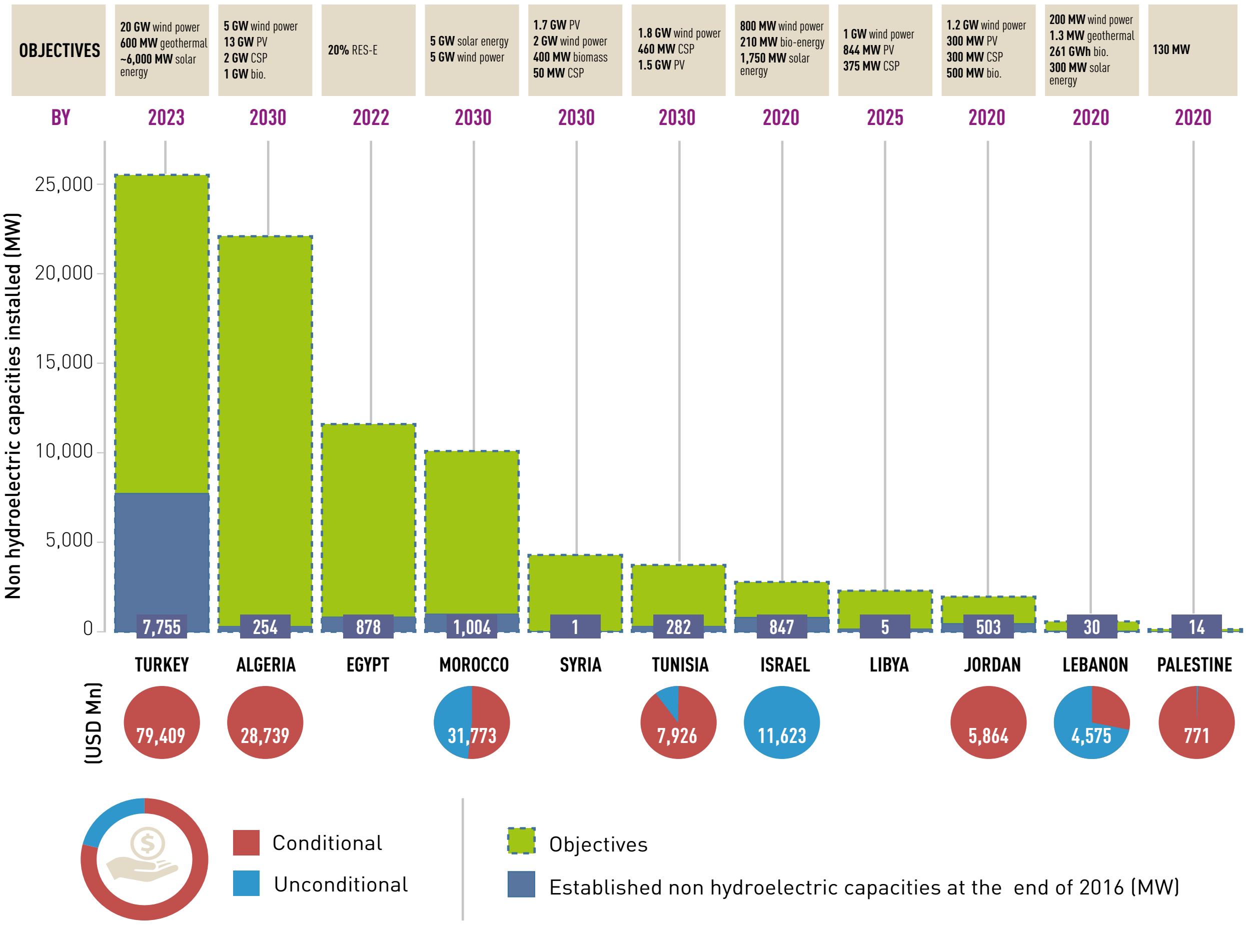

Figure 3.36 | Voluntary commitments of SEMC (Nationally Determined Contribution – NDC – and funding). The upper part shows the installed power capacity of non-hydro renewable energy technologies in 2018, and the extra effort needed to achieve the targets established by the SEMCs at the horizon 2020-2030. The lower part shows the level of funding needed to implement the measures included in the NDCs including the share covered by local vs. international climate funding (unconditional vs. conditional). Sources: OME/MEDENER (2018) - bottom part: UNFCCC[29]

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[29] https://www4.unfccc.int/sites/submissions/INDC/

damages for the whole region. Embarking on an energy transition path will also help improve social welfare in the region and contribute to job creation, among other positive externalities.

Nationally Determined Contributions (NDCs) are at the heart of the Paris Agreement and the achievement of the long-term goals to keep temperatures below 2°C. They are voluntary commitments to greenhouse gas emission reduction in all sectors, among which the energy sector, which is the main responsible for greenhouse, gas emissions at global scale. The NDCs of the Mediterranean countries and their implementation have been analyzed in depth by several organisations like IPEMED (Robin 2015), OME/MEDENER (2016), the UfM (Fernández and Hertz 2019) or the European Union project ClimaSouth (Rizzo and Maro 2018) and have served for elaborating energy transition scenarios. *Fig. 3.36* shows the voluntary commitments of SEMC to the required energy transition.

3.3.3.1 Energy transition scenarios

Since 2008, OME regularly issues a Mediterranean prospective analysis to 2040, the "Mediterranean Energy Perspectives" series (MEP). The MEP analyses the trends for energy demand in the different use sectors and the implications in terms of security of supply, CO_2 emissions, and environmental impacts. Within this framework, in 2015 MEDENER and OME published a joint Mediterranean Energy Transition Scenario (TS), an ambitious scenario that goes beyond the plans and targets announced by governments and policymakers. In all scenarios, the OME follows a structural econometric approach that combines economic theory and statistical methods to produce a system of equations establishing causal relationships between energy demand and activity variables (such as GDP, population etc.). This system of equations is then used to generate medium and long-term forecasts of future energy demand. The descriptions of the model and of the energy scenarios assumptions are available in the Appendix of the OME/MEDENER report (OME/MEDENER 2016).

The Mediterranean Energy Transition Scenario (TS) assumes the implementation of those measures that are currently the most technically, economically, and politically mature for large-scale rollout of energy efficiency and renewable energies. This scenario assumes no major technology breakthrough, but the deployment of existing technologies and sound energy efficiency policies and measures across all Mediterranean countries.

According to this analysis, under a Business-As-Usual or so-called "Conservative" Scenario (CS) the situation would evolve critically on all counts over the next 25 years: doubling of energy demand and tripling of electricity consumption, soaring infrastructure and import bills (+443 GW to be installed and doubling of the fossil-fuel imports) and a critical rise in carbon emissions (+45%). Such a scenario, based essentially on fossil fuels, would put further strain on the climate and exacerbate geopolitical tensions in the region. A change of energy trajectory is therefore necessary for all Mediterranean countries to curb the trends through increasing energy efficiency and renewable energy deployment.

Based on this exercise, in 2018, a new edition of the Mediterranean Energy Perspectives was realeased by OME, which includes two scenarios: i) the Reference Scenario (RS) which considers past trends, current policies and ongoing projects and incorporates the unconditional targets of Nationally Determined Contributions (NDCs); in other terms the RS assumes that international financing and other aids will not be forthcoming. ii) The Proactive Scenario (PS) is based on the implementation of strong energy efficiency programmes and increased diversification in the energy mix based on the NDCs submitted by each country and assumes that international financing will be made readily available and that all targets of the NDCs will be met in full.

3.3.3.2 Energy demand

In the Mediterranean region, energy demand increased from 711 Mtoe in 1990 to 978 Mtoe in 2015, an average growth of 1.3% yr^{-1}. The largest share of regional energy demand is in the North Mediterranean countries, which account for over 63%. Expected trajectories for energy demand in the region are very contrasted across the two shores of the Mediterranean *(Fig. 3.37)*.

The northern countries are ahead in terms of a transition path with substantial levels of renewables and effective demand-side management. The energy demand in the North has decreased by 8% since 2010. This decrease is not only due to to energy efficiency efforts but should also be seen in the light of a very moderate population growth (+0.5%) and decelerating gross domestic product growth, especially after the 2008 financial crisis (-2%). In both scenarios, by 2040, energy demand in the North Mediterranean would continue to decrease. In 2040, North Mediterranean energy demand would be 10% and 23% lower than 2015

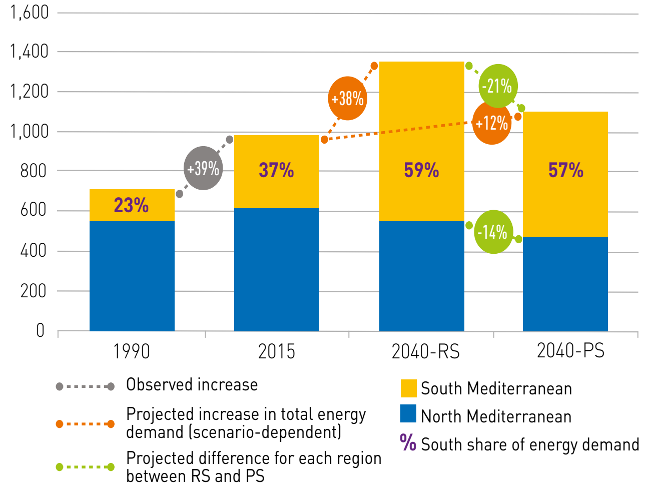


Figure 3.37 | Primary energy demand by region, in megatons of oil equivalent (Mtoe). RS = Reference Scenario; PS = Proactive Scenario (adapted from OME 2018), see *Section 3.3.3.1* for definition of the scenarios.

levels, in the Reference Scenario (RS) and Proactive Scenario (PS), respectively.

The South and East Mediterranean, on the other hand, have experienced sustained economic and population growth over the past years (+6% and +5% respectively), translating into growth in energy demand by +6% since 2010. In all scenarios, energy demand continues to increase by 118% and 72% from 2015 levels, for the Reference Scenario (RS) and Proactive Scenario (PS), respectively. Energy savings would be of 21% in the Proactive Scenario (PS) compared to the Reference Scenario energy demand forecasts.

The South and East Mediterranean would account for 61% of the energy savings with 2025 Mtoe, six times the 2015 primary energy demand of all south and East Mediterranean countries. Cumulative potential energy savings in the North Mediterranean, while less substantial than in the South and East, would still be considerable at around 1315 Mtoe over the same period – more than double current North Mediterranean primary energy demand.

The potential for energy efficiency is substantial in the Mediterranean region, particularly in the South and East. Despite some improvements, energy efficiency is still, at present, in its infancy stage in the region. Overall, energy intensity is decreasing in the region, largely related to shifts in the buildings, industry and transport sector. Globally, 45% of energy consumption (and a similar share of greenhouse gas emissions) are attributable to buildings (Butler 2008). New constructions in developing economies are numerous (Hui 2000). Building regulations aimed at energy efficiency are indispensable, especially in these developing economies, where the energy market alone, does not allow for the activation of incentive mechanisms. Substantial energy savings can be reached in the building sector (residential and tertiary sectors), especially in the South Mediterranean where over 50 million new dwellings are expected to be built over the next decades (OME/MEDENER 2015; OME, 2018). Barriers exist, including the high cost of efficient equipment, the difficulty of changing habits, the lack of adequate technology and also the ignorance of energy and climate issues by some architects in these countries (Iwaro and Mwasha 2010). Jaber and Ajib (2011) propose an assessment of the best orientation of the building, the optimal window size, the optimal thickness of thermal insulation from an energy, economic and environmental point of view for a typical residential building in the Mediterranean region. They suggest that about 28% of annual energy consumption can be saved by choosing the best orientation, optimal window size and optimal insulation thickness. The choice of new materials can also contribute to energy savings (Zabalza Bribián et al. 2011; Buoninconti and Filagrossi Ambrosino 2015).

Industry can substantially improve its efficiency of electricity consumption, but there is less scope to decrease its fossil fuel use in heavy industries, especially in the South and East Mediterranean countries. For all SEMCs, except Tunisia, the share of industry in the final energy consumption is declining. The share of industry in final energy demand is already low in Lebanon (12%) because the activity of this sector is traditionally less developed while it is high in Tunisia (35%). It fell sharply in Lebanon (-10%), after the war with Israel in 2005-2006, with the destruction of many industrial infrastructures, and to a lesser extent in Italy, France and Greece due to the economic crisis and the increasing trend of the service sector (MEDENER 2014). The transport sector would witness strong efficiency gains over the outlook period (18%) as they offer great scope for efficiency improvements in areas such as improved engines, and modal transport expansion.

3.3.3.3 Energy supply

In both OME scenarios, fossil fuels remain the dominant component of the mix. While oil alone is expected to remain the dominant fuel of the energy mix, mainly for its demand in the transport

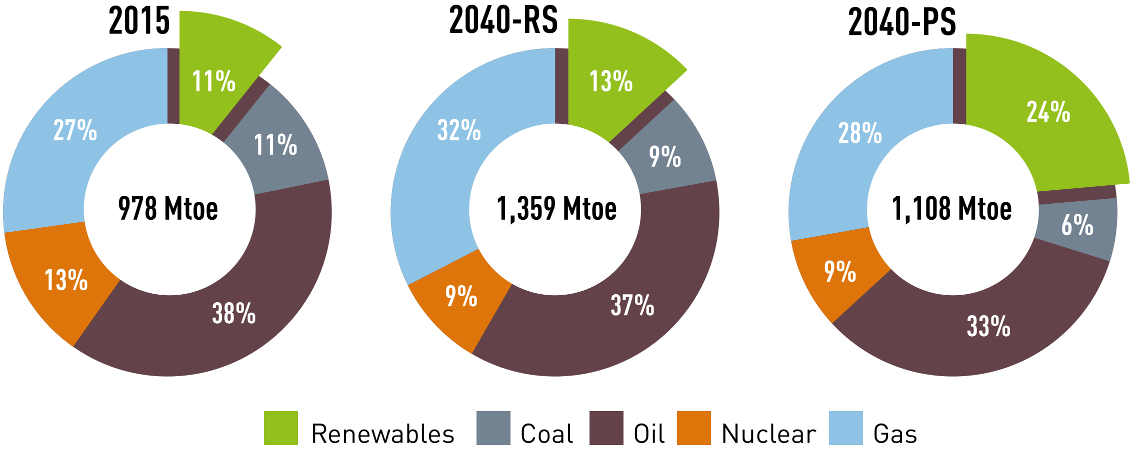


Figure 3.38 | Primary energy resources in the Mediterranean energy mix in megatonnes of oil equivalent. RS = Reference Scenario; PS = Proactive Scenario (OME 2018).

sector, a complete reshape is occurring in the electricity mix, where renewable energy sources have overtaken natural gas capacity and become the main fuel in the Mediterranean electricity mix. The Mediterranean region has abundant renewable energy resources. Yet, today renewables still account for a limited share of the region's primary energy supply (11% in 2015, *Fig. 3.38*). Traditionally the most exploited renewable energy sources have been biomass and hydropower. Geothermal energy contributes in a few countries mainly Italy, Turkey and, to a lesser extent, France, Spain and Portugal. In recent years, wind and solar, both for electricity and heat production have entered the energy mix. In 2040, the share of renewables would reach 13% in the Reference Scenario (RS) and 24% in the Proactive Scenario (PS) (OME 2018). Most of the increase is expected to come from wind and solar. Among the various renewable energy technologies, solar is expected to grow at the fastest pace in both sub-regions. End usage of solar thermal energy, in particular solar water heaters, offers great poten-

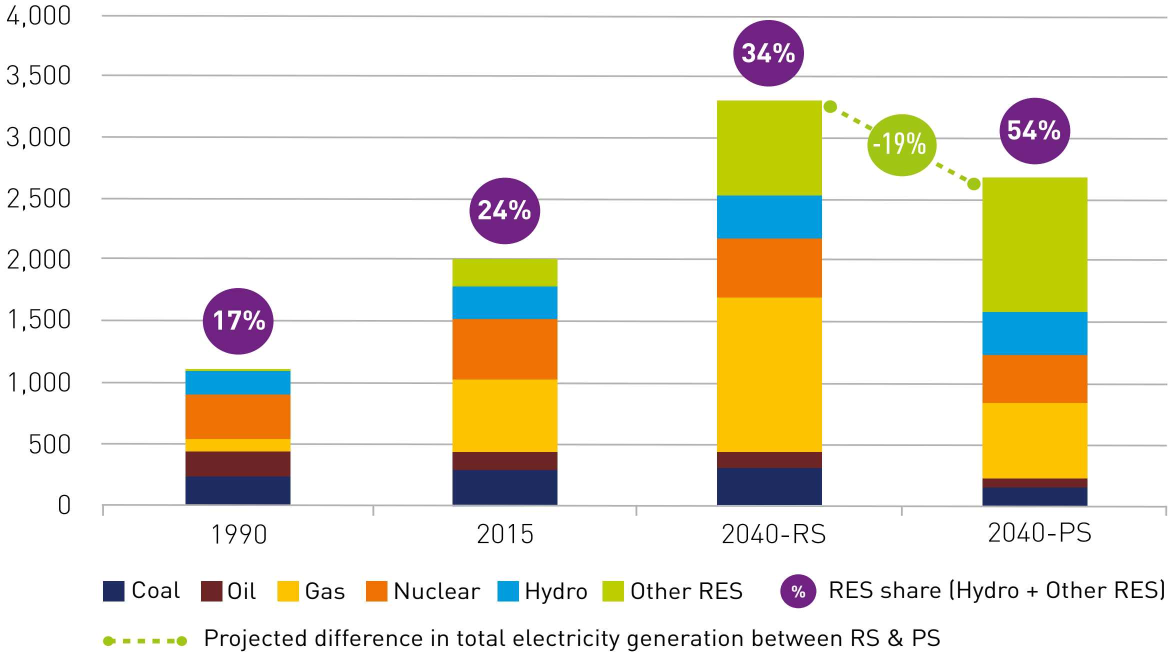


Figure 3.39 | Electricity generation mix by fuel type, in terawatt-hours (TWh). RS = Reference Scenario; PS = Proactive Scenario, RES = Renewable Energy Sources. (Adapted from OME 2018).

tial in the South and is efficient with good return on investment. Solar water heating and solar cooling demand will also increase by 2040.

The most significant change ahead is a substantial increase in the contribution of renewables to power generation *(Fig. 3.39)*. With 124 GW and 104 GW respectively, hydro and non-hydro renewable technologies covered 38% of the cumulative power capacity in the Mediterranean region in 2015. If current trends continue, renewable energy technology will dominate the Mediterranean electricity market in the next years in terms of net generation capacity additions. In 2015, the net renewable energy capacity added was almost the half of the one of natural gas, which historically represented the first-generation source in the Mediterranean electricity mix (10 GW against 5.6 GW). In particular, the net additions of non-hydro renewable electricity capacity in were larger than 8 GW yr^{-1} on average during the last 10 years.

The important growth in terms of new renewable electricity capacity expected will lead to a drastic restructuring of the power generation infrastructure. By 2040, renewables would in fact account for about 70% of total installed capacity and more than 50% of electricity generation in the PS. North Mediterranean countries are expected to add about 9 GW of new renewable capacity per year to reach a total of 410 GW by 2040 (thus more than doubling current power installed capacity). South and East Mediterranean countries will contribute some 6 GW yr^{-1}, to reach 181 GW by 2040, a five times growth in the PS compared to current levels. This would completely change the electricity market supply and demand structure in South Mediterranean countries.

In terms of electricity generation, renewables will generate 1,137 TWh in 2040 in the RS, or 34% of total electricity generation in the Mediterranean. This implies an average annual growth rate of 1.3% for hydro, which would generate 357 TWh, and 5.1% for non-hydro renewables (780 TWh) over the period 2015-2040. In the Proactive Scenario, electricity generated from renewables is expected to reach over 1,438 TWh, around 52% of total production in 2040. This trend is influenced by 20% less growth in electricity generation in the Proactive Scenario than in the reference case, the progressive phase out of oil and coal-fired electricity production plants and a further boost to renewable energy technologies, both in North Mediterranean countries, where non-hydro renewables would experience a compounded average annual growth rate (CAAGR) of over 5.5%, and in South and East Mediterranean countries, where non-hydro renewables are expected to grow at 11% CAAGR.

In terms of the outlook for the three fastest growing renewable energy technologies in the Mediterranean region, North West Mediterranean countries maintain their regional leadership in both scenarios for wind generation, with a projected electricity output of 267 TWh in the RS and 325 TWh in the PS by 2040, around 70% of wind electricity generation in the Mediterranean. The Proactive Scenario foresees a more accelerated rate of growth of wind in the South and East Mediterranean region, which would supply about one-third of the total wind-generated electricity by 2040 (over 148 TWh). The South and East Mediterranean should produce about 32% of the total solar CSP-based electricity in the region (15 TWh) by 2040 in the RS, and 43% (27 TWh) in the PS.

3.3.3.4 An NDC-based scenario for the Mediterranean region

While the energy transition raises common challenges for the entire region, the nature and scale of the challenges are different between the northern countries and SEMC. *Fig. 3.40* shows the demographic and energy projection in the Reference Scenario (RS) of OME MEP2018 which will be used as a reference in *Section 3.3.4.4* to discuss energy transition financing objectives. The countries on the northern shore have more than two decades of reforms that have gradually diversified their energy mix and controlled the growth of their energy demand, in a context of demographic stability. SEMCs are facing rapid population growth, which should lead to a significant increase in their energy demand. Their energy mix is widely relying on fossil fuels and fossil fuel export revenues which play a central role in the macro-financial balance of some countries (Algeria, Egypt, Tunisia) (MEF 2019).

Finally, compared to the RS by 2040, *Fig. 3.41* shows that the Proactive Scenario would lead to significant benefits, in terms of reduced energy dependence, energy efficiency, renewable energy growth and climate mitigation. More specifically, compared to the RS, the Proactive Scenario (PS) would reduce the energy dependency of the region by 45% (from 43% to 24%); as well energy demand and electricity generation would be reduced by 20%, each; the share of renewables in electricity production would be 57% higher in the PS compared to the RS. Finally, the PS would see a reduction of CO_2 emissions of 30%.

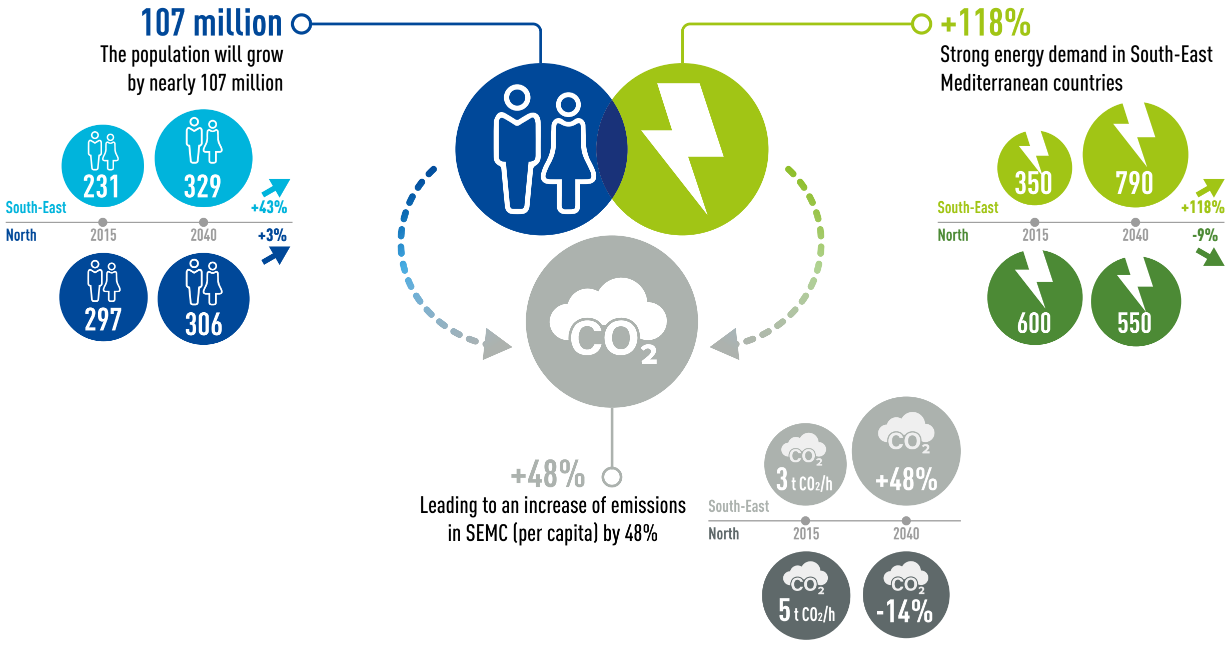


Figure 3.40 | Demographic and energy projections in the Mediterranean in 2040. Source: MEF (2019), based on OME (2018) Reference Scenario (RS).

3.3.3.5 Impact of climate change on energy resources

Although solar photovoltaics and wind power are growing rapidly, several scenario studies show that thermoelectric (fossil, nuclear, geothermal, biomass-fueled) power, together with hydropower, will most likely remain the dominant power-generating technologies during the whole of the twenty-first century (IEA 2018). Overall reduction in total power generation is projected under global warming as highlighted in a study investigating wind, solar, hydropower and thermoelectric power generation evolution in Europe (Tobin et al. 2018).

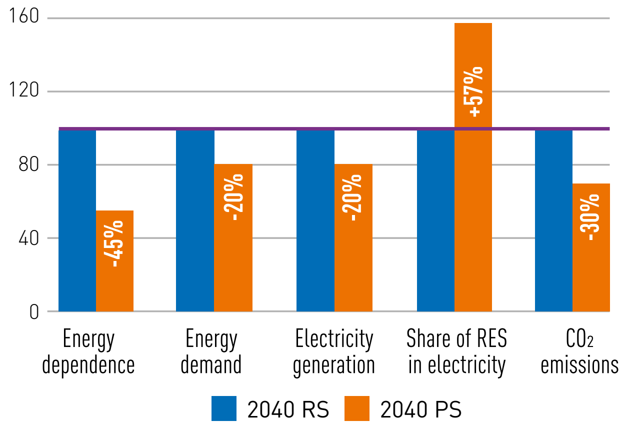
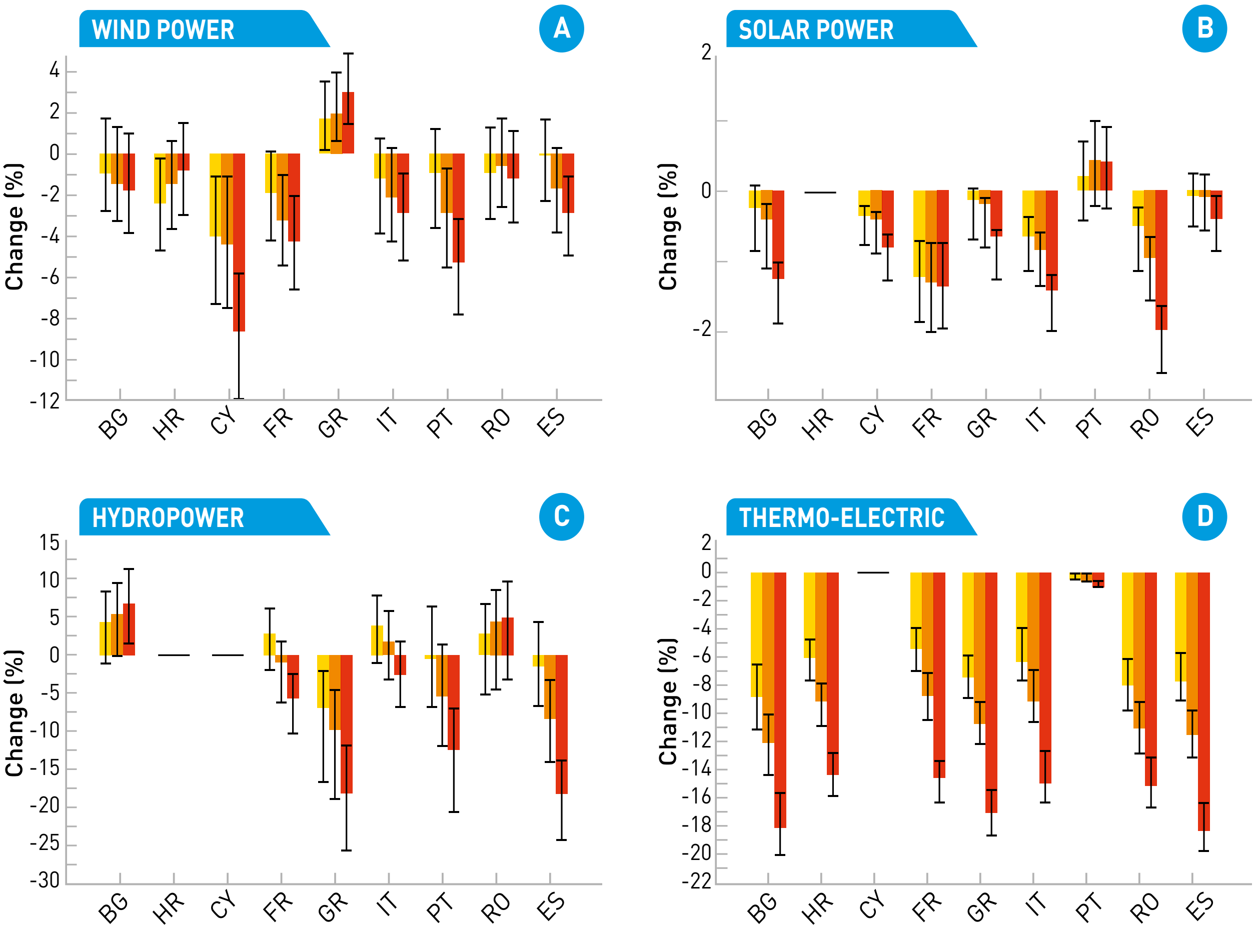


Figure 3.41 | Benefits of the implementation of the Proactive Scenario (PS) compared to the Reference Scenario (RS) at the horizon 2040 (OME 2018).

Several studies using regional or global climate projections show that the western Mediterranean Basin is likely to undergo slightly decreasing winds in future decades (Hueging et al. 2013; Tobin et al. 2016) due to the poleward shift of the Hadley cell *(Section 2.2.2.1)*. Surface wind speed declines remain moderate by the mid-century (generally of the order of a few percent). Wind speeds usually undergo small expected changes (Solaun and Cerdá 2020). By contrast, wind speeds are consistently projected to increase in the Aegean Sea (Tobin et al. 2015, 2016) where more persistent episodes of stable wind mill production regime are found *(Section 2.2.2.4)* (Weber et al. 2018). In any case wind resource is not threatened by climate change. Overall, the magnitude of change is small (< 5%) for all countries under a 1.5°C and 2°C global warming *(Fig. 3.42; panel A)*.

For a 3°C warming, most countries undergo changes with a magnitude also below 5% except for Portugal, Ireland and Cyprus where decreases in magnitude are expected to exceed 5%, approaching 10% for Cyprus. A 2°C warming does not systematically lead to higher change magnitudes than 1.5°C, while 3°C warming leads to stronger changes in most cases. In terms of individual cli-



(Country code: Appendix D)

Figure 3.42 | Future changes in national wind power (A), solar PV power (B), hydropower (C) and thermoelectric power (D) production under +1.5°C global warming (yellow bars), 2°C (orange bars) and 3°C (red bars). Changes are relative to the reference period 1971–2000. Colored bars correspond to the ensemble mean. The black thin error bars represent ensemble-mean confidence intervals (95% level based on the Wilcoxon-Mann-Whitney test). Adapted from Tobin et al. (2018).

mate model signals, the spread among the models is limited.

Climate change also impacts solar radiation and thereby solar energy resource. For solar PV generation *(Fig. 3.42; panel B)*, projected ensemble mean impacts show moderate reductions for most countries in Europe, expect for the Mediterranean countries, i.e., Portugal, Spain, Greece and Cyprus where changes are very small (but the magnitude and direction of changes are robust since most models agree). The overall magnitude of the signals is correlated with the amount of warming. Crook et al. (2011) and Wild et al. (2015, 2017) studied the global changes on PV and CSP outputs as a result from climate change, combining solar radiation with other factors such as cell temperature and wind. They found that solar PV output is generally declining in future scenarios worldwide except over a few areas in Europe and the Mediterranean region where the expected increase in solar radiation is expected to overpass the temperature effect.

Over Mediterranean areas there is agreement among studies that radiation will increase and this will lead to an increase in solar PV output despite the temperature increase (Jerez et al. 2015; Gil et al. 2019). There is large spread in estimated amplitudes and also significant differences between regional and global climate modeling results (Bartók et al. 2017), which may be at least partly explained by the lack of aerosol changes in most regional climate models.

CSP potential is also expected to increase with climate change. North-West Africa (Morroco and North of Algeria) appears to be one of the areas of Africa where solar potential is increasing in

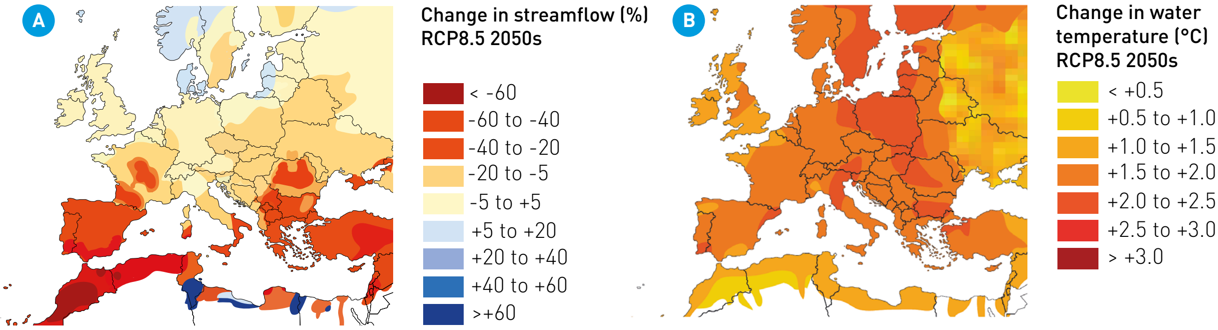


Figure 3.43 | Impacts of climate change on annual mean streamflow (A) and water temperature (B) for RCP8.5 for 2040–2069 (2050s) relative to 1971–2000 (adapted from van Vliet et al. 2016b).

climate change scenarios (Soares et al. 2019), but over the whole of North Africa projections indicate a small decrease in resource (Bichet et al. 2019).

Climate variability and the likelihood of heat waves and droughts are expected to increase in the Mediterranean (*section 2.2.4.2*; Raymond et al. 2019). This may have important impacts on water resources available for hydropower (e.g., Hamududu and Killingtveit 2012) and thermoelectric power generation (van Vliet et al. 2012b, 2016b) in Europe and Africa. Consistent decreases in streamflow are projected for the Mediterranean region (up to -30% to -50% in soth and east according to scenarios, *Fig. 3.7*). Water temperatures continue to increase during the twenty-first century for RCP8.5 (+1.0°C to +2.0°C for 2050s; van Vliet et al. 2016b; *Fig. 3.43*).

Spatial patterns of changes in hydropower usable capacities strongly correspond with the projected impacts on streamflow, showing overall decreases in hydropower usable capacity the Mediterranean, with reductions in the annual hydropower capacities of 2.5-7.0% for the 2050s (RCP2.6–RCP8.5; van Vliet et al. 2016b) (*Fig. 3.43*; panel A). Thermoelectric power usable capacities are projected to decrease for more than 60% (RCP8.5) of the power plants *(Fig. 3.43; panel B)*. Thermoelectric power plants in the Mediterranean are situated in areas with expected declines in mean annual streamflow *(Section 3.1.4.1)* combined with strong water temperature increases *(Section 2.2.4.2)*, which both amplify restrictions on cooling water use. *Fig. 3.43 (panel B)* shows considerable reductions in thermoelectric power usable capacity in the Mediterranean region of 10-15% (for the 2050s, RCP2.6–RCP8.5).

Impacts of climate change on gross hydropower potential have also been studied for Europe. Gross hydropower potential refers to "the annual energy potentially available when all natural runoff in a country is harnessed down to sea level (or to the border line of the country) without any energy losses" (Eurelectric 1997). Mean gross hydropower potential is projected to increase in northern, eastern and western Europe and to decrease in southern Europe *(Fig. 3.42; panel C)*. Overall, higher warming results in stronger changes. Results for the individual regional climate model projections show that many individual signals are not significant and the spread amongst models is substantial. The most negatively impacted countries will be Greece, Portugal, and Spain. Impacts in these southern European countries can be reduced by limiting global warming. A warming of 3°C reduces hydropower potential by 15-20% while limiting to 2°C warming would keep decreases below 10%.

The usable capacity of thermoelectric power plants using river water for cooling is expected to reduce in all European countries due to a combination of higher water temperatures and reduced summer river flows *(Fig. 3.42; panel D)*. The magnitudes of the decrease are about 5% for 1.5°C, 10% for 2°C and -15% for 3°C for most countries. Bulgaria, Greece and Spain will be the most strongly impacted (15–20% decrease). Results based on output of various climate models project significant changes and agree on the direction of changes as the spread among signals is limited. Robust and significant negative climate change effects are found, with a magnitude higher than for other power generating technologies in Europe (Tobin et al. 2018) *(Fig. 3.44)*.

Regarding bioenergy, in the long term (>2040), biomass is projected to be a key option to meet the most stringent climate targets (Clarke et al. 2014; Rose et al. 2014; Rogelj et al. 2015), because of its ability to produce negative emissions in association with carbon capture and storage *(Section 3.2.3.2)*.

Integrated assessment models involved in the IPCC 1.5°C report project that biomass will take a growing share in primary energy use in most regions of the world during the 21st century *(Fig. 3.45)*. The main driver behind this result is the need to decarbonize the energy sector (Bauer et al. 2018) and the availability of other sources of renewable energy.

Future environmental and climatic conditions of the Mediterranean Basin reinforce uncertainties related to bioenergy sector development. The Mediterranean zone is expected to have huge shifts in the distribution of agricultural and forest areas with climate change making the region vulnerable (Fernández-Manjarrés et al. 2018). The current low primary production and the fragmentation of private lands could limit the development of the bioenergy sector. Furthermore, the future increase of dry conditions and extreme natural events, reinforce tough environmental conditions for the biomass sources production especially forestry, agricultural and energy crops. Fires can be favored with increased dry conditions making many forest biomass reserves vulnerable, therefore needing adequate management (Fernández-Manjarrés et al. 2018). Also, the less pregnant decarbonisation constraint and the availability of solar energy explain why the share of biomass is not changing much in SEMCs.

Agriculture in the Mediterranean area is particularly vulnerable to climate change due to its reliance on rainfed systems and the increased water shortages, which are anticipated in this region *(Section 3.2.2.1)*. These are very likely to have a negative impact on crop yields, in particular for wheat in North Africa. A decrease in crop yields would directly affect the amount of land available to grow energy crops, which are scarce to start with, especially in the SEMCs. Herbaceous bioenergy crops (*Miscanthus, Panicum virgatum,* cardoon, *Arundo donax*) produced on marginal or abandoned land offer promising prospects in southern Europe with positive effects in terms of sustainability criteria (Pulighe et al. 2019). To ensure the feasibility of production with regard to environmental criteria, the choice of cultivars most resilient to water stress and agronomic management will play a critical role.

While there is a large body of work on the combined effects of CO_2 concentration rises and climate change on staple food crops (IPCC 2014), only few studies exist on lignocellulosic plants (Chum et al. 2011). One study on miscanthus (a perennial grass) concluded that this crop would no longer be suitable in the Mediterranean area by 2050 due to drought kill (Hastings et al. 2009). Conversely, a simulation study involving another perennial crop *(Arundo donax)* in northern Italy concluded that its

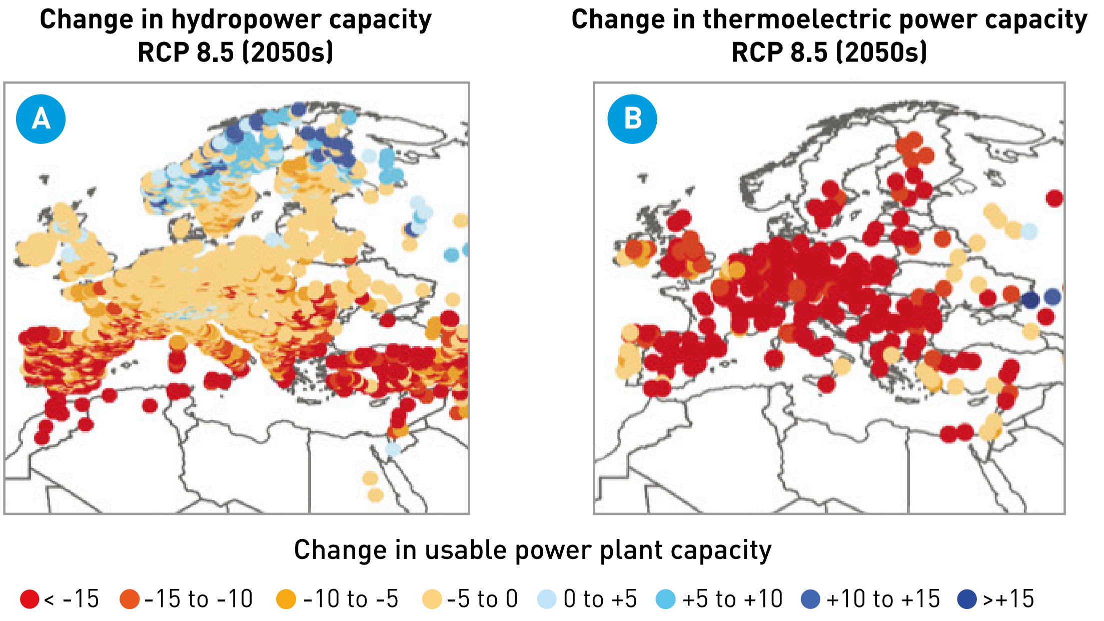


Figure 3.44 | Impacts of climate and water resources change on annual mean usable capacity of current hydropower and thermoelectric power plants. Relative changes in annual mean usable capacity of hydropower plants (A) and thermoelectric power plants (B) for RCP8.5 for 2040–2069 (2050s) relative to the control period 1971–2000 (van Vliet et al. 2016b).

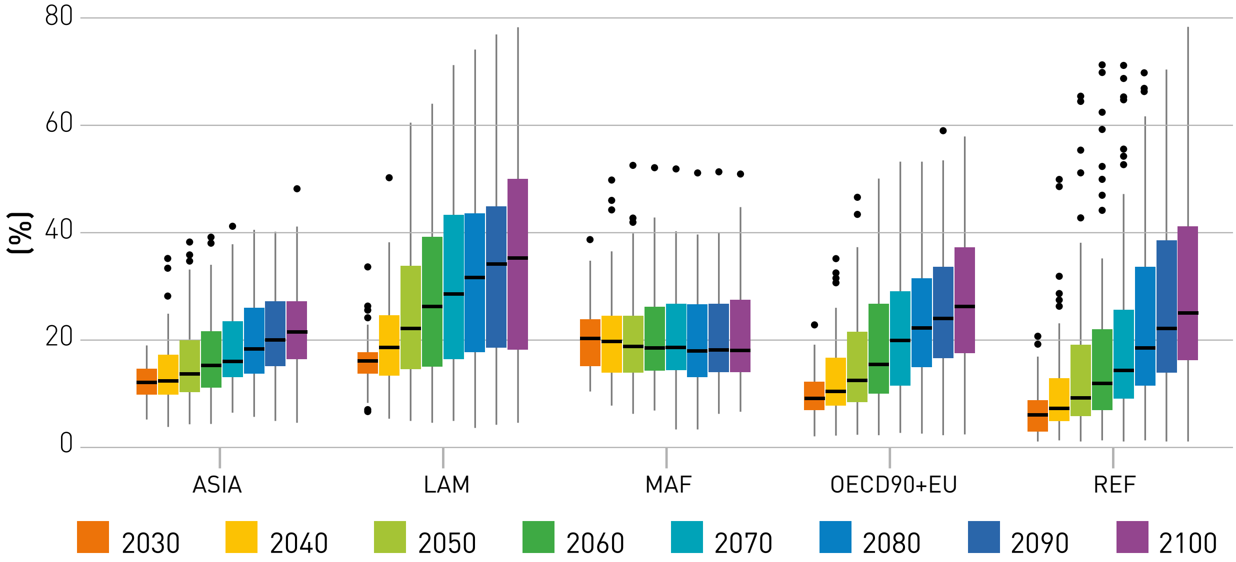


Figure 3.45 | Regional share of biomass in the primary energy use in the IPCC 1.5°C scenarios. Source: data available from the IAMC 1.5°C Scenario Explorer hosted by IIASA available at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/login?redirect=%2Fworkspaces. ASIA: Asian countries except Japan, LAM: Latin America, REF: Countries from Reforming Ecomonies of the Former Soviet Union, MAF: Countries of the Middle East and Africa, OECD90+EU: OECD90 and EU (and EU candidate) countries.

yield could increase by 20% within 2050 due to an increase in water-use efficiency permitted by higher ambient CO_2 concentrations (Cappelli et al. 2015). For any bioenergy project, the selection of the most appropriate feedstocks should clearly be based on the local conditions and contexts, but while there is an increasing body of data and technical knowledge available on energy crops (Laurent et al. 2015), there is a scientific gap as far as the impact of climate change is concerned, in particular in the Mediterranean. Finally, climate change should also reduce the amount of agricultural residues available for bioenergy, which projections usually consider stable. The same applies to forest residues or waste from the agri-food sector, although the latter may import raw material from other world regions to compensate for a decrease in local supply.

Biomass production in the Mediterranean coastal regions should eventually, be limited by the lack of available land suitable for bioenergy production (Daioglou et al. 2019) and by water constraints. In a scenario projecting a warming limited to 2°C, Near East and North Africa will become major importers of biomass with, by 2100, a level of biomass imports in monetary values higher than their current fossil fuel exports (*Fig. 3.46*; Muratori et al. 2016).

Factoring in food security and bioenergy production is usually seen as a dilemma in projections and foresight studies (Tilman et al. 2009). Integrated assessment models show that the agricultural and forestry sectors can meet an increasing demand both for food and bioenergy products by various adjustments (increase in crop yields via higher input rates, expansion of cropland area) (IPCC 2018), but in the Mediterranean area it is likely that there is less room for such adjustments given the environmental and economic constraints. Overall the highest potential should come from residue and waste streams, for which there are unfortunately few estimates available, and the use of marginal land – pending a proof of concept that this strategy can be implemented at a large enough scale beyond simulation studies (Gelfand et al. 2013). In the rural areas of the southern Mediterranean Basin where the use of traditional biomass predominates, the generalization of more efficient bioenergy technologies (improved cookstoves in particular) would also reduce the pressure on biomass resources and make biomass available for more refined uses (for power and transportation fuels) (Chum et al. 2011; Mulinda et al. 2013).

3.3.3.6 Impact of climate change on energy demand

Climate change in the Mediterranean is expected to impact the energy consumption mainly as a decrease (respectively increase) in space heating

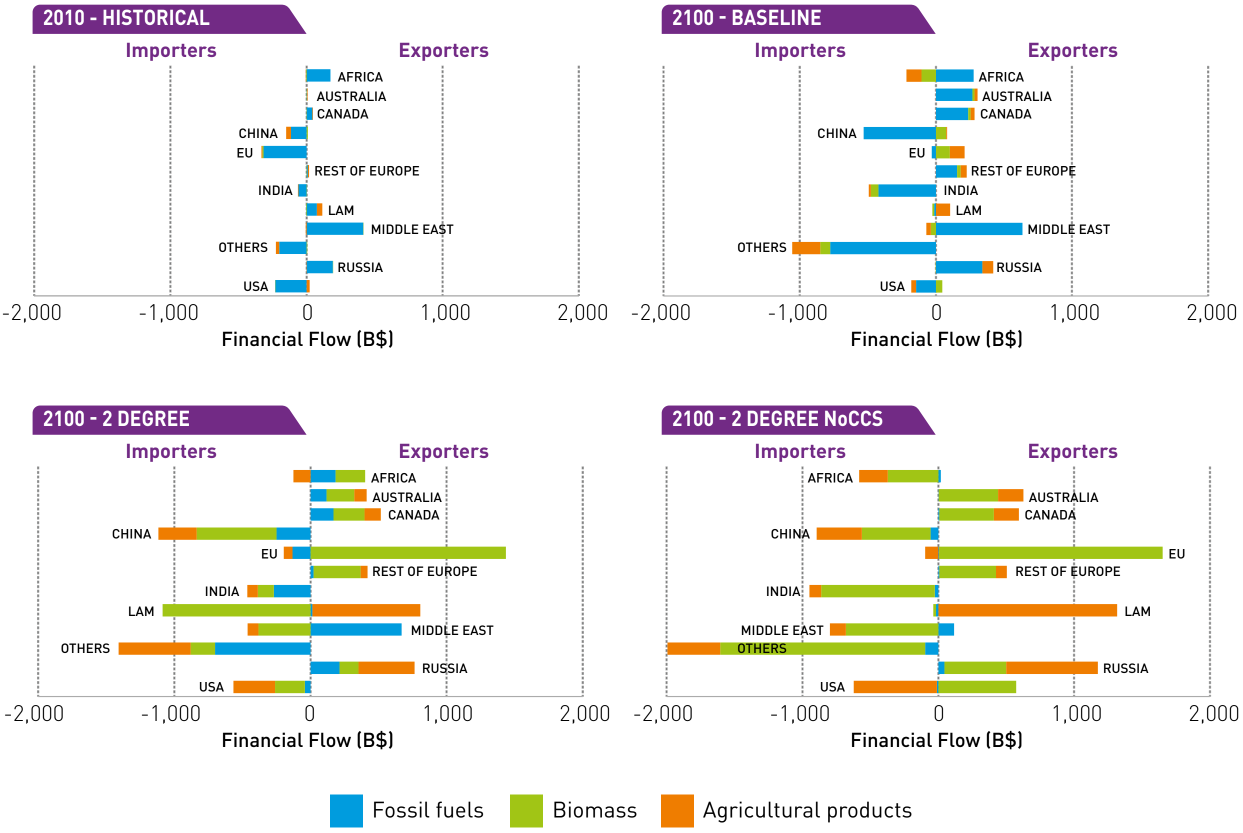


Figure 3.46 | Global fossil fuels, biomass, and agricultural products financial flows in 2010 and in 2100 (Muratori et al. 2016).

(respectively cooling) demand, all other factors remaining fixed. These results from a number of studies (see below) are derived from climate change projections from general or regional climate models reviewed by IPCC's 4th and 5th assessment reports, in combination with econometric analyses or with bottom-up energy models. The net change in the yearly energy demand for heating and cooling in the 21st century associated with climate change depends on location via both the distribution of temperatures and the thermal sensitivity of energy consumption (Wenz et al. 2017). Thermal sensitivity may be defined as the change in mean energy consumption or in peak load associated with a unit change in temperature. Thermal sensitivity is usually negative for low temperatures, due to increased energy consumption associated with heating and positive for high temperatures, due to increased energy consumption from cooling. Thus, thermal sensitivity depends on local efficiency of appliances and isolation and on consumer behavior.

Due to heating, countries historically experiencing relatively low temperatures, such as in northern Europe, are expected to see a net decrease in energy demand (Damm et al. 2017; Wenz et al. 2017) as opposed to countries which already or which will experience high temperatures, such as most Mediterranean countries (Giannakopoulos et al. 2009; Eskeland and Mideksa 2010), which are expected to see a net increase in the energy demand due to cooling. This is illustrated by the maps of *Fig. 3.47* which represent changes in average daily peak electricic load at the end of the 21st century relative to the beginning of the century estimated by Wenz et al. (2017) for the RCP4.5 (A) and RCP8.5 (B) scenarios. Differences between countries may not only be due to differences in temperature distributions, but also to varying thermal sensitivities between countries. Annual demand values do not reflect the seasonality of these changes, which may significantly impact the seasonal planning of energy resources.

Using regional climate models or statistical downscaling, case studies for specific countries such as Algeria (Ghedamsi et al. 2016), Cyprus (Zachariadis and Hadjinicolaou 2014), Slovenia (Dolinar et al. 2010), or Spain (Pérez-Andreu et al. 2018), offers

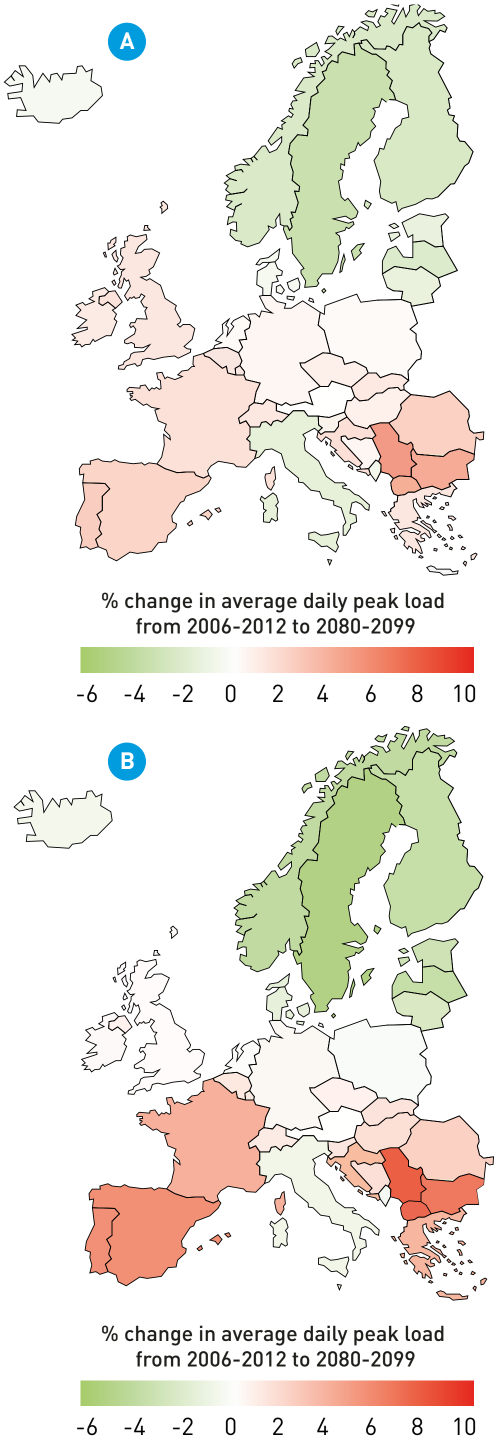


Figure 3.47 | Percentage change in average daily peak electric load from 2006–2012 to 2080–2099 for projected daily maximum temperatures under RCP4.5 (A) and RCP8.5 (B) climate change scenarios. While daily peak load decreases in northern European countries, it increases in southern and western European countries. This trend is most pronounced for a scenario of unabated climate change (RCP-8.5, B) but still holds for a scenario of mitigated climate change (RCP-4.5, A) (Wenz et al. 2017).

a more detailed picture showing that the expected distribution in demand changes may depend on local climates and that extremes in both heating and cooling demand may intensify even if the demand is reduced on average.

Energy demand may also be indirectly affected by climate change as impacts on the agricultural sector associated with reduced precipitation in North Africa may motivate replacing biomass as traditional energy source in rural areas (Schilling et al. 2012).

3.3.4 Adaptation and mitigation

3.3.4.1 Adaptation of energy systems to water constraints

Adaptation measures to mitigate the vulnerability of the electricity sector to future water constraints under changing climate have been investigated in the form of six options (van Vliet et al. 2016b). Options 1 and 2 assume increases in efficiencies of hydropower plants and thermoelectric power plants. Option 3 assumes replacement of fuel sources of thermoelectric power plants (coal- and oil-fired plants replaced by gas-fired plants). Option 4 assumes replacement of once-through cooling systems by recirculation (wet tower) cooling systems. Option 5 assumes switch to seawater cooling for thermoelectric power plants close to the coast (<100 km), and option 6 assumes decoupling from freshwater resources by switch to seawater and dry (air) cooling for 10% of the thermoelectric power plants that are most vulnerable to water constraints under climate change *(Fig. 3.48)*.

Increasing total efficiencies of hydropower plants up to 10% is able to completely offset the mean annual impacts of increased water constraints under changing climate for most regions, including the Mediterranean area (Europe and Africa) *(Fig. 3.48; panel A)*. For thermoelectric power, increased power plant efficiencies also positively contribute in reducing water demands and decreasing the vulnerability to water constraints under climate change *(Fig. 3.48; panel B)*. A strong increase in power plant efficiencies up to 20% is for most regions still insufficient to mitigate overall reductions in cooling water use potential under changing climate. This is the case for Europe, but not necessarily for Africa.

Changes in sources of fuel and switches in cooling system types (from once-through to recirculation with wet cooling towers or dry cooling) are for most regions more effective in reducing plant vulnerabilities to water constraints (Macknick et

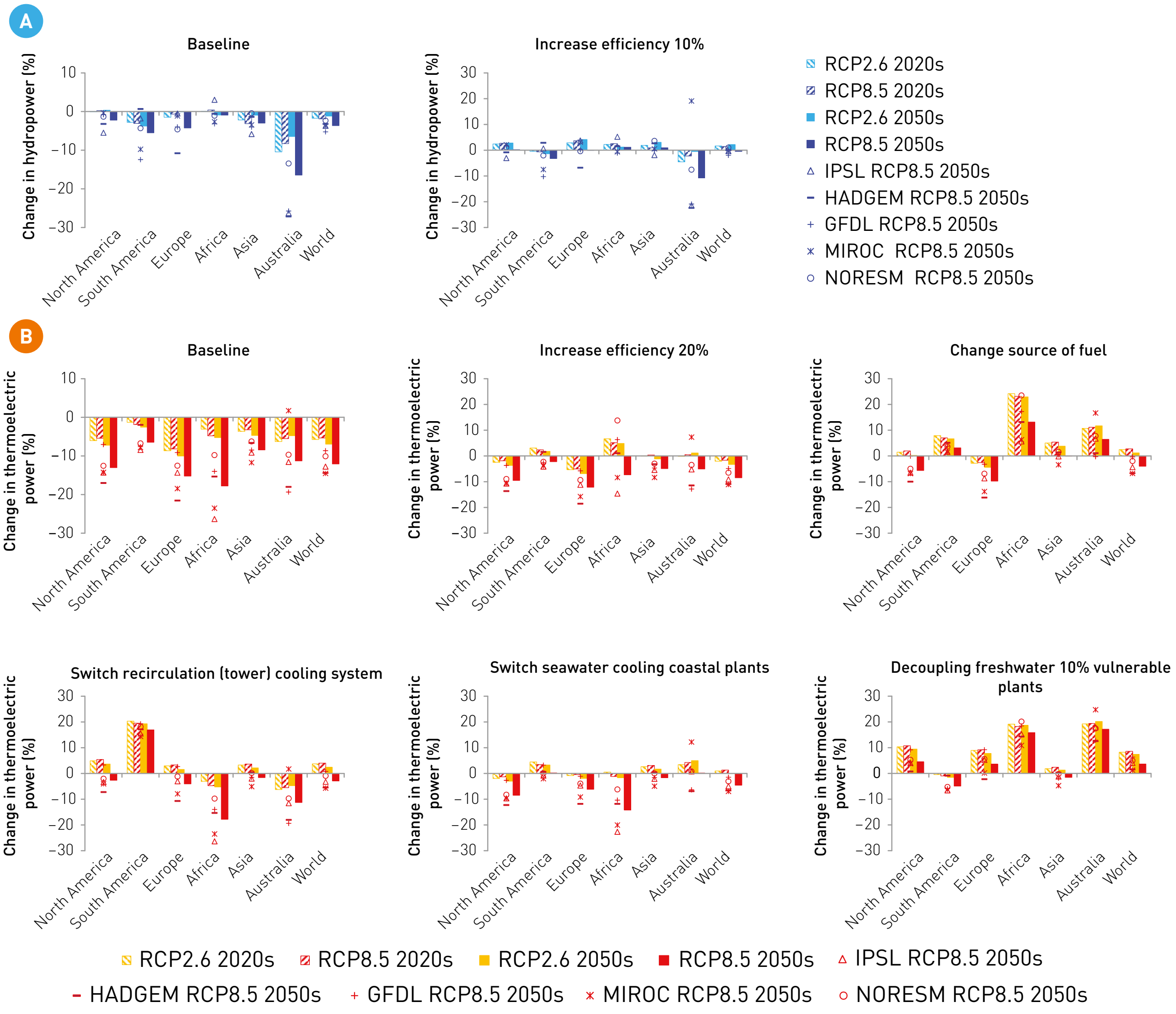


Figure 3.48 | Impacts of adaptation options on power-generation vulnerability to water constraints under climate change. Relative changes for the baseline settings and for various adaptation options of hydropower (A) and thermoelectric power (B). The GCM-ensemble mean changes are presented by the bars. In addition, changes for the five individual GCM experiments for RCP8.5 (2050s) are presented to show the range between the five different GCM experiments (van Vliet et al. 2016b).

al. 2012; van Vliet et al. 2016b). On average, fuel switching to higher efficiency gas-fired plants with lower cooling water demands can be sufficient to mitigate plant vulnerability to water constraints for the 2020s and 2050s under RCP2.6 scenario. This adaptation option will be insufficient for Europe under RCP8.5 scenario in the 2050s. The strongest positive impacts relative to the baseline settings are found for Africa, where the relative number of coal-fired plants that can be substituted by gas-fired plants is high.

A switch to recirculation (wet tower) cooling will decrease water withdrawals and reduce plant vulnerabilities to water constraints. A switch from freshwater cooling to seawater cooling for plants nearby the coast also reduces vulnerabilities to freshwater constraints. Decoupling of cooling water systems from freshwater resources (by switching to dry cooling or sea water cooling) for the 10% most severely impacted plants is a more effective adaptation option.

On top of these options, a higher share in non-water dependent power generating technologies, such as solar PV and wind power, will strongly reduce the dependency on freshwater resources. The uncertainty range is considerable and strongly depends on the relative share of different technologies within the energy transition (e.g., Mouratiadou et al. 2018).

3.3.4.2 Integration of renewables into the energy mix

In view of the current dynamics of energy supply and demand, a large gap is expected between anticipated demand and supply, particularly in SEMCs (Hawila et al. 2012). In order to address both the depletion of fossil fuels and climate change issues, it is necessary to improve rapidly the penetration of renewable energies. To this end, measures have already been taken to shift the energy mix in the SEMCs from fossile fuels to renewables. Large-scale deployment of renewable energy technologies and a necessary profound transformation of the energy sector are still lagging behind in some countries in the region (Vidican 2016).

Incentive effects of support mechanisms for renewable energy

SEMCs already consume a lot of energy and their energy demand is expected to continue to grow in the coming decades (El-Katiri 2014). As a result, energy plays an increasing role in national development policies in most of these countries. Given their climatic advantage, particularly in solar energy, the countries of the region therefore want to seize their comparative advantage. To achieve effective integration of renewable energy in these countries, a key solution would be to reform energy pricing mechanisms in the region and promote the participation of private actors in order to address the distortions of the energy market in the region. If this cannot be achieved for any reason, an alternative solution could be the introduction of tax and regulatory incentives aimed at reducing remaining cost disadvantages of renewable energies compared to fossil fuels (El-Katiri 2014). Since energy prices for the final consumer are heavily subsidized in most SEMCs renewable energy sources could also receive subsidies to make renewable energy production viable. Poudineh et al. (2018) argue that renewable energy support policy for SEMCs should meet criteria such as compatibility with the structure of the region's electricity system, harmonization with existing institutions, suitability at the project scale, coverage of economic risks and provision of efficiency.

Large-scale deployment of renewable energy could have significant positive impact on SEMCs. By examining the implications of renewable energy deployment in the SEMCs through the LEAP (Long Range Energy Alternatives Planning System) forecasting model, El Fadel et al. (2013) find that on a regional scale: (i) per capita greenhouse gas emissions could be drastically reduced, (ii) the return on investment in renewable energies promises up to 54% savings excluding positive externalities and (iii) the establishment of a CO_2 emissions trading market would provide economic incentives that make investment in renewable energies more attractive. An assessment by Timmerberg et al. (2019) of national renewable energy production targets and a diagnosis of the current energy sector in some SEMCs shows that the plans currently in place to expand renewable energy in these countries will be able to roughly meet the expected future growth in national electricity demand. Therefore, they estimate that if the targets set by the states for 2030 are met, CO_2 emissions per kWh, for example, could drop drastically to 341-514 g $CO_{2}e$ kWh^{-1} compared to 396-682 g $CO_{2}e$ kWh^{-1} in 2017.

Using a cost-minimizing electricity market model, Brand (2013) explores the option of optimized infrastructure for the integration of renewables into the interconnected North African electricity grids until 2030. The results show that the five countries, Morocco, Algeria, Tunisia, Libya and Egypt, could together achieve significant economic benefits of up to 3.4 billion € if they increase electricity grid integration, build interconnections and cooperate in the joint use of their power generation assets. The challenge remains to eliminate political obstacles to cooperation. Brand and Blok (2015) also assessed several studies (including Haller et al. 2012; Fragkos et al. 2013) using economic models of electricity supply and demand to assess the possible development paths of electricity systems in the North African region from today to 2030 (or even 2050). All studies agree that additional costs associated with the expansion of renewable energy in SEMCs could in most cases be offset by avoided fuel costs and avoided investments in fossil fuel power plants. Even electricity exports to Europe could become viable.

Despite the remarkable political objectives announced by SEMCs leaders to increase the deployment of renewable energy to meet growing energy demand and mitigate climate change in the region, there are still some inconsistencies between the approaches and the objectives. The deployment of renewable energy faces many obstacles in the region, namely, the state monopoly on the electricity sector, persistent fossil fuel subsidies, and weak regulatory institutions and bureaucratic issues (Lilliestam and Patt 2015). Al-Asaad (2009) notes mainly technical problems. For example, it points out that much of the region's network infrastructure (e.g., sub-stations and power lines) and network codes have long since become obsolete and therefore need to be upgraded to effectively meet the objectives of diversifying energy sources.

Finally, regarding renewable energy costs, Krupa and Poudineh (2017), using simulations, show that the levelized cost of energy (LCOE) of renewables is more sensitive to the discount rate compared to fossil energy sources in SEMCs. This is certainly due to the fact that the investment costs are very high whereas the production costs of fossils are more evenly spread over the life of the project.

The specific case of bioenergy: barriers and opportunities

There are four main barriers to develop bioenergy in Mediterranean area: financial, technological, social and institutional. Technical barriers include investment costs and lack of experience in biomass conversion technologies, and development of sustainable management of biomass sources. The regulation barrier requires new policies for bioenergy promotion, and socio-economic and environmental issues analysis. Financial decisions by funding agency adds the problem of competitiveness with other industry and energy markets. In fact, the development of bioenergy represents a new competitive sector because of the use of sources already used in industrial sectors as the paper industry or agriculture (Ferreira et al. 2017). For now, cultivation of energy crops is limited because of farmers' reluctance considering uncertainty of productivity and economic markets, and less attractive prices compared to cereal crops (Pulighe et al. 2019). In the same way, wood-biomass energy still remains low owing to the weak economic power of the forestry sector and the hard biodiversity regulation (Cavicchi et al. 2017).

The development of bioenergy implies increasing the production of local biomass sources, which raises ecological, economic and socio-political issues. Increasing biomass sources can be effective through tree plantations, forest management improvement, energy crops implementation, agricultural sources plantations, among others. Yet, these new biomass sources at large-scale production could increase greenhouse gas emissions considering the land-use changes associated (Fargione et al. 2008; Gibbs et al. 2008; Searchinger et al. 2008). In the Mediterranean Basin, tree plantations focus on *Eucalyptus* spp., *Populus* spp. and *Pinus* spp., but these species have high ecological impacts during the clearcutting and plantation operations, and soil preparation (Rodríguez-Loinaz et al. 2013). The development of agricultural energy crops would be competitive if some of the following situations happen: distinctive quality allowing competitive prices, new market opportunities that cover production costs, providing subsidies to these cultures by environmental reasons (Ferreira et al. 2017).

The development of bioenergy represents a larger opportunity than simple renewable and carbon neutral fuel source. The implementation of a holistic bioenergy sector can play a crucial role in the transition by improving Mediterranean forests management, promoting new socio-economic models and rethinking the relation between human and nature (Paredes-Sánchez et al. 2019; Sansilvestri et al. 2020). The bioenergy sector in Mediterranean Basin is an opportunity for land restoration and abandonment issues because bioenergy crops can be implanted on abandoned or polluted lands without sacrificing pastures, arable or protected lands (Pulighe et al. 2019).

It has been proposed that the evolution of the renewable energy based on biomass depends on two interacting variables: the strength of policy for centralization and the development of competitive markets for biomass-based alternatives. These two interacting axes will determine, by cascade effects, how much centralized policies will favor large industrial developments in contrast to a more widespread biomass conversion where sustainability of the resource is paramount. The development of biomass-based solutions also depends on how competitive solar and wind base solutions are *(Section 3.3.2.2).* In any case, northern Mediterranean countries have more margin of strategy evolution than southern ones, as biomass production is inherently much more restricted in the southern region.

Bioenergy has a place in a new economical organization with a clear position, rules and limits. Bioenergy can valorize residual productions from other industries, which can be upgraded in a bioeconomy sector. Pulighe et al. (2019) suggest that future support schemes and business models for mobilizing financing and attracting investors should be more aligned with greenhouse gas emissions, ecosystem services and sustainability indicators, avoiding criticism raised for the biogas sector regarding tradeoffs on land use pressure for biomass. For the time being, bioenergy is mostly based on an incentive economy, tax credits and fiscal exemptions, but to increase engagement of industry, foresters and farmers, it needs clear economic possibilities with a long-term visibility.

3.3.4.3 Energy access in developing countries of the Mediterranean region

Unlike the sub-Saharan African zone (only 45.6% electrification rate), SEMCs do not yet have major difficulties in providing electricity to their populations. The energy costs supported by households (very often subsidized) are largely lower compared to the world average. According to World Bank data, the electrification rate was almost 100% in 2017 for Algeria, Morocco, Tunisia, Egypt, Israel, Jordan and Lebanon. Libya is the only country with a lower rate (70.1%), due to the political instability (it had an electrification rate of 99.8% in 2000). Most analyses find that the energy dynamics of these countries are unsustainable in the long term, for several reasons. First, the region is experiencing strong demographic growth and prospects for strong economic growth are also expected. Therefore, energy demand is expected to grow strongly in the future for the net energy exporting countries (Algeria, Libya, Syria, Iran etc.) and for the net importing countries (Morocco, Tunisia, Egypt, Jordan and Lebanon) of the area (difficult combination of future depletion of reserves and energy subsidies). Second, the region is one of the most affected by the effects of global warming. Countries are therefore compelled to make an energy transition to renewable energy sources as quickly as possible and gradually move away from fossil energy sources. Finally, price control policies such as energy subsidies are quite widespread in the region. These policies are still costly to state budgets and quite ineffective. Energy subsidies frequently distort price signals and lead to systemic misallocation of resources (Fattouh and El-Katiri 2013). The main concerns are therefore how to produce enough renewable energy to meet the anticipated high future energy demand in the region, still considering potential political and economic barriers.

Financial, behavioral, institutional and regulatory impediments to energy access

The SEMCs are known for their oil and gas reserves, but also for their immense potential in renewable energies, particularly solar and wind energy. According to estimates, with only 0.2% of the land suitable for concentrating solar power, plants in seven countries of the region (Morocco, Tunisia, Algeria, Libya, Egypt, Jordan and Saudi Arabia) could cover 15% of the electricity demand expected in Europe in 2050 (Trieb et al. 2012). Thus, there are economic as well as environmental reasons to switch to renewable energy sources. But for those countries in the region that are highly dependent on fossil revenues (oil, natural gas), it would be very difficult to switch entirely to green forms of energy (El-Katiri 2014). The economies of these countries largely depend on the rents from hydrocarbons in the 1960s and 1970s. Also, the social contract between the government and citizens is based on the fact that energy is virtually free, making the investments into the transition difficult.

For the reasons mentioned above, the countries of the area need to make their energy transition quickly. By the end of 2013, some of them had set targets for the share of renewables in total electricity generation, in total installed power generation capacity or in total electrical and thermal energy (El-Katiri 2014). Algeria has set a target of 15% of electricity generation by 2020 and 40% by 2030, Morocco (42% of installed power generation capacity by 2020), Tunisia (25% of electricity generation by 2030), Egypt (20% of electricity generation by 2022) and Lebanon (12% of electrical and thermal energy by 2020). Despite high penetration of solar water heaters in Palestinian households (56%), solar thermal energy represents only a small fraction of the Palestinian Energy mix (8%). Transitions to renewable energy sources require huge investments, and therefore large-scale regional and international projects such as joint projects with the European Union. The realisation of large-scale energy projects between Europe and the region, such as the Mediterranean Solar Plan or Desertec, faces several barriers. Fritzsche et al. (2011) mainly refers to political constraints, such as the lack of subsidies, incentives and liberalization of the renewable energy market in the region. Authors including de Souza et al. (2018) rather refer to cultural barriers to renewable energy trade projects in the Mediterranean (between the EU and southern countries), alluding to the failures of energy cooperation projects between Europe and its former colonies.

While voices are being raised in the North of the shore to denounce what should increase Europe's energy dependence, and therefore additional diplomatic pressure (Lilliestam and Ellenbeck 2011), in the South, there is talk of a new form of resource exploitation, and therefore of the notion of solar colonialism (Marktanner and Salman 2011; Rowlinson 2015). There are three main risks to their implementation, risks that affect the cost of capital in particular: (1) the complexity and instability of national regulations, (2) low political stability and (3) terrorist threats in the region (Komendantova et al. 2011). The World Bank has repeatedly pointed out that among the constraints to investment in the renewable energy sector in the region are the narrowness of local markets (which discourages private investment in particular) and the need to consider a regional energy trading market, the weakness of public finance and the competition of energy investments with other public service and public infrastructure investments. Far from the reality of the major oil exporting countries of the region, Morocco depends heavily on its energy imports, i.e., 95% of its consumption in 2007 (Fritzsche et al. 2011), despite a rather remarkable potential in renewable energy. This energy deficit partly explains the strong pressure on traditional energy sources (wood, coal, etc.). According to Zejli et Bennouna (2009), between 30,000 and 50,000 hectares of forest disappear every year. Aware of this and aiming in particular at reducing its dependence and energy bill, the country is widely involved in projects and initiatives aimed at promoting renewable energy. With this in mind, in November 2009 the country launched the pharaonic Noor project (I, II and III) in Ouarzazate at an estimated cost of 2.5 billion US$ (9 billion US$ for the full Moroccan Solar Plan), a project that should eventually provide electricity to more than 2 million people in the country.

Regulatory framework and business models to reach universal access

According to de Souza et al. (2018), to facilitate the successful implementation of renewable energy projects, it is particularly important that the countries of the South are sufficiently integrated into the value chains of production, from distribution to transportation of energy (acceptability), put in place a plan to mitigate the environmental impacts of site operations and facilitate technology transfer. Fritzsche et al. (2011) point out that specialized agencies should be created to overcome political constraints to facilitate the establishment of renewable energy facilities in the area and multiply tax incentives to help attract foreign direct investment. They also point out that funding and technical assistance from international and regional donors and development banks are essential for the implementation of these types of projects. They also argue that technology transfer from North to South should be promoted, R&D should be encouraged and EU-SEMCs and PPP (public-private partnership) type partnerships should be implemented. Blimpo and Cosgrove-Davies (2019) argue that it would be viable to establish a regional energy exchange market between the countries in the area, since energy trade would halve the cost of kWh. As private investors are more attracted to large markets, establishing a common regional market will also allow small economies and countries that are not abundant in energy resources to benefit from cheaper electricity. As an example of an integration model, Blimpo and Cosgrove-Davies (2019) mention the example of the West African Power Pool (EEEOA), which brings together 14 countries of the zone and 27 companies. This system would have enabled many countries in the West African zone to benefit from an affordable, reliable and sustainable electricity supply (typical case of the Manantali dam on the Senegal River, which benefited from a lower investment cost to the benefit of Mali, Senegal and Mauritania). El-Katiri (2014) emphasizes the need to reform the system governing the energy price mechanism (local market prices strictly controlled by the State to its liking) at the national and regional levels and to implement a fiscal policy aimed essentially at reducing the cost disadvantage of renewable energies compared to fossil fuels.

The Green Transition in North Africa and the Middle East

With the exception of Libya, the other six states in the North African region have ratified the Paris Agreement of 2015. For countries in North Africa, the energy transition requires a profound structural transformation of the energy sector and all other sectors of the economy, but one of the major difficulties of this structural transformation is to effectively find a compromise between long-term and short-term political and economic objectives (Pye and Bataille 2016).

Another major difficulty remains the question of financing, as green projects are unfortunately still quite expensive and require large investments. To illustrate, estimates have shown that for some 28 countries on the African continent, for example, meeting national commitments for energy transition would require an overall investment of more than 240 billion US$. On the other hand, these investments would be quite beneficial for the economies of North Africa, particularly in view of their potential for renewable energy. Brand and Zingerle (2011) show that for every € spent on renewable energy, 0.15, 0.16 and 0.27 € of savings could be made in the national electricity system in Tunisia, Algeria and Morocco respectively. Also, according to Alnaser and Alnaser (2011), the costs of generating electricity from photovoltaic systems and wind turbines have been on a downward trend for several years. In some SEMCs, it is already possible to produce green power much cheaper than electricity production from fossil sources (IRENA 2018). The competitiveness of renewable energy sources depends not only on the technology used for energy production and the availability of energy resources, but depends especially on the cost of fossil fuels (substitutes for renewable energy). The costs of fossil fuels are much lower for most SEMCs compared to other regions of the world. This does not promote the competitiveness of renewable energies.

Timmerberg et al. (2019), based on an assessment of national renewable energy production targets and a diagnosis of the current energy sector in selected SEMCs (Algeria, Egypt, Morocco, Saudi Arabia and Tunisia), show that current plans for renewable energy expansion in these countries will be able to approximately meet the expected future growth in national electricity demand. They estimate that if the targets set by the States for 2030 are met, CO_2 emissions per kWh, for example, could drop drastically to 341-514 g CO_2e kWh^{-1} (compared with 396-682 g CO_2e kWh^{-1} in 2017).

3.3.4.4 Financing the energy transition

As discussed in the previous sections, the energy transition requires a significant transformation of the energy and economic model in the Mediterranean region. Mitigation and adaptation will require investments from households, companies and governments, which in turn require sources of financing. Policymakers in Mediterranean countries need to focus policies and public investment to achieve three main objectives: i) to bring the benefits of the new energy technologies to citizens via accelerated uptake of distributed generation, ii) incentivize the deployment of utility-scale PV parks, preferably including storage, and iii) to ease the opening of new energy technology factories in their countries. Today's low-cost solar energy and electricity storage technology, make the first objective achievable thanks to new legislation supporting distributed generation for example updating obsolete construction regulation making long and costly the permit process to functionalize buildings with solar modules. The growth potential is huge as less than 5% of the world's buildings, and even a lesser fraction of the large Mediterranean built environment, are functionalized with solar collectors. Achieving the second objective in industrialized countries such as Spain, Italy, and France is feasible by allowing renewable energy generation companies to take part not only to the day-ahead electricty market but also to the dispatching and energy services markets, so far opened to thermal production units only. Sunnier SEMCs will preferably continue with tenders to purchase clean electricity produced via utility-scale PV plants at prices

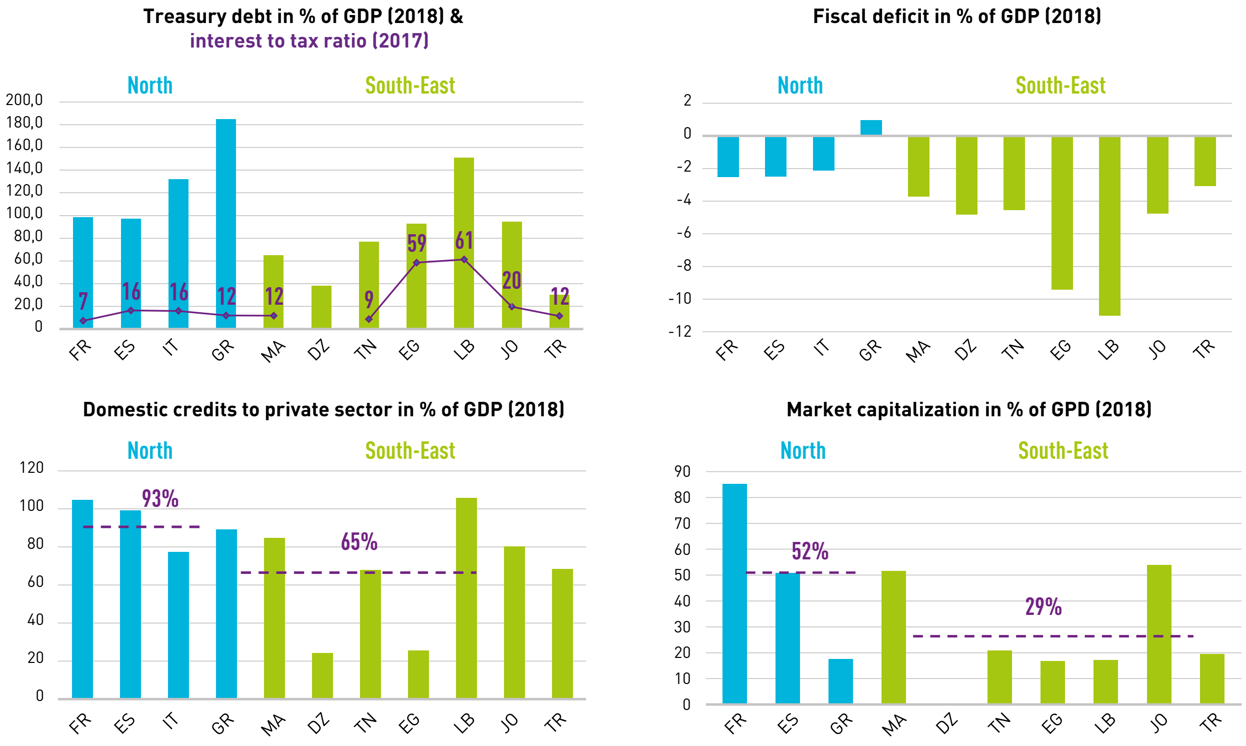


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Figure 3.49 | Economic and financial contexts around the Mediterranean (MEF 2019).

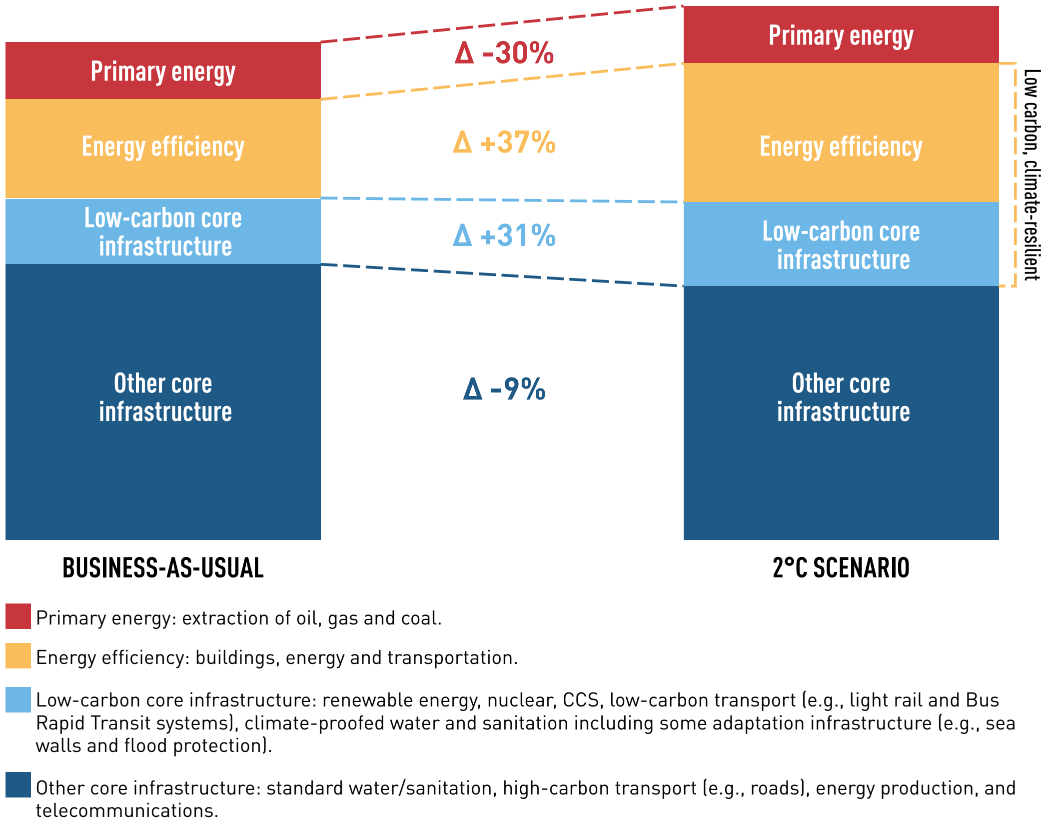

Figure 3.50 | Change in infrastructure spending for a 2°C scenario in the Mediterranean region, percentage change in expenditure over 2015-2030 compared to Business-as-usual. (MEF 2019).

that in the case of Egypt have already reached very low levels. Finally, the third goal is to make their countries home to new industrial plants of the solar economy, requires to concentrate the financial resources on establishing new partnerships with the leading renewable energy and energy storage technology manufacturers, which are not based in Mediterranean countries. There are many ways to incentivize foreign companies to invest, as shown by Morocco with their new electric vehicle plant; or by Algeria, requiring renewable energy compaies to use components made in Algeria for the utility-scale PV plants awarded the Public-Private Alliances.

Financial needs by sector and region

Beyond the economic contexts, public finance capacities of SEMCs are subject to strong tensions, with a high weight of the treasury's debt in terms of GDP. SEMCs financial systems are also characterized by a domination of banking, a weak development of financial markets and a low degree of international market openness *(Fig. 3.49).* In the Mediterranean region, financing needs for SEMCs NDC are estimated at more than 170 billion US$, of which 81% are related to conditional NDC (MEF 2019).

While there is no specific figure for the Mediterranean region, Western Europe benefited from 106 billion US$, while Middle East and North Africa benefited from 13 billion US$ during the period 2017/2018 (CBI 2019). Focusing on international public climate finance, Egypt, Turkey, and Tunisia were the top-3 recipients in 2017, altogether representing 5.6 billion US$ (of 8.1 billion US$ for the SEMCs) (UfM 2019). International public climate finance captured by the SEMCs has shown an encouraging trend since 2012, since the amounts committed have increased by an annual average of 21.5% over the 2012-2017 period (MEF 2019). In the Mediterranean region, 135 billion US$ per year in the energy sector will be needed until 2040 (approx. 1% of each country's GDP) and will have to be redirected from fossil fuels to renewables and energy efficiency (IEA 2018; IPCC 2018). Natural gas and renewables will dominate future investments in power generation across the region and close to 44 billion € per year will be needed to reach the

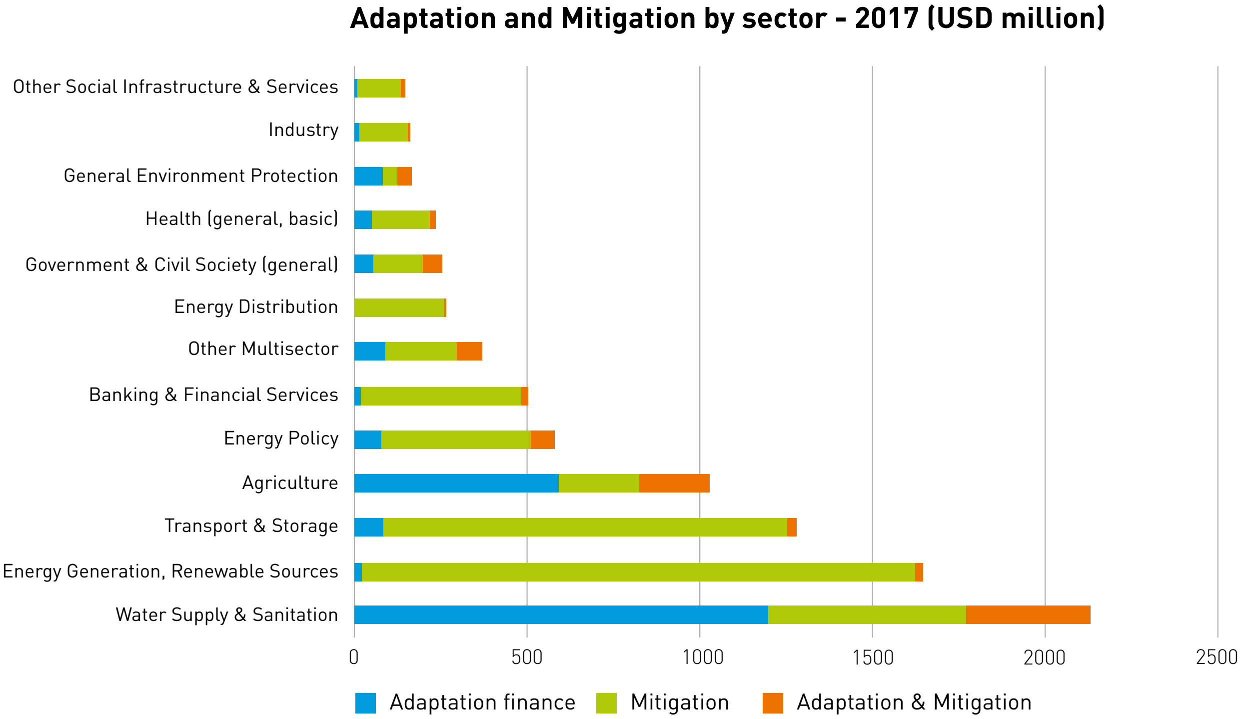

Figure 3.51 | International public climate finance by sector in SEMCs, 2017 (UfM 2019).

energy demand levels of the Reference Scenario (40% increase in demand) while energy efficiency investments will need to reach 61 billion € per year (Fig. 3.50). About 55% of these energy investments will be required on the north shore, 25% in North Africa and 20% in the South East (OME 2018).

In the 2017/2018 period, the following financial flows in SEMCs went to mitigation, and specifically to renewable energy generation (1.6 billion US$), water supply and sanitation (1.4 billion US$), transport and storage (1.2 billion US$) and agriculture (0.6 billion US$) (UfM 2019; *Fig. 3.51*).

Currently, adaptation flows account for a small percentage of total climate finance, illustrating what Abadie et al. (2013) call the 'mitigation bias'. This bias is also present in the SEMCs *(Fig. 3.51).* Beyond investment in hard projects for mitigation and adaptation of infrastructures, financial flows are needed to push R&D capabilities in both northern and SEMCs.

Financial actors

Different actors are expected to finance climate change mitigation and adaptation. In the 2017/18 period private actors represented 326 billion US$ while public actors represented 253 billion US$ of annual flows (CBI 2019). While 75% of climate finance is invested in the same country in which it is sourced, developed countries have pledged to raise 100 billion US$ per year by 2020 for global climate action to developing countries (UNFCCC 2018), including both public and private sources.

Climate-related multilateral funds, such as the Green Climate Fund (GCF) and the Adaptation Fund (AF), remain less important (0.39 billion US$). Major bilateral donors are member countries of the Development Assistance Committee, including France (0.88 billion US$), Germany (0.75 billion US$), EU institutions (0.62 billion US$) and Japan (0.43 billion US$ in 2017 after 1 billion US$ in 2016) (UfM 2019). Since 2013, the contribution of multilateral development banks has been steadily increasing, in line with their commitment taken at COP24 in December 2018 to align their activities with the goals of the Paris Agreement. On the northern shore, EU countries committed to dedicate at least 20% of the EU budget from 2014-2020 to climate-related actions (representing around 180 billion €, threefold increase from the 6-8% share in 2007-2013[30]).

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[30] Source: https://ec.europa.eu/clima/policies/international/finance_en

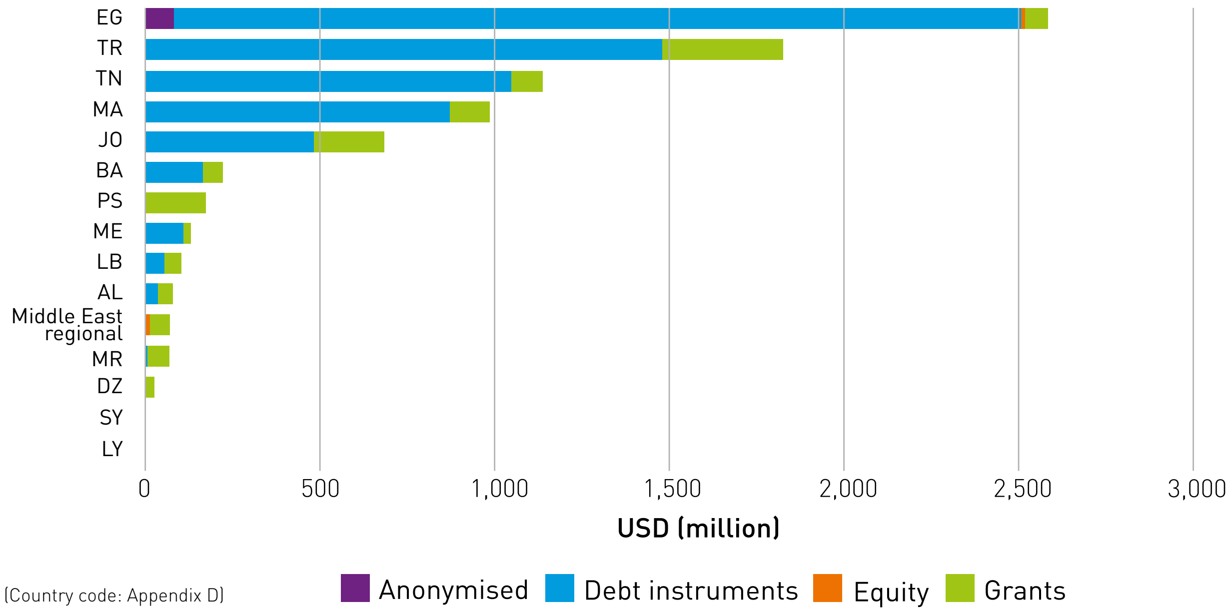


Figure 3.52 | International public climate financial isntruments by SEMCs recipient countries, 2017 (UfM 2019).

Financial instruments

Worldwide, debt is the main financial instrument of climate finance. SEMCs benefited mostly from debt instruments from international public finance *(Fig. 3.52)*. Financing the energy transition goes beyond debt, equity and grants. Above the various mitigation mechanism, putting a price on carbon with tax or quotas can encourage to consume and invest in goods and equipment that emit less greenhouse gases and generates a complementary source of financing for the energy transition. In the Mediterranean region, carbon price mechanisms are only present on the north shore. The EU Emission Trading System (EU-ETS), launched in 2005, is the world's biggest emissions trading system, accounting for 45% of total EU greenhouse gas emissions. Different countries have also applied carbon taxes (e.g., France, Portugal, Slovenia in the Mediterranean region).

Another tax measure to accelerate the energy transition and provide financing is to reduce fossil fuel subsidies. Subsidies were estimated to 130 billion US$ for SEMCs in 2015 (OECD 2018). These subsidies allocated to fossil fuels reach significantly high levels in countries such as Egypt, Lebanon and Algeria while Tunisia, Jordan or Morocco have relatively more moderate levels *(Fig. 3.53)*. In Egypt, a program was adopted in 2014 for gradually subsidy phase out taking into consideration the social impacts, with a foreseen deadline in 2021.

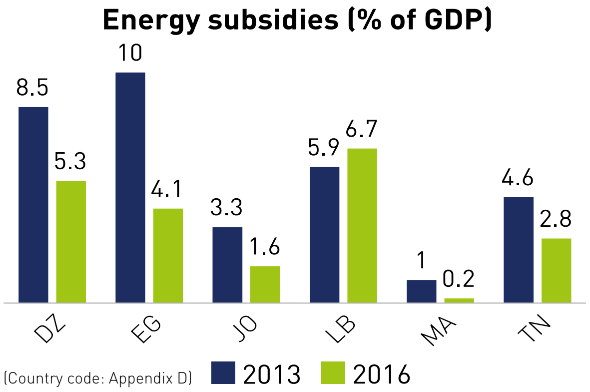


Figure 3.53 | Energy subsidies in SEMCs (World Bank 2018).

Among the new instruments of the climate finance, green bonds are bonds issued by companies, governments or local authorities on the financial markets to finance a project or activity with an environmental benefit and are subject to standards (Green Bonds Principles). Worldwide, $168 billion were issued in 2018 (40 billion US$ in 2014). Since 2007, Europe accounts for more than 36% of green bonds issued while Africa accounts for less than 0.4% (CBI 2019).

3.3.4.5 Supra-regional cooperation for energy transition

Faced with this economic, social and environmental situation, energy and climate challenges are of major importance. Accelerating the energy transition in the Mediterranean would help to control the growing demand for energy, to promote renewable resources and finally to optimize the use of fossil resources. The optimisation of the regional energy system, would pass through a better integration of markets, increased interconnection and intelligent management of networks, including the facilitation of access for renewable energy and demand side management.

Energy should be considered as part of the larger process of political shifting to a more inclusive, democratic and sustainable development paradigm (new social contract) that concentrates on a fair split of resources, opportunities and the results of growth all the while ensuring the right of all people to equitably participate in decisions that shape the future of their societies. This approach mirrors the dominant one that demands more decisive investment in renewable energies, but mainly as a tool for socio-economic development. For investments in renewable energies to have concrete value for the larger sustainable development goals of a country, projects should include technology transfers and capacity building for the population. In that regard, new initiatives for promoting renewable energies in the Mediterranean should avoid the 'Eurocentric focus' of the Mediterranean Solar Plan, which was seen as an instrument to support mostly the interests of European companies. Studies of the implementation of renewable enregy projects in the SEMCs have also alerted on their consequences in terms of reinforcing the private sector and central government at the expense of local populations. In brief, if Euro-Mediterranean energy cooperation wants to thrive, it is necessary to reconsider who matters in energy security, from market and state actors to society at large, and consider particularly marginalized sectors of the population.

The Euro-Mediterranean dialogue, under the chair of the European Commission and the Kingdom of Jordan, at the Rome conference in November 2014, decided to establish three platforms for exchange and cooperation. The ultimate goal for these platforms is to operate as permanent consultation forum on strategic objectives and measures to be implemented under the auspices of the Union for the Mediterranean. The three platforms cover: (i) the gas sector managed by the Mediterranean Observatory of Energy (OME), (ii) the electricity market with support provided by the Association of Mediterranean Regulators (MEDREG) and the Association of Mediterranean Transmission System Operators (MEDTSO) and finally (iii) the renewable energy and energy efficiency with support of MEDENER and RCREEE.

Many studies have shown that energy cooperation projects with North Africa aimed at large-scale energy production and exchange (mainly solar and wind power) would be an ideal instrument to achieve greenhouse gas reduction (Komendantova et al. 2012). Other studies have also analysed the barriers that constrain these energy projects, which Flyvbjerg et al. (2003) describe as "mega-projects" because they require huge costs. All of these studies are based on a perception of risk at two levels: regulatory and political risks, and force majeure or security risks (including, in particular, the terrorist threat in the region).

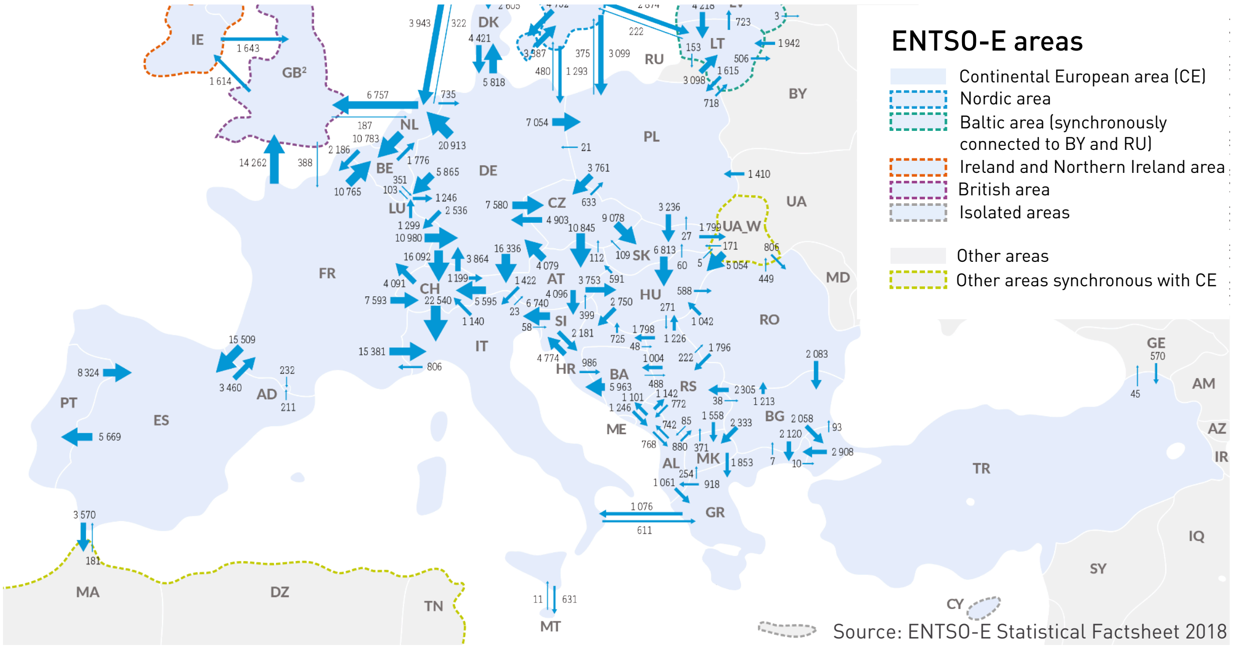
Mediterranean energy market integration

Achieving the objectives of the Paris Agreement requires a massive scale-up of renewable energy sources and regional energy market integration facilitates the large-scale development of renewable energy, as it increases the area over which electricity supply and demand must be balanced in real time, making it less likely that the resource will not be available when needed. Regional energy market integration offers numerous benefits to the power systems and the economies of participating countries: enhanced energy security and power system reliability, reduced need for back-up capacity thanks to reserve sharing, supply mix diversification, more efficient use of power plants, lower power system costs (both investment and operating) and therefore lower consumer prices (World Bank 2010; UK DECC 2013). With more ambitious climate mitigation objectives since the December 2015 Paris Agreement, the climate benefits of regional integration are increasingly acknowledged as being as important if not more than the energy and economy benefits. Some of the climate benefits result from the increased efficiency of the power system, but most of them are derived from the fact that regional integration increases power system flexibility, and therefore facilitates renewable energy scale-up.

Although several studies have estimated the costs and benefits of the integration of electricity markets, particularly in Europe (Bockers et al. 2013; Newbery et al. 2016), there is less research on the preconditions and the required policies for establishing a successfully integrated market for electricity and a truly seamless transmission system (Oseni and Pollitt 2016; Roques and Verhaeghe 2016). Newbery et al. (2016) estimate the benefits of integrating the European Union (EU)

Physical energy flows across Europe

GWh average over the year



Source: ENTSO-E Statistical Factsheet 2018

¹ Consolidated yearly values might differ from detailed flow data from the ENTSO-E database due to ex-post consolidation taking into account national statistical resources.
² All data with the country code GB represents monthly statistical data as sum of England, Northern Ireland, Scotland and Wales.

	Sum of imports	Sum of exports	Balance (imp-exp)		Sum of imports	Sum of exports	Balance (imp-exp)
AL	1,771	2,683	-912	**IT**	47,169	3,268	43,902
AT	29,393	19,057	10,336	**LT**	12,850	3,219	9,631
BA	3,091	7,796	-4,605	**LU**	7,514	1,349	6,166
BE	21,650	4,313	17,338	**LV**	5,179	4,272	907
BG	2,220	10,029	-7,809	**ME**	2,760	3,011	-251
CH	30,420	31,693	-1,274	**MK**	4,144	2,224	1,921
CZ	11,562	25,453	-13,891	**NL**	26,818	18,596	8,223
DE	31,542	82,673	-51,131	**NO**	8,085	17,954	-9,869
DK	15,606	10,413	5,193	**PL**	13,839	8,121	5,718
EE	3,514	5,364	-1,850	**PT**	5,669	8,324	-2,655
ES	24,014	12,910	11,104	**RO**	2,829	5,370	-2,541
FI	23,397	3,459	19,938	**RS**	7,300	6,703	597
FR	13,466	76,020	-62,554	**SE**	14,234	31,561	-17,328
GB	22,662	2,189	20,473	**SI**	8,928	9,320	-392
GR	8,552	2,265	6,288	**SK**	12,544	8,747	3,797
HR	12,692	6,533	6,160	**TR**	2,638	3,046	-408
HU	18,613	4,265	14,348	**ENTSO-E**	**458,274**	**443,734**	**-14,540**
IE	1,614	1,643	-29	Physical flow values in GWh			

(Country code: Appendix D)

Figure 3.54 | Cross-border physical electricity flows, in gigawatt-hours (GWh) (ENTSO-E 2019).

markets at 13-40 billion € per year for the EU as a whole, depending on assumptions on fuel and carbon prices, renewable enrgy costs and penetration. If the market integration were broadened to include the whole Mediterranean region, then the savings would be even larger possibly delivering additional savings of 30 billion € per year according to studies conducted by Desert industrial energy initiative (Dii) (Zickfeld and Wieland 2012).

An integrated energy market and a cooperative approach would reduce the cost of meeting the ambitious EU CO_2 reduction and renewable energy targets (Caldés et al. 2015; Szabó et al. 2015). Associating the southern shore of the Mediterranean would further reduce the cost of decarbonization of the EU power sector, as the region is endowed with a massive renewable energy potential and a vast stock of unused land where solar panels and other renewable plants can be sited without creating a nuisance for nearby population. The Sahara Desert is a prime location for solar power generation and could potentially produce several times the level of demand for carbonless electricity in Europe, while also covering demand in the SEMCs.

The two Mediterranean shores are already inter-connected, in the West by a submarine cable of 1,400 MW under the Strait of Gibraltar connecting Spain and Morocco, and in the East with Turkey connected to Bulgaria through two 400 kV lines (for a total capacity of 2,500 MW) and to Greece through a 400-kV line with a capacity of 500 MW. Other interconnections between Europe and the southern shore of the Mediterranean are being studied, in particular, the Italy-Tunisia connection to the centre of the Mediterranean *(Fig. 3.54).* Contrary to Europe, the network in the SEMCs is sparser, and interrupted between Tunisia and Libya. In this region, renewable energy integration often needs complementary developments in generation and transmission, due to more isolated systems requiring back-up capacity.

The idea of exporting solar electricity from the Sahara is not new and dates back to the 1940s (Escribano et al. 2019), but the concept gained momentum when the first EU renewable energy Directive (EU 2009) was being prepared. The period 2008-2012 saw a flurry of initiatives such as Mediterranean Solar Plan, Desertec, Dii and MEDGRID to connect the southern and northern shores of the Mediterranean when it seemed that many EU countries would face difficulties in meeting their commitments under the Directive. Most of these initiatives went into hibernation as EU countries did not express much interest in cooperation mechanisms with southern Mediterranean countries, either because they could meet their 2020 targets from their own renewable energy resources (in part because of stagnant demand), or because they preferred to use other mechanisms such as statistical transfers or cooperation mechanisms with other EU countries. Caldés et al. (2018) and Lilliestam et al. (2016) identified the following reasons for the failures of these ambitious Mediterranean integration initiatives: (1) underdeveloped legal and regulatory frameworks, (2) weak grid infrastructures (in particular lack of interconnection between the two shores), (3) lower than expected socio-economic benefits, (4) high upfront costs and lack of financing mechanisms, (5) high fossil fuel subsidies in SEMCs and (6) energy policy giving priority to domestic renewable energy production over electricity imports and electricity surpluses in EU countries.

The EU has now set more stringent targets for 2030 and is aiming for carbon neutrality in 2050 under the European Green Deal proposed by the Commission in December 2019. Furthermore, the benefits of regional market integration in terms of investment and operating cost savings, and facilitated renewable energy grid integration, are increasingly acknowledged. Regional electricity market integration appears to be recognized as one of the most cost-effective options to increase power system flexibility.

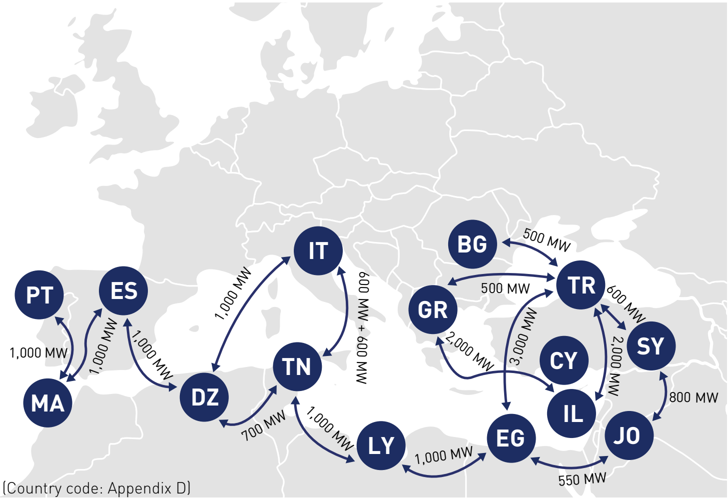
The need for supra-regional interconnections

The integration of a high-level of renewable energy requires that power systems have flexibility to cope with the stress resulting from sudden and unpredictable variations in the availability of renewable energy. Power system flexibility is defined as the ability to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to support the long-term security of supply (Taibi et al. 2018; Mohandes et al. 2019). Flexibility can be provided by dispatchable power plants, demand-side response, storage and network infrastructure, in particular, the one that supports regional market integration (Baritaud and Volk 2014) and requires a combination of regulatory, operational and investment measures (Hirth and Ziegenhagen 2015). Greater transmission interconnectivity yields substantial economic and environmental benefits and requires the strengthening of interconnectors, the hardware of regional electricity market integration (Crisan and Kuhn 2017). Ensuring that interconnectors are efficiently used and properly remunerated for their flexibility services both reduces the short-run cost of integrating renewables and increases the attractiveness of investing in additional interconnection (Newbery et al. 2016; Newbery 2017). Regional market integration through interconnectors expands the region's access to carbonless sources of energy, such as hydro reserves in the North or more predictable plentiful solar power in North Africa and reduces renewable energy sources curtailment.

The degree of interconnectivity will affect the need for new power plants and their location. Power generation and transmission planning, therefore, needs to be integrated. Successful renewable energy sources integration requires integration of power generation and transmission planning, of operational and investment decisions and of national markets into regional markets (Pariente-David 2014). A holistic approach is needed. Reaching high renewable energy shares entails "integration costs" elsewhere in the power system such as balancing services and firm back-up capacity on standby that are not reflected in traditional planning and economics approach based on the LCOE. A system-wide approach is needed that integrates all the costs and derived effects of renewable energy sources integration to determine the optimal mix of power generation plants and transmission lines to meet electricity demand at the lowest cost while satisfying the climate change and other policy objectives. This is the "total system cost" approach which focuses on the total cost of the power system, rather than trying to allocate some of the cost components to specific technologies, or part of the power system, to compare the technologies on the basis of LCOE (Pariente-David 2016).

After a period of lull, there is a revival of interest in electricity exchanges across the Mediterranean. Designed by Med-TSO between 2015 and 2018 in the framework of its Mediterranean project "the Mediterranean Master Plan plays a key role for consolidating a secure and sustainable electricity infrastructure through the development of interconnections, while facilitating the integration of Renewable Energy Sources in the Mediterranean Region" (Iliceto and Ferrante 2018). The Mediterranean Master Plan identified 14 clusters of projects for the interconnection of Mediterranean electricity grids according to a 2030 horizon scenario *(Fig. 3.55)*. The Plan targets 18 GW of new interconnection capacity, corresponding to 2,200 km of new transmission lines, requiring about 16 G billion € of additional investments.

The circumstances seem to be auspicious in 2019 to relaunch the Mediterranean Energy Union process. The EU "Clean Energy for All Europeans" (CE4ALL) Package (European Commission 2016) was fully adopted in May 2019, as the implementing instrument of the 2015 Energy Union strategy, which acknowledges that regional market integration is key in achieving EU climate change objectives at least cost and that strongly interconnected networks are required to support unhampered electricity trade and sharing of ancillary services. Cooperation, coordination (both on national policies and power system operations) as well as and regional market integration are a central part of the CE4ALL Package. Although the Package primarily aims at the European internal energy market, it recognises that the EU is not isolated and includes several cooperation mechanisms and financing instruments for joint projects with third-party countries (Held et al. 2019), so that the EU can tap into the best resources to achieve power sector decarbonisation.



(Country code: Appendix D)

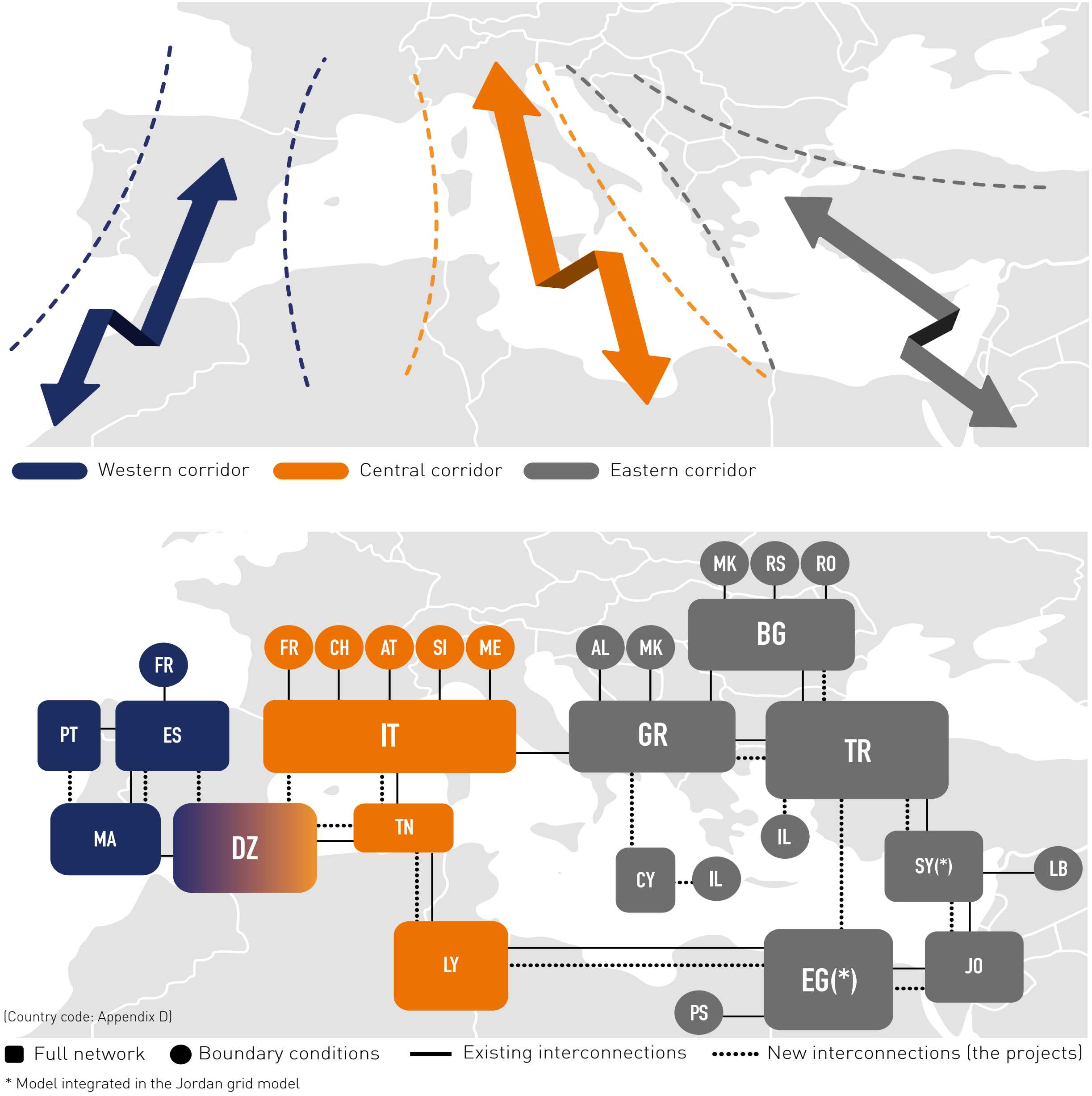
NO.	INTERCONNECTION PROJECT/CLUSTER
1	Cluster MA-PT *(Morocco-Portugal)*
2	Cluster MA-ES *(Morocco-Spain)*
3	Cluster DZ-ES *(Algeria-Spain)*
4	Cluster DZ-TN *(Algeria-Tunisia)*
5	Cluster DZ-IT *(Algeria-Italy)*
6	Cluster TN-IT *(Tunisia-Italy)*
7	Cluster TN-LY-EG *(Tunisia-Lybia-Egypt)*
8	Cluster GR-TR-BG *(Greece-Turkey-Bulgaria)*
9	Cluster GR-CY-IL *(Greece-Cyprus-Israel)*
10	Cluster TR-EG *(Turkey-Egypt)*
11	Cluster TR-IL *(Turkey-Israel)*
12	Cluster EG-JO *(Egypt-Jordan)*
13	Cluster JO-SY-TR *(Jordan-Syria-Turkey)*

Figure 3.55 | Mediterranean interconnection projects (Iliceto and Ferrante 2018).

In summary, regional energy market integration and cooperation are crucial to unleashing the region's solar potential for cost-effective climate change mitigation in the Mediterranean. Many obstacles remain, including lack of the necessary transmission/interconnection infrastructure, difficulty in siting renewable energy plants in the best locations because of high up-front costs that makes financing risky, geopolitical considerations, insufficient coordination of power systems and lack of alignment of market rules. It is necessary to ensure interoperability of wholesale markets, value properly flexibility services and allocate interconnection costs to reflect the benefits accrued to the different stakeholders. This will extract value from regional market integration. The process can take years, happens in stages and requires appropriates national and regional institutions (Oseni and Pollitt 2016; Pariente-David and Jannet Allal 2019).

Strategy of transnational associations of regulators

Regulations regarding energy transmission systems and operations vary significantly among Mediterranean countries (MEDREG 2018). Transnational partnerships thus require forming a common set of



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* Model integrated in the Jordan grid model

Figure 3.56 | Strategy of Mediterranean regulators for regional integration (Iliceto and Ferrante 2018).

BOX 3.3.1

Climate variability and energy planning

The variability of the renewable energies production, such as from wind and PV energy, adds to that of the energy demand and may pose challenges to the adequation and stability of networks which can translate into a decreased quality of services or into an increase in system costs (Ueckerdt et al. 2015) due to additional flexibility requirements. The variability of renewable energies production becomes critical when their penetration reaches a level, which is higher than what existing flexibility mechanisms allow the energy system to cope with (Cretì and Fontini 2019, chap. 26).

Not only the variability of meteorological conditions at single locations is relevant to energy planning, but also the relations between electricity demand and capacity factors, between capacity factors at different locations, and between capacity factors for different technologies. These correlations influence the potential smoothing of production once aggregated by interconnections, illustrated in *Fig. 3.57* for the case of wind and PV energy in Italy analyzed by Tantet et al. (2019). In panel a, points in the curves represent optimal distributions of wind and PV capacities among the six Italian electric regions for a varying trade-off between maximizing the mean and minimizing the standard deviation of the wind and PV penetration. Due to the variability of the wind and PV production, changing the weight put on each objective results in mixes with different characteristics, a higher mean penetration also leading to an increased variance. In addition, ignoring capacity-factor correlations between regions leads to sub-optimal mixes as shown by the weaker slope of the dashed lines (which corresponds to a weaker increase of the mean penetration as the variance is allowed to increase). The blue curve represents the optimal frontier with the addition of the constraint that the total wind-PV capacity be the same as in 2015. The blue dot (resp. blue diamond) on this frontier represents the optimal mix that has the same renewable energies penetration variance (resp. mean) as the actual 2015 mix (represented by the gray dot). The geographical wind-PV distribution of the capacities corresponding to the blue dot and the blue diamond are represented in panels b and c, respectively. Depending on whether more weight is put on the mean or on the variance of the renewable energy penetration, different optimal mixes are obtained.

Regarding locations for renewable energy development, the European case is studied by Pryor et al. (2006), specifically for wind energy, by Pfenninger and Staffell (2016) for photovoltaic energy and by Rodriguez et al. (2014) for both wind and PV energy with network constraints; the case of northern Spain by Marcos et al. (2012); and the case of Italy by Tantet et al. (2019). Concerning technologies, the complementarity of wind and solar energy in Europe is analyzed by Buttler et al. (2016) and Miglietta et al. (2017), in Italy by Monforti et al. (2014) and Tantet et al. (2019), and in Spain by Santos-Alamillos et al. (2012, 2017); and the case of run-of-the river hydropower and wind and PV energy with countries including France, Greece, Italy, Spain and Tunisia by François et al. (2016).

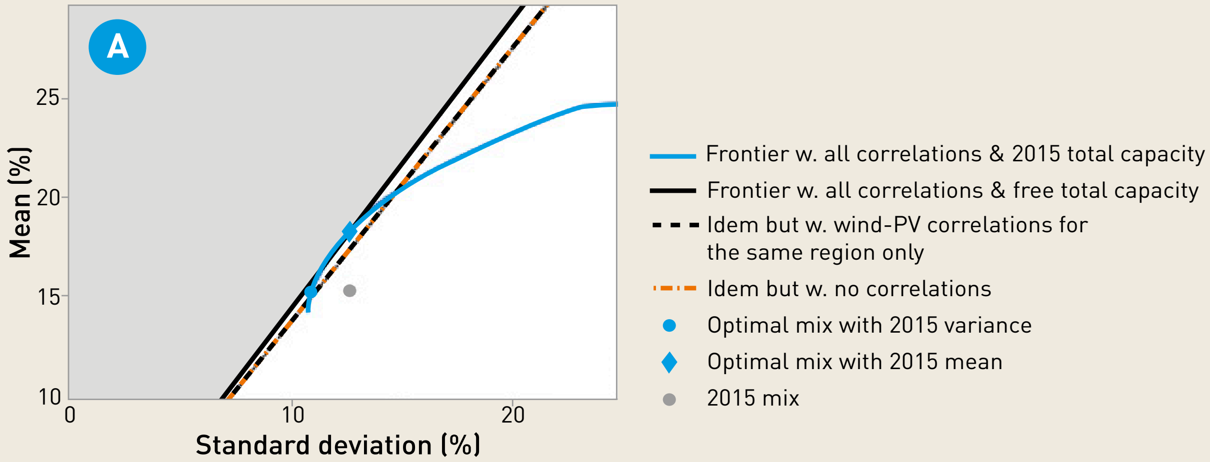
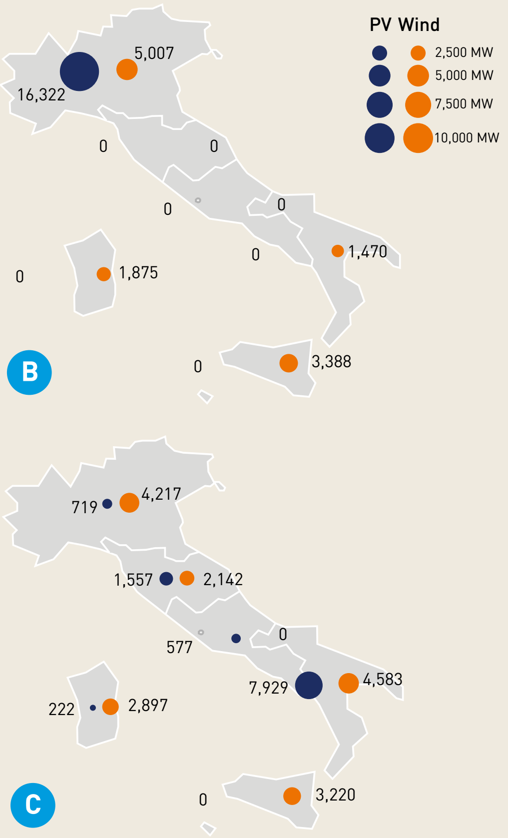


Figure 3.57 | Panel A: Illustration of the optimal, or Pareto, frontiers for two objectives – maximizing the mean (y-axis, in % of the total demand) and minimizing the standard deviation (x axis) of the total wind-PV penetration obtained by distributing wind and PV capacities among the six bidding zones (electric regions) of Italy. The gray area represents infeasible mixes. The thick line is the frontier when taking all capacity-factor correlations between regions and technologies into account in the bi-objective optimization, while the dashed line (resp. the point-dashed line) represents the frontier when only capacity-factor correlations between wind and PV energy in the same region (resp. when no correlations) are considered. The thick blue line is like the thick black line, but with the constraint that the total wind-PV capacity be the same as in 2015. The blue dot (resp. blue diamond) represents the optimal mix with the same renewable energy penetration variance (resp. mean) as in 2015. The gray dot represents the actual 2015 mix.

To our knowledge, there are no studies analyzing how past changes in climate variability has impacted energy systems and their planning, let alone in the Mediterranean. With the development of various renewable energy types, as well as with existing or new hydroelectric capacities, changes in climate variability in the Mediterranean potentially affect the variability of the energy production (Widén et al. 2015) on time scales ranging from seconds (Apt 2007) to years or more (Pryor et al. 2006; Pozo-Vazquez et al. 2011; Pfenninger and Staffell 2016; Collins et al. 2018). Only few studies analyze past changes in the variability of the wind, solar and hydroelectric resources. No clear trend is found in European wind variability over the last 140 years or so (Bett et al. 2013), but there is significant variability between decades, depending on location and specific conditions. For instance, only small changes in the occurrence of Mistral and Tramontane winds are found in regional climate simulations forced by a reanalysis over the 1950-2010 period (Obermann et al. 2018).



Panel B: PV (blue) and wind (orange) optimal capacity distribution resulting in the same variable renewable energies penetration variance as the actual 2015 mix.
Panel C: same as panel b for the same variable renewable energy penetration mean as the actual 2015 mix. (Tantet et al. 2019).

regulations so as to enable enhanced connectivity of energy markets. Setting such conditions for a future Mediterranean energy community is the aim of the Association of Mediterranean Energy Regulators (MEDREG). Gathering 27 energy regulators from 22 countries spanning the EU, the Balkans and the SEMCs, MEDREG targets the establishment of a level playing field for all Mediterranean energy actors through an adapted legal and regulatory framework.

The stability and reliability of the regulatory framework is key to provide clear rules for investors to develop their confidence and ensure technical standards compatibility, which is a prerequisite for interconnecting markets. As a result, regulators have a crucial mission in implementing a good investment climate ensuring that network developments are delivered in due time, in providing guidance to Transmission System Operators about how to use interconnections and regulatory compatibility, in articulating a sound regulatory framework and a clear strategy, in ensuring an effective coordination between regulated networks and private/competitive activities, in improving the investment planning capacity, with long term assessment of energy needs and financial charges, and in ensuring a high level of transparency and education. MEDREG recognizes the importance of developing inter-operable electricity systems at sub-regional level. This requires first working on assessing the usage and problems of current interconnections and at a second stage evaluate what added value new interconnections could bring.

In this framework, the development of renewable energy sources requires a specific focus on network regulation. At the national level, it implies the connection and integration of renewable energy sources. Cross-border regulations require convergence of national regulations to allow interconnections to work effectively. Investment regulation requires the design and develop infrastructure that will be needed for promoting international complementarities.

The framework of EU Projects of Common Interest is an example of reflection that aims to build a shared vision to ensure the security of supply and facilitate renewable energy development in a coordinated way. *Fig. 3.56* highlights the three strategic corridors regulators aim at to ensure a full integration of the Mediterranean (Iliceto and Ferrante 2018).

BOX 3.3.2

Energy issues for Mediterranean islands

Islands are physically isolated territories, a characteristic that sets specific threats, challenges and opportunities in the context of global change and energy transition. The European Union recognizes that "insular regions suffer from structural handicaps linked to their island status, the permanence of which impairs their economic and social development" (Treaty of Amsterdam 1999). Geographical and socioeconomic singularities of Mediterranean Islands put additional pressure on water and energy, leading to resource depletion and degraded environment, threatening sustainable development (Gold and Webber 2015). More than 11 million people live in Mediterranean islands (Sen Nag 2017). Except for Sicily, Sardinia and Cyprus, all Mediterranean islands are below the million permanent inhabitants, with notable cases, such as Majorca, which frequently double its population during high touristic season. Mediterranean islands suffer strong limitations due to the limited range of their accessible resources, the inability to achieve economies of scale, the strong seasonal population variation, higher infrastructure costs and particular climatic conditions (Erdinc et al. 2015).

Characteristic aspects of Mediterranean climate such as large seasonal temperature and irradiance variations, occurrence of strong winds, heavy precipitations and the impacts of a range of cyclone, interact with the islands, rendering unique climates, even at local scales (Homar et al. 2010). They also enhance Mediterranean islands vulnerability, especially in the context of global climate change. In addition to the Mediterranean specificities, the IPCC 4th and 5th assessment reports state with high confidence that, globally, coasts are undergoing adverse consequences from climate change, such as sea level rise, inundation, erosion, and ecosystem loss. The reports also state that coasts are highly vulnerable to extreme events such as cyclones, extreme waves, storm surges, altered rainfall and runoff patterns, and ocean acidification. Therefore, Mediterranean islands are essentially isolated coastal territories with double penalty from climate change impacts.

Energy production and demand in the Mediterranean islands

Climate effects on the energy transition process in Mediterranean islands are of capital importance. On the one hand, the water-energy nexus is a central aspect in islands, as pressure on water resources is exceptional and highly anticorrelated with the seasonal precipitations and the availability of fresh water depends on techniques such as dwelling, impoundment and desalination. This severe fresh water scarcity is projected to aggravate in the future, since a drying of the region is expected throughout the 21st century (Dubrovský et al. 2014) and dry spells are projected to increase in duration and increasingly affect the wet season (Raymond et al. 2019). This climate and the projected scenarios not only severely hamper the adoption of hydropower electric sources in Mediterranean islands, but also increases the projected electricity demand derived from increased use of desalination strategies. On the other hand, Mediterranean islands have an important wind power climatic resource originating from various climatic features. Larger islands develop sea breeze very in a consistent way, especially during summer, in phase with the highest seasonal electricity demand. In contrast, smaller -and usually flatter- islands do not develop relevant sea breezes, but are more exposed to the weakly dragged maritime winds. The Mediterranean is well known to have the highest concentration of cyclones across the globe (Petterssen 1956). An additional climatic resource for Mediterranean islands, that has raised some attention in recent years, is the wave energy (Franzitta and Curto 2017) and maritime underwater flows *(Section 3.3.2.2)*. Despite wave energy converters are becoming more efficient, the spatial and temporal variability of this maritime resource hampers its general implementation. Wave energy in the Mediterranean Sea is larger during the cyclogenetic cold season and over the area of influence of the most frequent cyclogenetic regions (Ponce de León et al. 2016). This resource is significantly weaker during the summer season, when energy demand steered by tourist activity is higher. This characteristic favors its use in energy transition planning as a complementary electricity generation technology to photovoltaic, which has an opposite seasonal phase (Curto and Trapanese 2018; Curto et al. 2019). Climate projections for wave energy in the western Mediterranean show that this resource will remain reliable with a reduced temporal variability and slight reduction of the annual and seasonal wave power (Sierra et al. 2017).

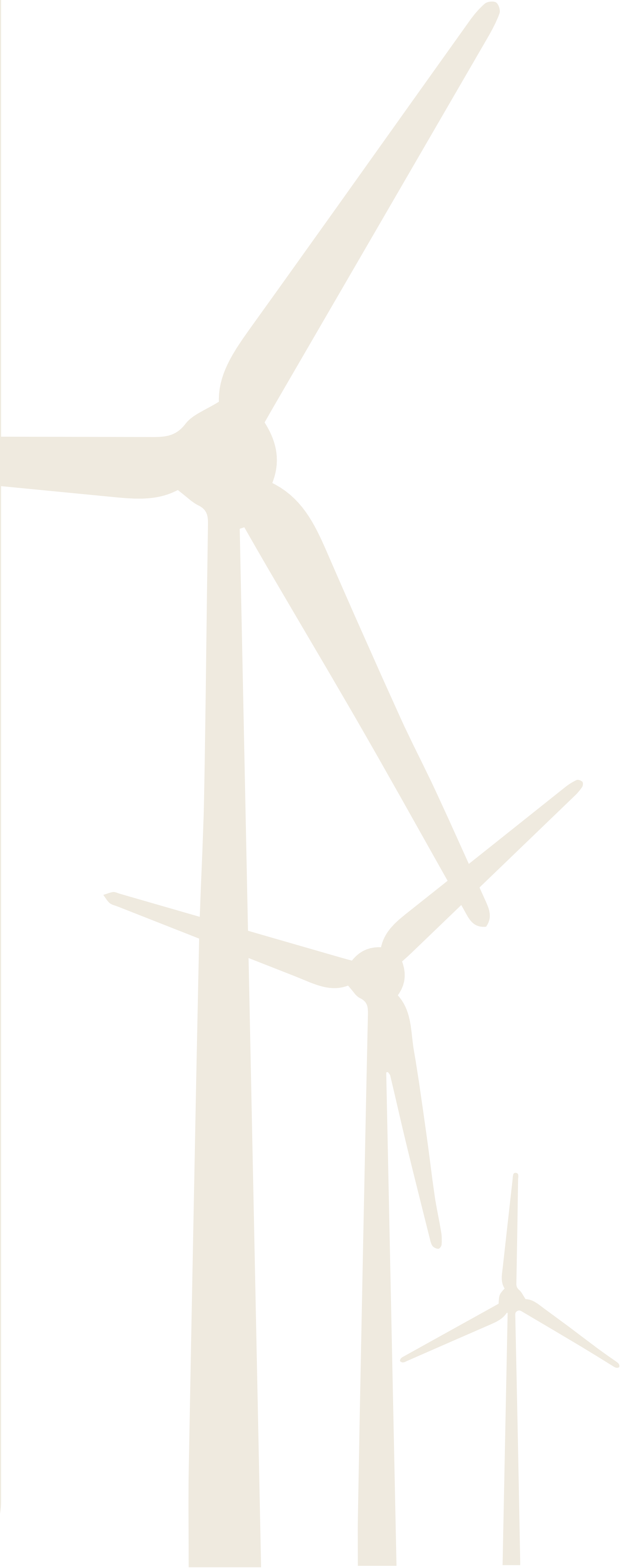
Regarding the demand side, islands are expected to follow the Mediterranean mainland projections of increases of 6% in demand by 2050 (Zachariadis and Hadjinicolaou 2014), even possibly amplified due to larger tourist activity in currently underexploited environments. The non-linear relation between consumed energy and total population could be explained by differences in existing economic activities, geographical site and cultural aspects (Neves et al. 2014).

Interlocking challenges of energy security and climate resilience

In addition to the effects of climate and climate change as an energy resource to consider in sustainable energy transition planning for the Mediterranean islands, climate extremes pose both energy extraction opportunities (i.e., for wave energy) but more importantly engineering and protection challenges. Strong winds and heavy precipitation are projected to decrease in frequency but become more intense *(Subchapter 2.2)*, threatening renewable energy infrastructure both in centralized plants and distributed generation topologies.

These climatic conditions add upon other economic, sociocultural and differential characteristics of Mediterranean insular territories compared to mainland, a fact that is also reflected to their power system structures and the energy transition objectives (Erdinc et al. 2015). Challenges such as the geographical limitations, protection of natural and cultural values, or the technical limitations of small size grid structures with low inertia, are all barriers to overcome in order to seize the opportunities of the energy transition for ensuring a sustainable insular power system (Andaloro et al. 2012). Nowadays, in most non-interconnected islands the electricity generation cost is extremely high due to the utilization of outdated autonomous power stations based on oil-fuel imports and diesel-electric generators, and the most frequent energy mix proposed considers solar, wind and sea wave renewable sources (Franzitta and Curto 2017; Curto et al. 2019). Interconnection with mainland is frequent although not for all cases profitable (Lobato et al. 2017). This solution may alleviate the reduced inertia challenge and externalize the dependency on fossil fuel, but does not contribute to achieve the near zero energy system proposed by some insular communities (Sanseverino et al. 2014).

For stand-alone power systems, the management of renewable energy surplus is an important concern. Hydrogen generation, commercial batteries and the deferrable load of desalinated water-production are proposed as two effective renewable energy buffering strategies for Mediterranean islands (Corsini et al. 2009; Kaldellis et al. 2012). In the absence of a single solve-all solution, hybrid solutions are hypothesized to lead to a remarkable reduction in power generation costs, although more efforts are needed for making battery/hydrogen systems technically and economically viable (Corsini et al. 2009; Beccali et al. 2018; Wang et al. 2020). Besides generation-side measures and energy storage for reserve provision, demand-side measures have also some specificities in Mediterranean insular areas which can foster their transition to a sustainable and autonomous energy system. Outdated distribution grids, impact of the lack of economy of scale on the reduced budgets for new investments and the low penetration of automation in domestic utilities prevent the widespread implementation of solutions for the automation of the end-user's electrical installations, in order to offer to the utility flexibility to be used for the improvement of the generation and distribution efficiency (Zizzo et al. 2017). In this regard, electric vehicles have ranges suitable for the great majority of Mediterranean islands sizes, also offering new grid-to-vehicle and vehicle-to-grid managing alternatives which can catalyze the solutions for the inherent reduced grid inertia problems (Groppi et al. 2019).



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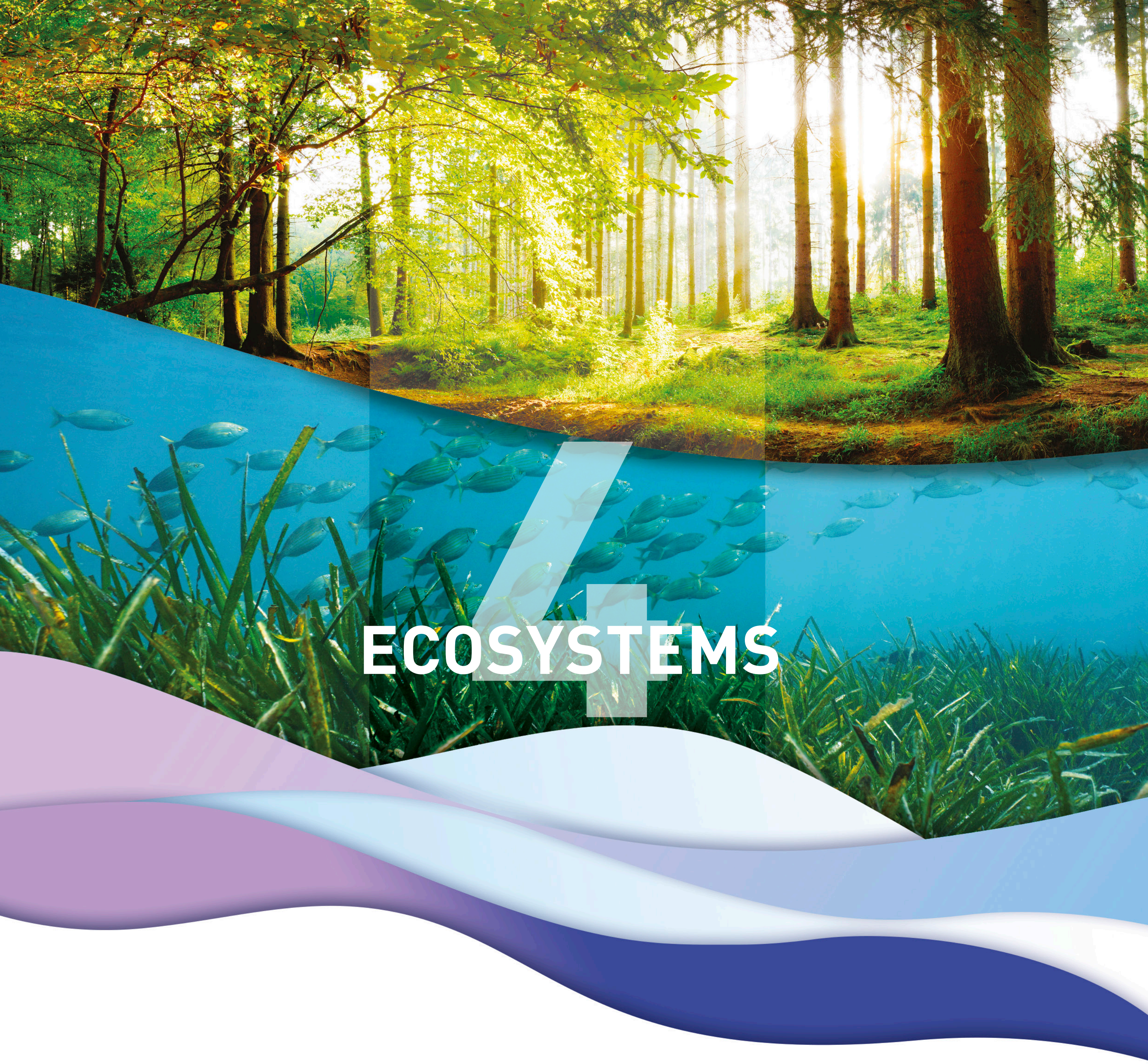

4

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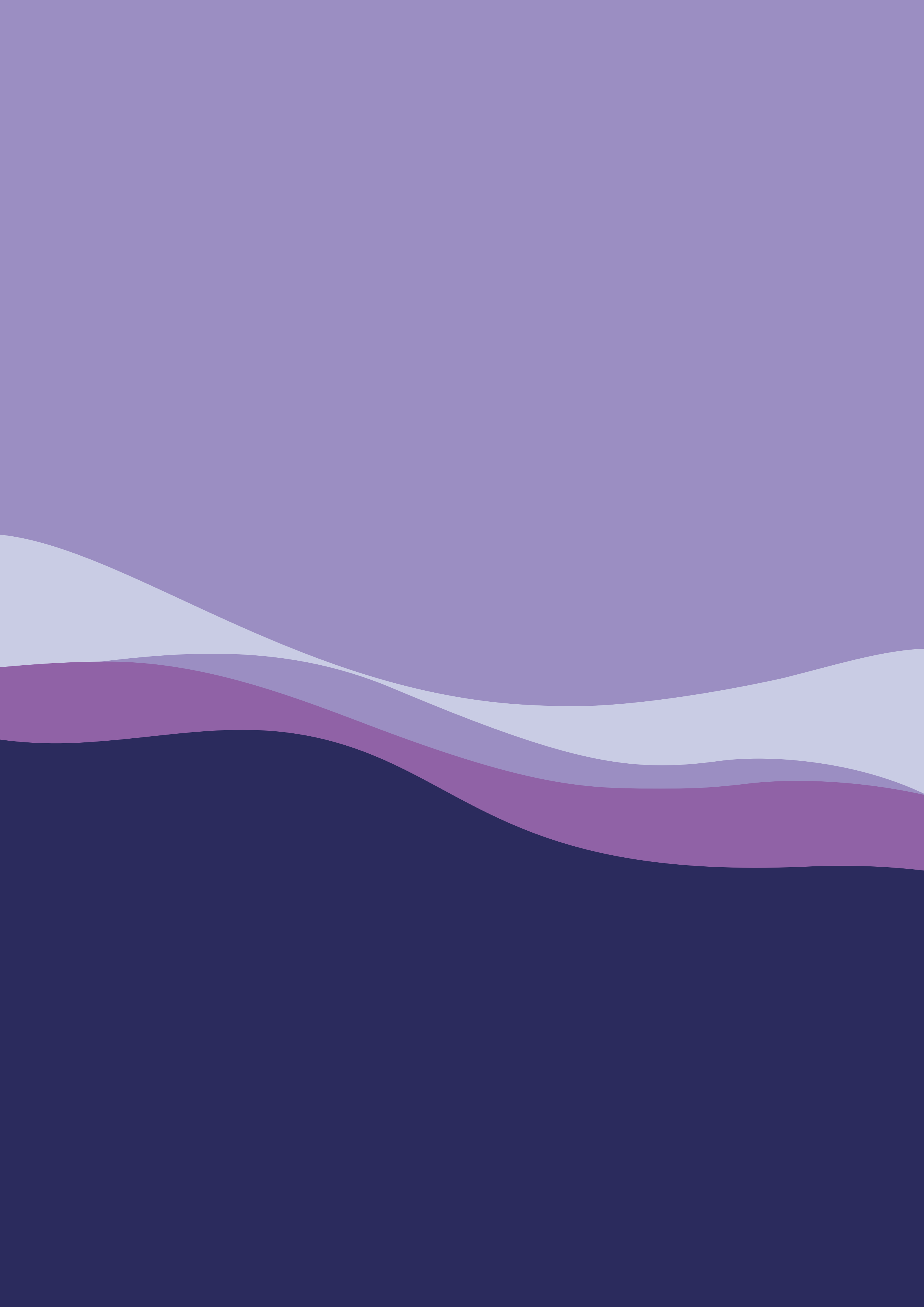
This chapter should be cited as: Balzan MV, Hassoun AER, Aroua N, Baldy V, Bou Dagher M, Branquinho C, Dutay J-C, El Bour M, Médail F, Mojtahid M, Morán-Ordóñez A, Roggero PP, Rossi Heras S, Schatz B, Vogiatzakis IN, Zaimes GN, Ziveri P 2020 Ecosystems. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 323-468, doi:10.5281/zenodo.7101090.*



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4 Ecosystems

Executive summary

Marine ecosystems

Despite covering only 0.82% of the ocean's surface, the Mediterranean Sea supports up to 18% of all known marine species, with 21% being listed as vulnerable and 11% as endangered. The accelerated spread of tropical non-indigenous species is leading to the "tropicalization" of Mediterranean fauna and flora as a result of warming and extreme heat waves since the 1990s. The acidification rate in the Mediterranean waters has ranged between 0.055 and 0.156 pH units since the pre-industrial period, affecting the marine trophic chain, from its primary producers (i.e., coccolithophores and foraminifera) to corals and coralline red algae.

Projections for high emission scenarios show that endemic assemblages will be modified with numerous species becoming extinct in the mid 21st century and changes to the natural habitats of commercially valuable species, which would have many repercussions on marine ecosystem services such as tourism, fisheries, climate regulation, and ultimately on human health.

Adaptation strategies to reduce environmental change impacts need effective mitigation policies and actions. They require anticipatory planning to enable them to tackle problems while they are still manageable. Given the diversity of each Mediterranean sub-basin, wider monitoring coverage is needed to strengthen our knowledge about the different adaptation processes that characterize and best suit each geographical zone. Adaptation implies the implementation of more sustainable fishing practices as well as reducing pollution from agricultural activity, sustainable tourism or developing more effective waste management. Marine protected areas can potentially have an insurance role if they are established in locations not particularly vulnerable to ocean acidification and climate change.

Coastal ecosystems

The coastal zone, i.e., the area in which the interaction between marine systems and the land dominate ecological and resource systems, is a hotspot of risks, especially in the south-eastern Mediterranean region. Alterations to coastal ecosystems (lagoons, deltas, salt marshes, etc.) due to climate change and human activities affect the flow of nutrients to the sea, the magnitude, timing and composition of potentially harmful/toxic plankton blooms. They also significantly increase the number and frequency of jellyfish outbreaks, and could have negative impacts on fisheries. 1.2 to 5% of seagrass meadows in the Mediterranean Sea, which represent 5 to 17% of the worldwide seagrass habitat, are lost each year. Among them, almost half of the surveyed *Posidonia oceanica* sites have suffered net density losses of over 20% in 10 years. As for fish, non-indigenous species and climate change cause local extinction.

Projected temperature increases combined with a decrease in nutrient replenishment and ocean acidification, are expected to cause changes in plankton communities, negative impacts on fish, corals, seagrass meadows and propagation of non-indigenous species. Projected sea level rise will impact coastal wetlands deltas and lagoons. Extensive urbanization added to climate change is also expected to threaten coastal ecosystems, human health and well-being.

A nexus approach is required when trying to establish adaptation methods for the entire Mediterranean, while taking into account ecosystem-based management, synergies and conflicts, integrating local knowledge and institutions. Suitable adaptation policies include reducing pollution runoff, both from agriculture and industry and waste management, and policies to limit or prevent acidification. Conservation planning and management should focus on cross-cutting approaches and building resilience between structural and functional connectivities of various fields.

Terrestrial ecosystems

Biodiversity changes in the Mediterranean over the past 40 years have occurred more quickly and been more significant than in other regions of the world. Urbanization and the loss of grasslands are key factors of ecosystem degradation across the region. Since 1990, agricultural abandonment has led to a general increase in forest areas in the northern Mediterranean, while in the southern Mediterranean, ecosystems are still at risk of fragmentation or disappearance due to human pressure from clearing and cultivation, overexploitation of firewood and overgrazing. Drylands have significant biodiversity value, with many of the plants and animals highly adapted to water-limited conditions. They are undergoing

an overall increase in response to climate change and extensive land abandonment. 48% of Mediterranean wetlands were lost between 1970 and 2013, with 36% of wetland-dependent animals in the Mediterranean threatened with extinction. Because of the reduction in river flows, 40% of fish species in Mediterranean rivers are endangered.
Projections for the 21st century indicate drier climate and increased human pressure, with negative impacts on terrestrial biodiversity, forest productivity, burned areas, freshwater ecosystems and agrosystems. Future projections indicate that burnt areas can increase across the region by up to 40% in a 1.5°C warming scenario and up to 100% from current levels for 3°C warming at the end of the century. Mediterranean drylands will become drier and their extent is expected to increase across the region. Projections suggest decreased hydrological connectivity, increased concentration of pollutants during droughts, changes in biological communities as a result of harsher environmental conditions, and a decrease in biological processes such as nutrient uptake, primary production, and decomposition.

Promotion of "climate-wise connectivity" through permeability of the landscape matrix, dispersal corridors and habitat networks are key to facilitating upward the migration of lowland species to mountains in order to adapt to new climate change conditions. Promotion of mixed-species forest stands and sylvicultural practices such as thinning, and management of understory can promote the adaption of Mediterranean forests to climate change. Promotion of the spatial heterogeneity of the landscape matrix can help reduce fire impacts. The preservation of the natural flow variability of Mediterranean rivers and streams and wide riparian areas, along with reductions in water demand are key to the adaptation of freshwater ecosystems to future climate change.

4.1 Marine ecosystems

4.1.1 Current condition and past trends

4.1.1.1 Observed changes

Despite only covering 0.82% of the ocean surface, the Mediterranean Sea supports a high level of biodiversity, including about 18% of all known marine species (~17,000) (Bianchi and Morri 2000; UNEP/MAP-RAC/SPA 2009; Coll et al. 2010). The Mediterranean Sea is biologically diverse because it is a warm sea at temperate latitudes, and is thus home to both temperate and subtropical species, and has been further diversified by its complex geological history (Bianchi and Morri 2000; Merheb et al. 2016). As a result, the present marine biota of the Mediterranean is composed of species belonging to: (1) temperate Atlantic-Mediterranean species; (2) cosmopolitan species; (3) endemic elements, comprising both paleoendemic (Tethyan origin) and neoendemic species (Pliocenic origin); (4) subtropical Atlantic species (interglacial remnants); (5) boreal Atlantic species (ice-age remnants); (6) Red Sea migrants (especially into the Levantine Basin); (7) eastern Atlantic migrants (especially into the Alboran Sea) (Bianchi and Morri 2000).

In marine ecosystems, specific drivers of environmental change include: i) the increasing temperature and salinity of surface waters (Coma et al. 2009; Conversi et al. 2010; Calvo et al. 2011) and the deep-sea (≥400 m) (Béthoux et al. 1990; Rixen et al. 2005; Vargas-Yáñez et al. 2010; Skliris et al. 2014; Schroeder et al. 2016), ii) enhanced thermal stratification (Powley et al. 2016), which can increase eutrophication and O_2 consumption due to increasing dissolved organic carbon (DOC) concentrations in the mixed layer (Ferreira et al. 2011; Santinelli et al. 2013; Ngatia et al. 2019), and iii) decreasing ocean pH fundamentally changing ocean carbonate chemistry (Calvo et al. 2011; The MerMex Group et al. 2011; Flecha et al. 2015; Hassoun et al. 2015, 2019; Merlivat et al. 2018). Detailed information about these drivers, namely temperature and salinity changes, Mediterranean hydrology and ocean acidification can be found in *Sections 2.2.4, 2.2.7.2* and *2.2.9.* Risks and vulnerabilities caused by these drivers are also affected by non-climate related anthropogenic stressors, such as industrialization, urbanization and agriculture, fishing, maritime traffic, harbor activities, tourism (Macías et al. 2014; Thiébault et al. 2016) and floating plastics and other polymers (Fossi et al. 2012, 2018; Suaria et al. 2016). These non-climate drivers are thoroughly described in *Chapters 2* and *3.1 (Section 3.1.2.3)* and can be classified as pollution *(Section 2.3)* and land and sea-use changes *(Section 2.4).*

The interconnected effects of climate change and several non-climate related drivers, covered in *Chapter 2*, *Section 2.6* affect the way the Mediterranean marine ecosystem functions at all levels, from primary producers to upper trophic-levels (The MerMex Group et al. 2011; Doney et al. 2012; IPCC 2014) *(Fig. 4.1)*. Consequences include enhanced mortality of key marine habitat species, e.g., coralligenous outcrops, maërl beds (Pairaud et al. 2014; Molina et al. 2016) and the bivalve *Pinna nobilis* (Vázquez-Luis et al. 2017), as well as the increased establishment of new communities and disease outbreaks (Rubio-Portillo et al. 2018; Berzak et al. 2019). Impacts of warming on marine biota not only result from the direct impact of increasing temperature on organism physiology, but also from the effect of warming on other biological (e.g., microbial activity, metabolic rates) and abiotic (e.g., oxygen solubility) components of ecosystem functions (Vaquer-Sunyer and Duarte 2013).

Since the mid-1980s, regime shifts in the Mediterranean Sea have impacted different ecosystem components (e.g., diversity and abundance of zooplankton, abundance of anchovy stocks, frequency of harmful algal blooms, mucilage outbreaks), possibly due to regional effects of climate modes *(Section 2.2.2)*, such as a positive state of the North Atlantic Oscillation (NAO) that affects the physical properties of the water column (Conversi et al. 2010; Barausse et al. 2011). The recent study by Fortibuoni et al. (2017), while confirming the existence of some regime shifts, does not support the hypothesis of climatic change as a main driver for these, and rather points to the impact of local pressures, i.e., overexploitation and nutrient loads.

Increasing temperatures are driving the northward spread of warm-water species (Sabatés et al. 2006; Tsikliras 2008; Bianchi et al. 2018), and have contributed to the spread of the non-indigenous Atlantic coral *Oculina patagonia* (Serrano et al. 2013). The recent spread of warm-water species that have entered from Red Sea and Atlantic Ocean into cooler northern areas is leading to the "tropicalization" of Mediterranean fauna (Vergés et al. 2014; Bianchi et al. 2018; Galil et al. 2018). Non-indigenous species are extensively detailed as a driver in *Section 2.5.* Species that need certain temperature ranges cannot migrate further, as the different areas in which they usually live and span are becoming more and more restricted, e.g., the anchovy *Engraulis engrasicolus* (Sabatés et al. 2006). Warming water may also have strong effects on deep Mediterranean areas of the two zones were cold water is formed, as increasing temperature may slow the potential downwelling and the provision of oxygen both in the Gulf of Lions and in the Adriatic Sea, leaving the cold-water coral communities exposed to a certain degree of hypoxia (Taviani et al. 2016).

In addition to the general warming patterns, periods of extreme temperatures have had large-scale and negative consequences for Mediterranean marine ecosystems *(Sections 2.2.1* and *2.2.2)*. A link between positive thermal anomalies and observed invertebrate mass mortalities has been observed in the Mediterranean Sea (Rivetti et al. 2014). Also, unprecedented mass mortality events, which affected at least 25 prominent sessile metazoans, occurred during the summers of 1999, 2003, and 2006 across hundreds of kilometers of coastline in the northwest Mediterranean Sea (Cerrano et al. 2000; Calvo et al. 2011). These events coincided with either short periods (2 to 5 days: 2003, 2006) of high sea temperatures (27°C) or longer periods (30 to 40 days) of less extreme temperatures (24°C: 1999) (Crisci et al. 2011). Impacts of these events on marine organisms have particularly been reported between 0 and 35 m depths, such as gorgonian coral mortality (Coma et al. 2009) or shoot mortality and flowering of seagrasses (Díaz-Almela et al. 2007; Marba and Duarte 2010). A collaborative database for tracking mass mortality events in the Mediterranean Sea has been recently launched to support the analysis of relationships between thermal conditions and/or other environmental drivers (Garrabou et al. 2019), and can be helpful for better detecting changes across the Mediterranean Basin.

In addition, ocean acidification is an emerging human health issue, that also threatens the marine realm (Falkenberg et al. 2020) *(Section 2.2.9)*. Studies of the consequences of ocean acidification on marine Mediterranean ecosystems report diverse responses (Martin and Gattuso 2009; Rodolfo-Metalpa et al. 2010; Movilla et al. 2012; Bramanti et al. 2013; Gazeau et al. 2014; Lacoue-Labarthe et al. 2016). Insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia and Vulcano in Italy, where biodiversity decreases with decreasing pH toward the vents, with a notable decline in calcifiers (Hall-Spencer et al. 2008; Prada et al. 2017). Transplants of corals, mollusks, and bryozoans along the acidification gradients around seeps reveal a low level of vulnerability to CO_2 levels expected over the next 100 years (Rodolfo-Metalpa et al. 2010, 2011). However, periods of high temperature increase vulnerability to ocean acidification, thereby increasing the long-term risk posed to

Mediterranean organisms and ecosystems as temperatures rise (Gazeau et al. 2014; Lacoue-Labarthe et al. 2016). Ocean acidification seems to have a slower but unstoppable effect on several organisms, the increase of temperature being a more immediate stress factor in most species (Lejeusne et al. 2010). A recent overview (Gao et al. 2020) showed that the combination of ocean acidification and warming may affect food webs from different directions; ocean acidification is more likely to follow bottom-up controls (resource driven), while temperature drives top–down controls (consumer driven).

Key habitats undergoing change

Rapid warming of the Mediterranean Sea, in synergy with other climate and non-climate related drivers (see *Chapter 2*), threatens marine biodiversity, and particularly some key ecosystems that have high vulnerability to such pressures, as presented below.

Coralligenous

The coralligenous is a typical Mediterranean underwater seascape, present on hard bottoms from ~15 to 120 m depths and is mainly produced by the accumulation of calcareous encrusting algae (*Lithophyllum, Lithothamnion, Mesophyllum* and *Peyssonnelia*) growing in dim light conditions and relatively calm waters (Ballesteros 2006; Boudouresque et al. 2015). These outcrops foster one of the richest assemblages found in the Mediterranean, harboring approximately 10% of Mediterranean marine species (Ros et al. 1985; Boudouresque 2004; Ballesteros 2006; Casas-Güell et al. 2016), most of which are long-lived algae and sessile invertebrates (sponges, corals, bryozoans and tunicates) (Garrabou et al. 2002; Ballesteros 2006). The different habitats that make up these biogenic formations are mainly determined by light exposure, so that some coralligenous habitats can be dominated by calcareous algae and others completely dominated by macroinvertebrates with almost no algae (Gili et al. 2014; Casas-Güell et al. 2016). Red coral, *Corallium rubrum*, is one of the habitat-forming species that plays a key role in the functioning of coralligenous habitats because of its trophic activity, biomass and perennial biogenic structure, like other Mediterranean gorgonian species (Gili et al. 2014; Ponti et al. 2014b, 2016, 2018). Red coral is a slow-growing, long-lived species that grows in dim light habitats (e.g., caves, vertical cliffs and overhangs) between 10 and 200 m depths. Despite its essential ecosystemic role, little is known about the geographical distribution of red coral up to 400 km offshore the coastline due to its large bathymetric range and afferent constraints (Casas-Güell et al. 2015, 2016), and the major studies focus on the phytobenthic component (Piazzi et al. 2009, 2012; Boudouresque et al. 2015). Studies at an intermediate scale (tens of km) have been conducted with key species, pinpointing the fact that their distribution may be very heterogeneous depending on the environmental factors (Gori et al. 2012; Coppari et al. 2014, 2016). Due to this lack of baseline data, the structure of coralligenous outcrops is still poorly understood, preventing a proper assessment of its current state of biodiversity and the potential impacts of harvesting, and other disturbances related to global change, on red coral assemblages. A recent study (Mallo et al. 2019) based on historical red coral data from the north western Mediterranean Sea, documented the halt in the C. rubrum decrease and the first recovery response due to effective protection measures in some areas.

Coralligenous outcrops are affected by several consequences of global change such as nutrient enrichment, non-indigenous species, increased sedimentation, mechanical impacts, mainly from fishing activities, e.g., mechanical injuries and sediment re-suspension (Cebrián et al. 2012; Piazzi et al. 2012; Gatti et al. 2015), as well as sea warming (e.g., massive mortalities related to temperature anomalies) and the potential effects of ocean acidification (Bramanti et al. 2013; Cerrano et al. 2013; Gili et al. 2014). Recently, potential synergies between these stressors have been hypothesized *(Section 2.6)*, especially in shallow areas were heat waves may have a large impact on several organisms (Galli et al. 2017), resulting in a fragmentation of the habitat that can open new space for non-indigenous species (Vezzulli et al. 2013). It has also been demonstrated that a decrease in the abundance of coralligenous habitat-forming species leads to a rapid fragmentation in community structure and a loss of species benefiting from the structural complexity these species provide (Ponti et al. 2014b; di Camillo and Cerrano 2015; Valls et al. 2015).

In addition to marine heat waves (Garrabou et al. 2001, 2009), one of the main past threats for the red coral *Corallium rubrum* has been intensive harvesting (see *Section 2.4*), which has caused an overall shift in population structure, resulting in a decrease in both biomass and colony size (Tsounis et al. 2010; Bramanti et al. 2014; Montero-Serra et al. 2015). Moreover, its Mg-calcite skeleton makes it vulnerable to ocean acidification (Bramanti et al. 2015). Bramanti et al. (2013) experimentally evaluated the effects of low pH on *C. rubrum* over a 314-day period under two pH levels (8.10 and 7.81). This study concludes that exposure to lower pH conditions negatively affected skeletal growth and spicule morphology (i.e., abnormal shapes).

Mediterranean gorgonian "forests" (e.g., *Paramuricea clavata, Eunicella cavolinii*) are threatened by several human activities and are affected by climatic anomalies that have led to mass mortality events in recent decades (Ponti et al. 2014b, 2018; Verdura et al. 2019). Observed mortality events have been linked to temperature-dependent bacterial pathogens (Bally and Garrabou 2007). Also, diverse responses to thermal stress have been shown in gorgonians (Pivotto et al. 2015; Crisci et al. 2017). This may condition the future response of these species to climate change.

The ecological role of these habitats and the possible consequence of their loss are still poorly understood. The experimental study of Ponti et al. (2014b) reports a significant effect of gorgonians (*E. cavolinii,* and *P. clavata*) on the recruitment of epibenthic organisms and their presence mainly limits the growth of erect algae and enhances the abundance of encrusting algae and sessile invertebrates. This effect could be due to microscale modification of hydrodynamics and sediment deposition rate by i) a shading effect that reduces light intensity, ii) intercepting settling propagules, iii) competing for food with filter-feeders and/or iv) competing for space by producing allelochemicals. Although the biological interaction between gorgonians and other species deserves further study, changes to the edaphic conditions caused by gorgonian forests influences the larval settlement and recruitment processes of benthic assemblages (Ponti et al. 2014b, 2018).

In addition to the long-term effects of global change and its consequences on the Mediterranean coralligenous, short-term extreme events may be even more devastating than heat waves. Teixidó et al. (2013) show how an extreme storm event affected the dynamics of benthic coralligenous outcrops in the northwestern Mediterranean Sea using data acquired before (2006–2008) and after the impact (2009–2010) of a major storm. The most exposed and impacted site experienced a major shift immediately after the storm and over the following year. This impact consists of changes in the species richness and diversity of benthic species such as calcareous algae, sponges, anthozoans, bryozoans and tunicates. In this site, benthic species recorded a 22% to 58% loss of cover on average, with those with fragile forms showing cover losses up to 50 to 100%. Small patches survived after the storm and began to grow slightly during the following year, and the sheltered sites showed no significant changes in all the studied parameters, indicating no variations due to the storm (Teixidó et al. 2013).

Deep sea ecosystems

Although poorly known, deep seafloor ecosystems provide services that are vitally important to the entire ocean and biosphere, and play a particularly major role in climate change mitigation. For instance, by storing a large amount of anthropogenic CO_2 and by absorbing heat accumulated from the greenhouse effect, the deep sea Mediterranean waters and ecosystems capture large quantities of carbon and, as such, slow down the warming of surface waters and land (Luna et al. 2012; Palmiéri et al. 2015) (*Sections 2.2.7* and *2.2.9*). Rising atmospheric greenhouse gases are affecting water column oxygenation, temperature, pH and food supply *(Section 3.2),* with similar impacts on deep-sea ecosystems (Sweetman et al. 2017). As they are deprived of light, deep-sea ecosystems are greatly dependent on surface primary production: "marine snow" (Gambi et al. 2014). Surface water also oxygenates deep-sea environments when they sink to form deep and intermediate water masses. When surface water is warmer, it does not mix well with deep water *(Section 2.2.7).*

In the Mediterranean, the deep sea covers about 79% of the Mediterranean Basin, including habitats potentially able to deliver multiple ecosystem services and numerous resources of high economic value (Manea et al. 2020). Despite this fact, very few studies address the response of deep-sea ecosystems to ongoing climate change in this sea. In contrast with most oceans where the flux of particulate organic matter to the seafloor is likely to decline significantly in response to climate change (Sweetman et al. 2017), a study from the eastern Mediterranean shows that climate change has caused an immediate accumulation of organic matter on the deep-sea floor in recent decades (Danovaro et al. 2001). This led, together with deep-sea warming, to alteration of carbon and nitrogen cycles and has had negative effects on deep-sea bacteria and benthic fauna (Danovaro et al. 2001, 2004). For instance, the observed salinity and temperature changes in eastern Mediterranean deep and bottom waters from 1987 to 1994 (Roether et al. 1996; Theocharis et al. 2002) led to the uplift of these water masses by several hundred meters, reaching shallower depths (100–150 m; i.e., close to the euphotic zone) under the influence of cyclonic circulation. This resulted in increased biological production and therefore enhanced flux of organic carbon to the deep sea, thereby significantly and quickly changing the way deep-sea ecosystems function (Psarra et al. 2000; Danovaro et al. 2001). The review of Yasuhara and Danovaro (2016) on temperature impacts on deep-sea Mediterranean biodiversity shows that minor temperature shifts of around 0.1°C or less are sufficient to cause significant changes in biodiversity and the community structure of deep-sea nematode assemblages.

Planktonic ecosystems

Several studies have addressed the possible impact of climate change on marine phytoplankton diversity and distribution in the Mediterranean Sea, highlighting highly contrasting regional patterns (Duarte et al. 2000; Goffart et al. 2002; Marty et al. 2002; Bosc et al. 2004; Ribera d'Alcalà et al. 2004; Marty and Chiavérini 2010; Herrmann et al. 2014; Oviedo et al. 2015; D'Amario et al. 2017). Some studies from the northwestern Mediterranean have reported a positive trend in phytoplankton biomass in response to the expansion of the summer stratification. This trend was accompanied by an increase in picoplankton and nanoflagellates (i.e., small-sized phytoplankton) and a decline in diatoms, which are responsible for new production (Goffart et al. 2002; Marty et al. 2002; Mena et al. 2019; Ramírez-Romero et al. 2020). However, other studies report that the spring bloom in many Mediterranean regions tends to occur earlier in the year, possibly in relation to earlier water warming and high irradiance, in contrast with the autumn bloom that tends to disappear because of a longer stratification period (Bosc et al. 2004). Bosc et al. (2004) also reveal significant interannual variations in biomass and primary production, not only in the northwestern basin (e.g., the exceptional bloom in spring 1999), but also, and more surprisingly, in the oligotrophic waters of the eastern basin (e.g., the 9% decrease in primary production from 2000 to 2001). In this latter basin, phytoplankton shifts seem to be concurrent with rising winter precipitation and sea surface temperature (Mena et al. 2019) (*Section 2.2.4, 2.2.5* and *2.2.7*).

In some Mediterranean settings, such as the central Ligurian Sea, increased deep-water convection (as deep as 2,000 m) has been attributed to greater surface salinity causing increased nutrient supply near the surface, and thus more primary production (Marty and Chiavérini 2010). In contrast, in the productive northwestern Mediterranean Sea, deep convection could significantly decrease under the influence of climate change (Herrmann et al. 2014), impacting pelagic planktonic ecosystem, which are strongly influenced by these hydrodynamics. The weakening of deep convection and surface warming modifies the pelagic planktonic ecosystem and associated carbon cycle indirectly only: the spring bloom occurs one month earlier, and the bottom up control of phytoplankton development and bacteria growth by nitrogen and phosphorus availability strengthens, and the microbial loop intensifies as the small-sized plankton biomass increases (Herrmann et al. 2014). Net carbon fixation and deep export do not change significantly. In the Tyrrhenian Sea, Ribera d'Alcalà et al. (2004) explain the significant changes in the long-term patterns of rare copepod species as a symptom of large-scale meteorological phenomena of the North Atlantic sector.

In the NW Mediterranean Sea, decadal climatic oscillations linked to the NAO forcing of the precipitation regime led to an increase in the upper salinity in the 1980s and in the late 1990s and early 2000s *(Chapter 2, Section 2.2.7)*. In saline years, the annual abundance of zooplankton is higher than otherwise (Fernández de Puelles and Molinero 2007). According to Molinero et al. (2008), large-scale climate forcing has altered the local environment and the pelagic food-web dynamics in the NW Mediterranean Sea through changes in biological interactions, competition and predation. The authors also suggest that warming, the dominance of small phytoplankton and predation pressure by jellyfish negatively affected copepod populations (recruitment, life-history traits and physiological thresholds) in the early 1990s, whereas chaetognaths were surpassed by jellyplankton as the most frequent copepod prey. A more recent study from the same Ligurian time-series updated with ten more years (up to 2003) revealed that the zooplankton, mainly copepods, recovered their initial concentrations after 2000, suggesting a quasi-decadal cycle (Coma et al. 2009). This illustrates the difficulty in identifying long-term changes from decadal oscillation in short time-series in plankton. However, surface salinity appears to be a common physical indicator of changes in the pelagic ecosystem of the NW Mediterranean Sea for jellyfish (Buecher et al. 1997), crustaceans (García-Comas et al. 2011) and phytoplankton (Marty and Chiavérini 2010).

Gallisai et al. (2014) report that aerosol deposition from the Sahara may explain 1 to 10% of seasonally detrended chlorophyll variability in the nutrient-low Mediterranean with main effects in spring over the eastern and central Mediterranean, corresponding to dust events fueling needed nutrients for the

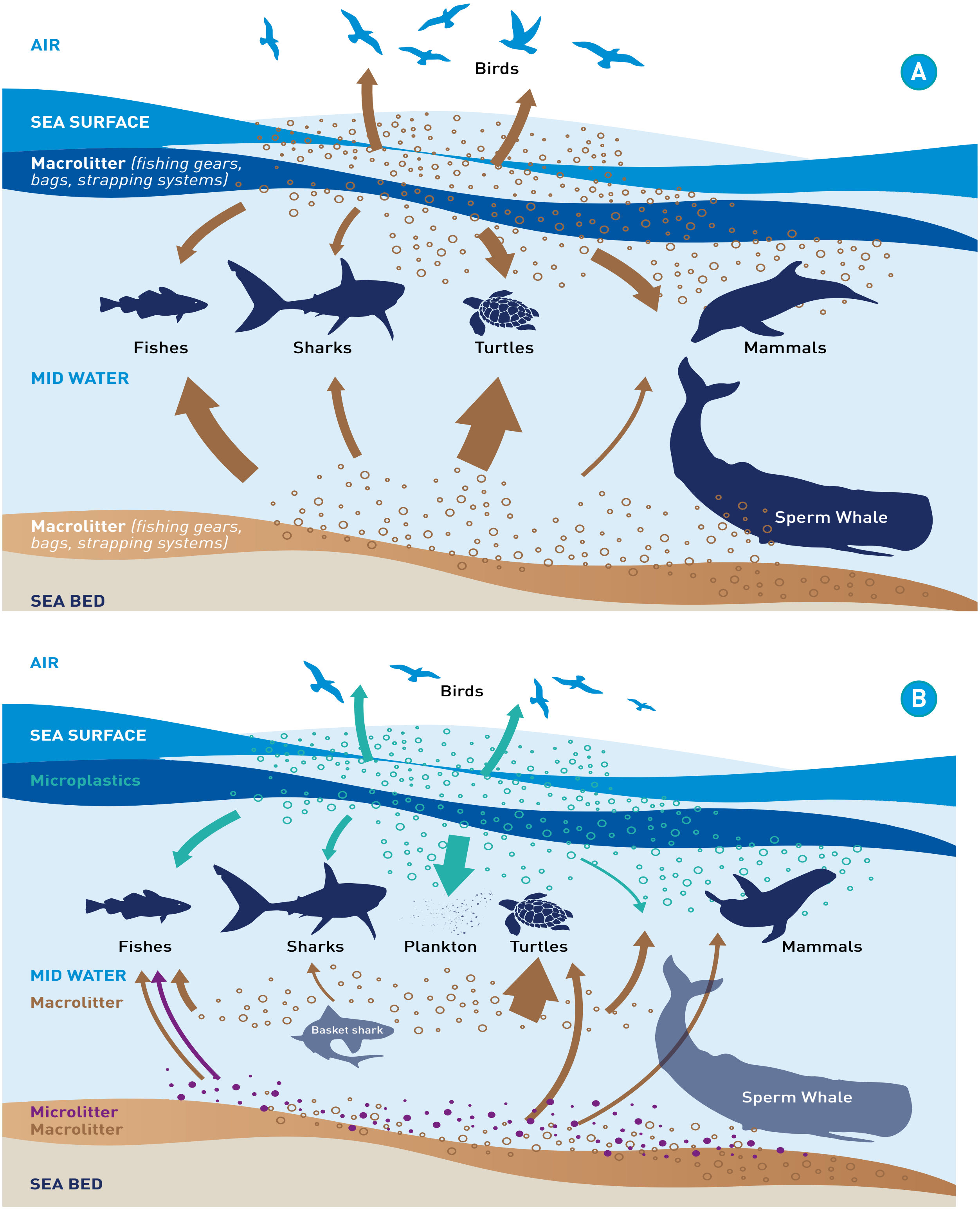

Figure 4.1 | Summary of interactions between large marine vertebrates and marine litter (Galgani et al. 2014). Fluxes of litter in the life cycle and intensity of its effects on large marine vertebrates, (a: entanglement; b: ingestion), depending on various factors such as ingestion mechanisms (predation, active or passive filter feeding), development stage (benthic or pelagic phases for sea turtles), behavior and foraging strategy (feeding on the sea floor, in the water column or on the surface, selectivity according to color, shape etc., ecological plasticity in diet and habitat), types of litter (micro/macro litter) and types of fishing gear (nets, hooks and lines). The thicker arrows indicate key processes. Although trophic transfer from one level to another has been demonstrated in vitro for microplastics in plankton, it remains controversial in situ, as most ingested litter is excreted in feces.

planktonic community (Ternon et al. 2011). The areas showing negative effects on chlorophyll from dust deposition are regions under significant influence from European aerosols. Anthropogenic aerosol deposition of nitrate and phosphate largely influence primary production in the northern Mediterranean Sea (Richon et al. 2018a, 2018b) *(Section 2.2.3)*. This response of chlorophyll dynamics to dust deposition is important when knowing that future scenarios predict increased aridity and shallowing of the mixed layer (Gallisai et al. 2014) *(Section 2.3.2)*.

From around the island of Lampedusa (central Mediterranean), the multi-year evolution of biogenic dimethylsulfide (DMS) production in the marine surface layer and the resulting methanesulfonate on the atmosphere are mainly attributed to phytoplankton physiology (Becagli et al. 2013). High phytoplankton productivity can also be the expression of stressed cells, especially during summer when high irradiance and the shallow depth of the upper mixed layer prevails. This therefore leads to higher methanesulfonate concentrations in the atmosphere. These dynamics can be further controlled by the North Atlantic Oscillation, and related oceanic and atmospheric processes (Becagli et al. 2013).

Large vertebrates

One of the biggest threats to large marine vertebrates is litter debris, such as fishing gear or other large items (Galgani et al. 2014) *(Fig. 4.1)*. Regularly, in the Mediterranean Sea and worldwide, large vertebrates such as sea birds (van Franeker et al. 2011), cetaceans (de Stephanis et al. 2013; Notarbartolo di Sciara 2014) and marine turtles (Lazar and Gračan 2011; Campani et al. 2013; Camedda et al. 2014) accidentally swallow micro and macro-plastic debris that is often found in their digestive tracts. The plastic debris *(Section 2.3.2.3)* affects the marine biota of the Mediterranean at macro, micro- and nano-levels.

Sperm whales *(Physeter macrocephalus)* in the Mediterranean Sea, which are believed to be fewer than 2,500 mature individuals, are endangered world-wide (Notarbartolo di Sciara 2014). A decline in sperm whales in the Mediterranean has been observed over the last half-century. In addition to ingestion of solid debris, other anthropogenic activities at sea are suspected to have caused the decline of this species and continue to threaten its survival in various ways: bycatch, collisions with vessels, debilitation by chemical pollution, anthropogenic noise, disturbance from irresponsible whale watching and most likely climate change, and prey depletion (Notarbartolo di Sciara 2014). Regarding specifically ingested debris, ingestion rates are as high as 31% in some marine mammal populations, and sub-lethal effects could result in impacts at the population level (Baulch and Perry 2014). Campani et al. (2013) and Camedda et al. (2014) investigated the interaction between loggerhead sea turtles *(Caretta caretta)* and marine litter in the northern Tyrrhenian Sea and around Sardinia, respectively. In thirty-one *C. caretta* individuals found stranded or accidentally bycaught in northern Tyrrhenian Sea, marine debris, mainly plastics, were present in 71% of specimens (Campani et al. 2013). In Sardinia, only 14% of the 121 monitored turtles had debris in their digestive tracts but plastic was the main physical category (Fossi et al. 2013; Camedda et al. 2014).

Sharks and rays are also seriously threatened by anthropogenic pressures, mainly as a result of overfishing (Dulvy et al. 2014) *(Fig. 4.2)*, as described in *Section 2.4.2* in the context of the increasing sea use changes. Some sharks live in narrow climatic ranges (Chin et al. 2010), putting them at risk in a climate change hotspot such as the Mediterranean (Ben Rais Lasram et al. 2010). Microplastic (<5 mm) ingestion has been recorded in 16.8% of the analyzed specimens of the blackmouth catshark *Galeus melastomus* around the Balearic Islands, with higher quantities of filament-type microplastics (Alomar and Deudero 2017). In three striped dolphin populations living in the Pelagos Sanctuary (bordered by western Italy, southern France and northern Sardinia), the highest toxicological stress was from PBT (persistent, bioaccumulative and toxic substances) chemical levels, combined with correlated biomarker responses (Fossi et al. 2013). More on chemical pollution is covered in *Section 2.3.*

Changes in biodiversity

To date, changes in Mediterranean marine biodiversity are essentially driven by human activities (Mannino et al. 2017), i.e., pollution *(Section 2.3)*, sea use changes *(Section 2.4.2)*, the introduction of non-indigenous species *(Section 2.5)*, together with climate change *(Section 2.2)* (Lejeusne et al. 2010; Zenetos et al. 2012; Katsanevakis et al. 2013, 2014b). In general, the Mediterranean Sea represents the highest proportion of threatened marine habitats in Europe (32%, 15 habitats) with 21% being listed as vulnerable and 11% as endangered (see review in Mannino et al. 2017). This threat includes several valuable and unique habitats (e.g., seagrasses and coralligenous), supporting an

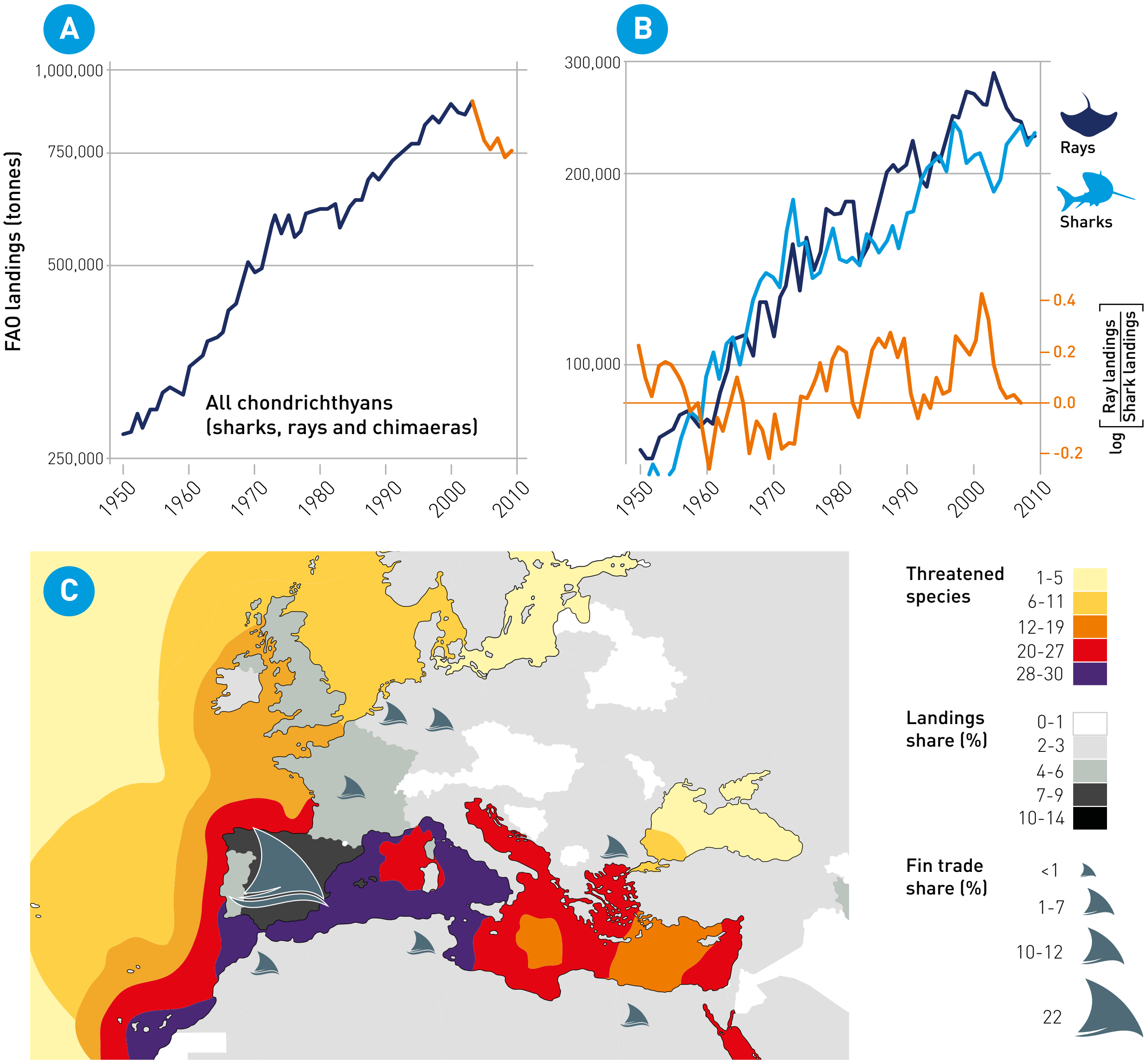

Figure 4.2 | The trajectory and spatial pattern of chondrichthyan (cartilaginous fishes that include sharks, skates, rays and chimaeras) fisheries catch landings and fin exports. (A) The landed catch of chondrichthyans reported to the United Nations Food and Agriculture Organization from 1950 to 2009 up to the peak in 2003 (dark blue) and subsequent decline (orange). (B) The rising contribution of rays to the taxonomically-differentiated global reported landed catch: shark landings (blue), ray landings (dark blue), log ratio [rays/sharks], (orange). Log ratios >0 occur when more rays are landed than sharks. The peak catch of taxonomically-differentiated rays peaks at 289,353 tonnes in 2003. (C) The main shark and ray fishing nations are gray-shaded according to their percentage share of the total average annual chondrichthyan landings reported to the FAO from 1999 to 2009. The relative share of shark and ray fin trade exports to Hong Kong in 2010 are represented by fin size. The taxonomically-differentiated proportion excludes the 'nei' (not elsewhere included) and generic 'sharks, rays, and chimaeras' category (adapted from Dulvy et al. 2014).

extensive repository of biodiversity (Gubbay et al. 2016).

The shallow depth (on average 1,450 m) of the Mediterranean Sea and the relatively fast deep-water turnover in comparison to the open ocean, coupled with a high degree of endemism (about 20% of Mediterranean marine species; Coll et al. (2010)) point to a potential amplification of climate change impacts. These are expected to cause earlier changes in biodiversity in comparison with other seas, thus making this system a model for investigating biodiversity response to direct and indirect effects of temperature changes and other climate-related and non-related drivers *(Chapter 2)*.

Species with low dispersal ability are particularly affected by climate change, which may also lead to local extinctions, greatly contributing to biodiversity loss (Mannino et al. 2017). Any change in biodiversity may affect ecosystem functioning, even in the case of the establishment of a single species and may lead to important consequences both for nature as well as for society. However, the extreme richness of microclimates in the Mediterranean (ranging from climate conditions similar to those of the Northern Sea in the Adriatic to an almost tropical condition in the eastern basin) makes prediction at large spatial scales difficult. Most effects of climate change (or climate anomalies) on marine biodiversity have been so far identified at regional scales (Philippart et al. 2011).

During recent decades, Mediterranean marine communities have shown significant changes in taxa composition and distribution. In the western Mediterranean, climate change is influencing the boundaries of biogeographic regions and thus warm water marine species are extending their ranges and colonizing new regions where they were previously absent (Katsanevakis et al. 2014a). For instance, mucilages have appeared more frequently (associated with a malfunctioning of the microbial loop) in the Adriatic Sea, where it was documented for the first time, and in several regions beyond, in recent decades, concomitantly with a significant increase in sea surface temperature (Danovaro et al. 2009). Mucilage is not closely associated with the presence of eutrophic conditions, as several mucilage outbreaks have been recently observed in oligotrophic seas, such as the Aegean Sea (Danovaro et al. 2009). The Ligurian Sea, one of the coldest areas of the Mediterranean Sea, displays a low number of subtropical species and a higher abundance of cold-temperate water species. However, the recent warming of Ligurian seawater has favored the penetration of warm-water species (e.g., *Thalassoma pavo*), which from 1985 onward, established large and stable populations (Parravicini et al. 2015).

Temperature anomalies, even of short duration, can dramatically change Mediterranean faunal diversity. The largest mass-mortality event recorded in the Mediterranean Sea so far occurred in 1999 along the French and Italian coasts (Cerrano et al. 2000; Perez et al. 2000; Garrabou et al. 2001). That year was characterized by a summer with a positive thermal anomaly that extended the thermocline down to a depth of 40 m (Romano et al. 2000) and resulted in the extensive mortality of 28 epibenthic invertebrate species *(Fig. 4.3)* (Perez et al. 2000; Rivetti et al. 2014). Among benthic organisms, sponges and gorgonians were most severely affected (Cerrano et al. 2000; Perez et al. 2000; Romano et al. 2000; Garrabou et al. 2001; Rivetti et al. 2014). The shortage of food over several weeks is a common phenomenon in the Mediterranean Sea due to summer water stratification, but very long periods with high temperatures may explain such mass mortalities (Rossi et al. 2017a).

In the eastern Mediterranean, the rise of seawater temperatures may also be partly responsible for the entrance of non-indigenous species *(Section 2.5),* mostly from the tropical Indo-Pacific (Galil 2000; Por 2009; Zenetos et al. 2012; Rilov 2016). The increased introduction and spread of non-indigenous species may be a supplementary stress factor for native species already weakened by climate variations resulting in the dislocation of indigenous species' niches and possibly cascade effects on the food webs (Rilov 2016; Corrales et al. 2018). Non-indigenous species are a recognized threat to diversity and the abundance of native species as well as a threat to the ecological stability of the infested ecosystems. Despite the overall tendency towards ocean warming, the eastern Mediterranean also experiences occasional climate anomalies, for example between 1992 and 1994, when temperatures dropped by about 0.4°C (Danovaro et al. 2001). This caused a drastic decrease in nematode abundance and overall faunal diversity (e.g., a roughly 50% decrease in nematode diversity, Danovaro et al. 2004). After 1994, when the temperature gradually recovered, biodiversity started to reverse to previous conditions but had not recovered fully in 1998 (Danovaro et al. 2004).

Sea warming may also have effects on the virulence of pathogens, favoring the frequency of epidemiological events, as most pathogens are temperature sensitive (Bally and Garrabou 2007; Vezzulli et al. 2013). Mass mortalities of the gorgonian *Paramunicea clavata,* scleractinian corals, zoanthids, and sponges observed in 1999 in the Ligurian Sea were indeed promoted by a temperature shift, in conjunction with the growth of opportunistic pathogens (including some fungi) (Cerrano et al. 2000). Increased surface temperatures and altered circulation and precipitation regimes have been evoked to explain the increased frequency of bottom water hypoxia or anoxia in coastal areas of the northern Adriatic. These phenomena, often associated with mass mortalities of fish and benthic fauna, alter food webs and might have important cascade effects on biodiversity (Coll et al. 2010). The Adriatic Sea can undergo dramatic change in the lower part of its temperature ranges. In winter 2001, the

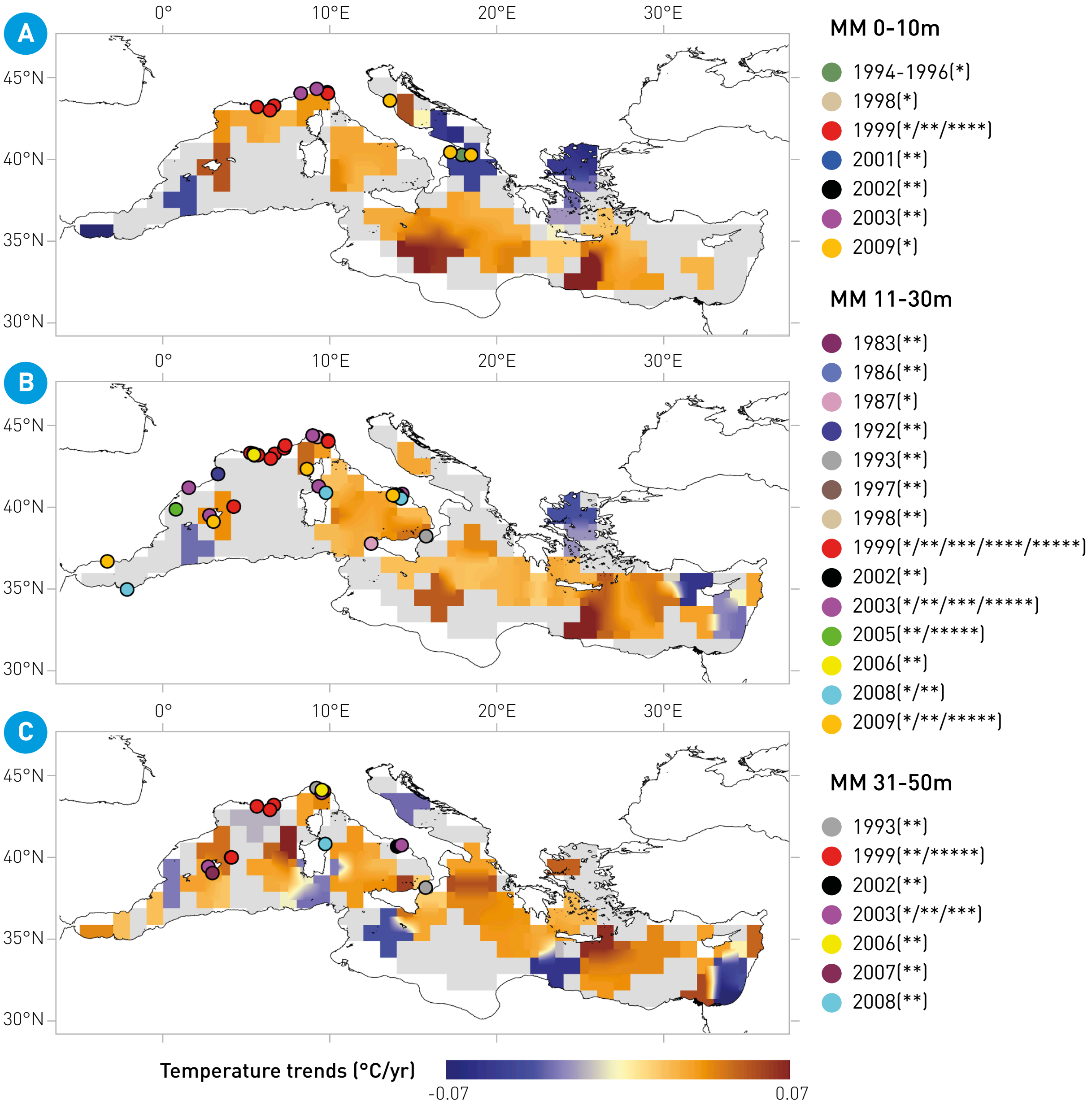

Figure 4.3 | Temperature trends across the Mediterranean Basin. (Temperature trends at 0–10 m (A), 11–30 m (B), 31–50 m (C) depth layers for the period 1945–2011 in July-November. Linear regressions have been calculated on grids of 1° latitude by 1° longitude and tested for statistical significance at the 90% level. Significant increased/decreased temperature trends are reported as colored cells, non-significant increased/decreased temperature trends are reported as grey areas. Dots show the locations of documented mass mortalities for a depth layer, each color represents a single event. The asterisks in the legend of mass mortalities (MM) events refer to the taxa affected: * stands for sponges, ** for cnidarians, *** for bryozoans, **** for ascidians, ***** for bivalves (Rivetti et al. 2014).

Adriatic Sea experienced a period of abnormally low surface temperatures (from 9°C to freezing) that led to mass mortalities of sardines *(Sardinella aurita)* (Guidetti et al. 2002), with resulting alteration of the food webs. The Adriatic Basin is also the site for deep-water formation, as a result of the bora winds associated with decreased temperatures, but recent studies have reported the shift of this water formation site towards the Aegean Sea by a phenomenon known as eastern-Mediterranean Transient (EMT), related mainly to climatic sea and atmosphere conditions (Hassoun et al. 2015). EMTs change the salinity distribution with surface water freshening linked to enhanced deep-water production and in turn to strengthened Mediterranean thermohaline circulation (Incarbona et al.

2016). This phenomenon can thus affect the marine biodiversity not only in the Adriatic and Ionian Seas but much further, as documented by Ouba et al. (2016), who have correlated the salinity variations and increase in total zooplankton abundance in Lebanese waters to the activation of the Aegean Sea as a major source of dense water formation as part of an "eastern Mediterranean Transient-like" event (see *Section 2.2.7* for more details about Mediterranean circulation changes).

In response to ocean acidification, calcifying organisms (planktonic and benthic) such as corals, foraminifera, coccolithophores and coralline red algae, important contributors of marine calcium carbonate production, may be greatly affected (Langer et al. 2009; Moy et al. 2009; Bramanti et al. 2013; Cerrano et al. 2013; Kroeker et al. 2013). Based on experiments, the impact of ocean acidification on Mediterranean corals was examined and a significant decrease in calcification rates in most tested species was reported (Movilla et al. 2012, 2014). In the latter study, there was a heterogeneous effect of low pH on the skeletal growth rate of the organisms depending on their initial weight, suggesting that those specimens with high calcification rates may be the most susceptible to the negative effects of acidification. Also, a significant effect on benthic foraminiferal communities of low-pH seawaters around the island of Ischia (Italy) has been demonstrated as a result of volcanic gas vents with significant changes in distribution, diversity and nature of the fauna (Dias et al. 2010).

Coccolithophores, which are the primary calcifying phytoplankton group, and especially the most abundant species, *Emiliania huxleyi,* have shown a reduction of calcification at increased CO_2 concentrations for the majority of strains tested in culture experiments (Meyer and Riebesell 2015). Meier et al. (2014) analyzed in situ *E. huxleyi* coccolith weight from the NW Mediterranean Sea in a 12-year sediment trap series, and surface sediment and sediment core samples. Their findings clearly show a continuous decrease in the average coccolith weight of *E. huxleyi* from 1993 to 2005, reaching levels below pre-industrial (Holocene) and industrial (20th century) values recorded in the sedimentary record, as most likely a result of the changes in the surface ocean carbonate system. Also, a drastic decrease in production, species diversity and anomalous calcification in coccolithophores has been shown along a natural pH gradient caused by marine CO_2 seeps off Vulcano Island (Italy) (Ziveri et al. 2014).

To conclude, (1) Mediterranean fauna is highly vulnerable to human activities and climate change; (2) both structural and functional biodiversity of continental margins are significantly affected by very small temperature changes; and (3) the impact of human activities and climate change on marine biodiversity might be non-reversible. Since there are close interactions between deep and shallow systems, the vulnerability of deep-sea ecosystems to climate change might also have important implications on the biodiversity and functioning of continental shelves.

The extent of changes caused by climate and non-climate drivers, the responses of Mediterranean marine biota to these changes and their local-regional consequences are yet to be investigated, as slow but significant transformations that may modify the neritic, pelagic, and benthic zones are still ongoing.

4.1.1.2 Past changes

Understanding the degree to which changes in Mediterranean marine ecosystems point to a directional trend driven by global warming remains a challenge for marine ecology (Bertolino et al. 2017a). Reconstructing the temporal variability of Mediterranean marine ecosystems on time scales longer than a few centuries beyond the instrumental records, crossing relevant climate variations and historical periods, can be critical for interpreting these changes.

Climate forcings of Mediterranean marine ecosystems over the past thousand years have occurred on different time scales (Abrantes et al. 2005; Hennekam et al. 2014; Xoplaki et al. 2018). During the Holocene, rapid warming and cooling events have occurred which can, to some degree, provide analogues for the projected changes for the coming centuries (Blois et al. 2013; Benito-Garzón et al. 2014; Raji et al. 2015). In the Mediterranean, these past climate changes impacted the marine physico-chemical parameters of surface and deep waters (e.g., salinity, temperature, oxygenation, pH) which in turn affected marine ecosystems (Frigola et al. 2008; Schmiedl et al. 2010a; Mojtahid et al. 2015; Bertolino et al. 2017b).

Response of marine ecosystems to past temperature changes

In the Mediterranean region, the most abundant Holocene temperature proxy data, especially for the Common Era (the last 2,000 years) are alkenone-derived records (Abrantes et al. 2012; Jalali et al. 2016; Sicre et al. 2016). These studies document natural long-term trends superimposed on a multidecadal variability in response to external (e.g., solar) and internal forcings (e.g., NAO) which might explain some recently observed sea surface temperature trends (Versteegh et al. 2007). These studies also reveal a strong regional component. For example, a high resolution study from the Gulf of Lion shows an overall sea surface temperature cooling trend since the mid-holocene followed by a rapid warming from ~1850 AD onwards that may parallel recent climate change (Jalali et al. 2016). In contrast, south of Sicily and in the eastern Levantine Basin, sea surface temperature records show progressive warming since the early Holocene without a clear signature of the recent anthropogenic change (Castañeda et al. 2010; Luterbacher et al. 2012; Jalali et al. 2017). The planktonic ecosystem in the Siculo-Tunisian Strait responded to this progressive warming of the sea surface temperature by increasing the abundance of warm dinocyst species (*Spiniferites mirabilis* and *Impagidinium aculeatum*) and planktonic foraminifera (*Globorotalia inflata* and *Globigerinoides ruber*) (Rouis-Zargouni et al. 2010).

The Holocene was interrupted by at least four brief cooling events at ~9.2 ka, ~8 ka, ~7 ka and ~2.2 ka cal. BP, which may be correlated to climate events recorded elsewhere, including in Greenland ice cores and in Atlantic Ocean sediments. Investigations on cetacean bones from the Grotta dell'Uzzo in northwestern Sicily (Italy) show that the rapid climate change around 8 ka coincided with increased strandings in the Mediterranean Sea (Mannino et al. 2015). Also, the diversity of sponge species living in coralligenous habitats from the Ionian and Ligurian was strongly affected by Holocene warming episodes with a significant loss of their biodiversity in recent decades (Bertolino et al. 2017b, 2019).

In the eastern Mediterranean, multiproxy records derived from sediments from the southeastern Levantine (Schilman et al. 2001b; Mojtahid et al. 2015) and the Adriatic Sea (Piva et al. 2008) reveal complex paleo-oceanographic changes during the late Holocene, with pronounced anomalies during the Medieval Warm Period (MWP) (ca. AD 1150) and the Little Ice Age (ca. AD 1730). These temperature anomalies were accompanied in the eastern Levantine Basin by a drastic change in planktonic foraminiferal successions indicating periods oscillating between cold and warm surface waters in opposite phase with the western Mediterranean records (Mojtahid et al. 2015). This east–west contrast in the climate signals has been confirmed by other proxy data (Jalali et al. 2016, 2017).

These findings imply that long-term and short-term climate-driven environmental changes, caused by global warming, will likely impact the entire food chain from planktonic ecosystems to large mammals (e.g., cetaceans) in the near future.

Response of marine ecosystems to past changes in stratification and ventilation

Throughout the Pleistocene, the eastern Mediterranean experienced numerous anoxic events recorded by the cyclical deposition of organic-rich layers or sapropels (Rossignol-Strick et al. 1982; Rohling 1994), the most recent being Sapropel S1 from ~10 to 6 cal ka BP. Maximum insolation due to the Earth's orbital precession minimum significantly intensified the northeast African monsoon, leading to enhanced discharge of fresh and nutrient-rich Nile River water into the eastern Mediterranean (Rossignol-Strick et al. 1982; Emeis et al. 2000). In the Levantine Basin, sea surface salinity during S1 dropped by about 2.0 to 4.0 units compared to present values (Kallel et al. 1997; Myers et al. 1998). This led to severe water column stratification and organic enrichment from the Nile river water. In the Ionian Sea, the correspondence of recent sapropel layers with peaks of the lower photic zone coccolithophore species *Florisphaera profunda* indicated the development of a deep chlorophyll maximum, due to the pycnocline/nutricline shallowing in the lower part of the photic zone (Incarbona et al. 2011). In the SE Levantine Basin, a severe drop in planktonic foraminiferal diversity was recorded in response to the water column stratification and expressed by the near exclusive presence of the euryhaline tropical-subtropical species *Globigerinoides ruber* and the disappearance of deep-dwelling species (Mojtahid et al. 2015).

The combination of higher organic matter remineralization and decreased ventilation resulted in widespread bottom water anoxia (Rohling 1994; Hennekam et al. 2014). In the Southern Aegean and Levantine Seas, there was a gradual increase in deep-water residence times, preceding S1 formation by approximately 1–1.5 kyr. Once oxygen levels fell below a critical threshold, the benthic ecosystems collapsed almost synchronously with the onset of S1 deposition. The recovery of benthic ecosystems during the terminal phase of S1 formation is controlled by subsequently deeper convection and re-ventilation over a period of approximately 1500 years. After the re-ventilation of the various sub-basins during the middle and late Holocene, deep-water renewal was more or less similar to recent rates (Schmiedl et al. 2010b). Several species of deep-water ostracods that are still common in the western Mediterranean became extinct in the eastern Mediterranean Basin at the onset of early Holocene S1 sapropel deposition and the related anoxia (Van Harten 1987). The deep-water ostracode *Bythocypris obtusata* apparently survived the oxygen crisis in the eastern basin itself. This suggests that full oxygen depletion may not have affected the bottom of all deep sub-basins and supports a midwater oxygen-minimum model for these sub-basins (Van Harten 1987; Schmiedl et al. 2010b).

These paleoclimatic findings suggest that eastern Mediterranean pelagic and benthic marine ecosystems are capable of abrupt transitions in response to gradual forcing. This is crucial for the projection of whether an increase in oceanic moisture availability under current and future warming could trigger a sudden intensification of monsoon rainfall further inland from today's core monsoon region (Schewe and Levermann 2017).

Response of marine ecosystems to past changes in productivity

In the western Mediterranean, productivity has shown an overall decreasing trend since the early Holocene with a marked fall in productivity after the 8.2 ky BP dry-cold event (Ciampo 2004; Jiménez-Espejo et al. 2007; Melki et al. 2009). Superimposed on this long-term pattern, some studies show millennial–centennial time scale variability linked with weakening and strengthening of upwelling conditions that have been simultaneous to changes in Western Mediterranean Deep Water (WMDW) formation in the Gulf of Lions and by extent to the NAO over the past 7.7 ka (Ausín et al. 2015). These changes were accompanied by re-organization in coccolithophore assemblages showing in particular, several high-amplitude oscillations of the productivity indicator species *F. profunda* (Ausín et al. 2015).

In the eastern Mediterranean, several proxy data support overall increased productivity during Sapropel S1 in a high-nutrient stratified environment (Gennari et al. 2009; Castañeda et al. 2010; Mojtahid et al. 2015). This period is characterized by the highest accumulation rates of planktonic foraminifera together with the productivity indicator coccolithophore species *F. profunda* (Incarbona et al. 2011; Mojtahid et al. 2015). After Sapropel 1, a progressive decrease in surface water productivity was recorded and surface and deep-sea ecosystems were driven by short-term changes in food quantity and quality as well as in seasonality, all of which are linked to millennial-scale changes in river runoff and associated nutrient input (Kuhnt et al. 2008; Schmiedl et al. 2010b). Particularly, the last 2.9 ka encompassed a succession of three ecosystem states characterized by nutrient-limiting surface waters from 2.9 to 1.1 ka, and during the Little Ice Age, and by nutrient-rich waters from 1.1 to 0.54 ka (Medieval Climate anomaly) (Mojtahid et al. 2015). These conditions were linked to periods of low and high Nile River runoff respectively, in line with arid and humid climate conditions in the Levant and Nile headwaters.

These findings imply that surface productivity in the overall oligotrophic Mediterranean Sea responds rapidly to short and long-term changes in nutrient input, either via rivers, winds or upwelling activity, modifying the benthic-pelagic ecosystems by extending into the entire food chain (Marino and Ziveri 2013), ultimately increasing eutrophication.

Response of marine ecosystems to past changes in pH

Holocene reconstructions of paleo-pH have yet to be undertaken in the Mediterranean. There is a promising raw data record of planktonic foraminiferal *(Neogloboquadrina incompta)* $\delta^{11}B$ and B/Ca. These geochemical proxies can be used for paleo-pH and show an overall decreasing trend in both sub-basins of the Mediterranean Sea during the last deglacial episode of glacial-interglacial CO_2 rise (Grelaud et al. 2012; Marino and Ziveri 2013). The response of marine calcifiers to this trend can be estimated via planktonic foraminifera shell weight that shows overall decreasing planktonic calcification in response to this variability. In addition to this general trend, periods of changing seawater carbonate chemistry can be observed, which could be linked to low/high primary production activity such as the anomaly observed during Sapropel 1 period, which can be linked to enhanced mineralization of organic matter.

These first studies show that Mediterranean marine calcifiers responded to past changes in surface seawater carbonate chemistry conditions. The extent to which this affects marine ecosystems needs to be analyzed in the context of the current acidification in the Mediterranean's surface and deep seawaters.

4.1.2 Projected vulnerabilities and risks

4.1.2.1 Projected impacts and risks

As already discussed in *Section 2.2.4.1,* annual mean temperatures in the Mediterranean are now 1.5°C above late 19th century levels with magnitudes that vary locally depending on the period of analysis, the region and the type of dataset. The diurnal temperature range has also changed in some parts of the Mediterranean *(Section 2.2.4.1)*. In absolute terms, the warmest parts are the southern and eastern Mediterranean and the major impact in these parts is the immigration of Indo-Pacific species (around a thousand species), which has accelerated in recent years, mainly for thermophilic species, due to rapid warming conditions (more than 50% of Mediterranean non-indigenous species are in the eastern Mediterranean) (Azzurro et al. 2011; Marbà et al. 2015; Kletou et al. 2016; Bariche et al. 2017). All Mediterranean waters, even the deepest, are affected by ocean acidification driven by Mediterranean Sea uptake of atmospheric CO_2 (Flecha et al. 2015; Hassoun et al. 2015; Palmiéri et al. 2015; Ingrosso et al. 2017) *(Section 6.11)*. In addition, the effects of climate change are amplified by other major non-climate-related anthropogenic forcings, as the Mediterranean has one of the most populated coastlines with a long human history of exploitation of marine resources (with presently one of the world's most intense coastal and maritime tourism areas), habitat degradation and plastic pollution (Cózar et al. 2015; Compa et al. 2019). More information about sea use changes and pollution are covered in *Chapter 2.*

The combination of various ongoing climate change processes (e.g., sea warming, ocean acidification, and sea level rise; *Section 2.6*) has caused detectable effects on marine organisms at individual, population, and ecosystem scales *(Fig. 4.4)*. Future risks of seal level rise, marine heat waves, and ocean acidification are also highlighted in *Sections 6.9, 6.10* and *6.11* respectively. In fact, sponges, gorgonians, bryozoans, molluscs, and seagrasses are all affected by these drivers (Cerrano et al. 2006; Garrabou et al. 2009; Bensoussan et al. 2010; Marba and Duarte 2010), but primary producers, mainly calcifiers such as coccolithophores, are among the most vulnerable organisms (Meier et al. 2014). The impacts are expected to affect endemic and iconic ecosystems including major reorganizations of the biota distribution, species loss, marine productivity, increases in non-indigenous species, and potential species extinction (Malcolm et al. 2006; Ramírez et al. 2018; Gao et al. 2020).

Projected impacts on microbes

Sea warming may have effects on the virulence of pathogens (viruses, parasites, etc.), favoring the frequency of epidemiological events, as most pathogens are temperature sensitive (Vezzulli et al. 2013) (see *Section 4.1.1* and *Section 2.3.4* in *Chapter 2* for more information about biological pollutants), as observed for *Vibrio shiloi,* responsible for the whitening of the coral *Oculina patagonica* in the eastern Mediterranean (Kushmaro et al. 1998). This warming is also responsible for the expansion of harmful and/or toxic microalgae, mainly dinobionts such as *Ostreopsis ovata,* which produces palytoxins, a serious public health hazard (Accoroni et al. 2016; Vila et al. 2016). Temperature anomalies also seem to negatively affect the chemical defenses of marine organisms (Thomas et al. 2007), allowing pathogens to act undisturbed. Given the predicted rise in temperatures over the coming decades, a better understanding of the factors and mechanisms that affect the disease process will be of critical importance in predicting future threats to temperate gorgonians communities (Bally and Garrabou 2007), and other affected species in the Mediterranean Sea.

In deep waters, a recent study has shown that deep-sea benthic Archaea can be more sensitive to temperature shifts than their bacterial counterparts. Changes in deep-water temperature may thus alter the relative importance of Archaea in benthic ecosystem processes (Danovaro et al. 2016). With rising deep-water temperatures, the predicted positive response of prokaryotic metabolism to temperature increases may accelerate oxygen depletion in deep Mediterranean waters, with domino effects on carbon cycling and biogeochemical processes across the entire deep basin (Luna et al. 2012). Along canyon-cut margins (e.g., the western Mediterranean), warming may additionally reduce density-driven domino effects, leading to decreased organic matter transport to the seafloor (Canals et al. 2006), though this very process is also likely to reduce physical disturbance on the seafloor and therefore affect deep-sea ecosystems.

Projected impacts on primary and secondary production

Climate change affects the functioning of the biological components of ecosystems, from the basis of the food webs (plankton) to the higher trophic levels (e.g., predator fish). Phytoplankton constitutes the autotrophic primary producers in the pelagic food chains in marine waters and their annual cycle is affected by many physical features that in turn control nutrient levels. These include large horizontal gradients in temperature (Izrael 1991). Due to their rapid turnover and fast responses to environmental changes, plankton is considered a suitable proxy to highlight either environmental changes circumscribed in space and/or time or wider climatic variations. Warming, for example, is responsible for the expansion of harmful and/or toxic microalgae, mainly the dinobionts such as *Ostreopsis ovata*, which produces palytoxins, a serious public health hazard (Accoroni et al. 2016; Vila et al. 2016). A new study in the Eastern Mediterranean has shown the occurence of important concentrations of biotoxins (domoic acid, gymnodimines and spirolides) in various marine organisms sampled from the Lebanese shores (Hassoun et al. 2021). These concentrations were correlated with the abundance of biotoxins' producers such as *Pseudo-nitzschia, Prorocentrum, Alexandrium,* and other species that could be occurring more frequently due to climate change (Hassoun et al. 2021).

Moreover, phytoplankton species responsible for bloom at late winter and at the beginning of spring (like *Skeletonema costatum, Nitzschia* spp., *Leptocylindrus danicus* and *L. minimus* and others) could start earlier, because features of temperate marine planktonic ecosystems are not only sensitive to annual variations in weather, but also any trends that might result from greenhouse warming or other factors that affect the climate system and both the density and timing of spring blooms will be altered in some regions (Townsend et al. 1994).

The taxonomic compositions of phyto- and zooplankton may change under the influence of changes in ocean structure (Kawasaki 1991; Berline et al. 2012; Howes et al. 2015) *(Section 2.2.7)*. A thermophilic phytoplankton species could proliferate especially in some enriched areas and could be ichthyotoxic or even toxic for humans (Abboud-Abi Saab 2008, 2009; Accoroni et al. 2016; Abboud-Abi Saab and Hassoun 2017). Some examples can explain such variations. In the Mediterranean Sea, phytoplankton biomass abundance and sea surface thermal stratification show a strong inverse relationship at seasonal and sub-basin scales. At inter-annual and sub-basin scales, a gradual decline of the phytoplankton biomass across the entire central Mediterranean occurs with a delay of one year (Volpe et al. 2012). In the Adriatic Sea, during the past decade, the community structure and seasonality of phytoplankton have changed significantly. The phytoplankton annual cycle has become more irregular with sudden diatom blooms, reflecting the variability of meteorological events in recent years (Totti et al. 2019).

Only a few regional studies have investigated the sensitivity of the oligotrophic Mediterranean Sea to future climate change. The first investigations considered only the changes in circulation. For instance, a regional model of the northwestern Mediterranean domain found that the effect of local stratification due to climate change would have no drastic effect on the pelagic ecosystem (Herrmann et al. 2014). However, one study investigated the overall effects of a moderate climate change scenario (A1B SRES) on Mediterranean biological productivity and plankton communities and found an overall decrease in phytoplankton biomass in response to the stratification simulated in their dynamic climate change scenario (Lazzari et al. 2014). A simulation was carried out for an increase in integrated primary productivity across the eastern Mediterranean Basin as a result of changes in density (decreased stratification) (Macías et al. 2015). However, conclusions from these studies remain limited by the fact that they are based on non-transient simulations and present-day nutrient inputs.

A new study has investigated the influence of both changes in circulation and biogeochemical forcings (rivers and input at Gibraltar) (Richon et al. 2019). It suggests that climate change and nutrient inputs from river sources and fluxes through the Strait of Gibraltar have contrasting influences on Mediterranean Sea productivity *(Section 2.3.3)*. Increased future stratification globally reduces surface productivity in the eastern basin, but the biogeochemistry in the western basin is strongly controlled by nutrient input across the Strait of Gibraltar, while the eastern basin is more sensitive to vertical mixing and river inputs. In the near future, longer water stratification and warmer conditions may be essential clues to understanding local stress and species mortalities, especially because of the changes in primary productivity and lack of enough resources to face starvation periods (Rossi et al. 2017a). Once some species are eradicated, other species, pre-adapted to the new conditions, can replace locally extinct species, thus hampering ecosystem resilience to pre-impact conditions.

Unfortunately, the future evolution of nutrient atmospheric deposition has not been considered in modelling studies so far, despite the important role of nutrients for marine primary production (Richon et al. 2018b, 2018a). Using aerosol sampling and microcosm experiments performed during the TransMed BOUM cruise (June–July 2008), Ternon et al. (2011) showed that primary production significantly increased at all tested stations after aerosol addition collected on-board and after Saharan dust analog addition, indicating that both additions relieved on-going co-limitations, whereas a decline in the future of primary production is predicted and associated with trophic amplification toward phytoplankton and zooplankton (Richon et al. 2019).

Abrupt community shifts are expected in plankton communities coinciding with climate changes that alter local thermal regimes, which in turn interact with the thermal niche of species to trigger long-term and sometimes abrupt shifts at the community level (Beaugrand et al. 2019). Planktonic calcifying organisms such as foraminifera, pteropods and coccolithophores are expected to be particularly affected by ocean acidification and climate change. A recent study in the Mediterranean found foraminifera to be highly susceptible to temperature-induced surface water stratification and food availability. In correlation with these results, rapid warming increased surface ocean stratification impacting food availability and changes in trophic conditions could be the causes of reduced foraminiferal abundance, diversity, and species-specific changes in planktic foraminiferal calcification (Mallo et al. 2017). Coccolithophores, an abundant unicellular calcifying phytoplankton, are known to have a haplo-diploid life cycle with environmental affinities. This dimorphic life cycle might provide the ability to adapt to the "tropicalization" of Mediterranean environments under climate change, in conditions characterized by surface water with a relatively high calcite saturation state, high temperature, stratification and nutrient limitation (D'Amario et al. 2017).

Projected impacts on macrobenthic and pelagic species

Sea warming, ocean acidification, sea level rise and changes in circulation patterns will likely change Mediterranean benthic and pelagic ecosystems, as shown in *Fig. 4.4*, where potential impacts related to climate change are presented (Rossi et al. 2019). Repercussions will be different depending on the region and on the dominance of certain benthic organisms, species interactions, metabolic constraints, dispersion capability, and the presence of alien species that may take advantage of the new physical, chemical, and biological conditions in the future oceans. Changes in trophic relationships will likely change biodiversity, both in the water column and in the different benthic communities. The nursery effect (i.e., sheltering and feeding grounds for juveniles and larvae) may be compromised if massive mortalities or deoxygenation affect the three-dimensional live structures (i.e., Posidonia meadows, gorgonian forests, pluriannual macroalgae, cold water corals, etc.). Also, changes in river runoff due to different rain frequency/quantities will also have effects on coastal nutrient and pollutant inputs. Nutrient and pollutant equilibria will also have direct or indirect effects on pelagic and benthic communities (Rossi et al. 2019).

Corals

Environmental change-driven modifications to the environment of gorgonian forests influence the larval settlement and recruitment processes of the benthic assemblages (Ponti et al. 2014b). In experiments, red coral *(Corallium rubrum)* showed a 59% decrease in its calcification rate at lowered pH based on experimental studies (Bramanti et al. 2013). Disturbances such as harvesting pressure could act in synergy with ocean acidification bringing local populations to extinction. The changes in the likelihood of occurrence obtained by differences between present conditions and future scenarios show that the projected extent of potential mortality zones is higher than in the current climate for red coral and that coralligenous formations along the Mediterranean sites are less likely, mostly due to acidification increase. However, the adverse impact is localized to certain regions: an increase in likelihood is also reported for the presence of coralligenous in the North Aegean and northern Adriatic Seas (MEDSEA 2015; Gómez-Gras et al. 2019).

The effects of in situ exposure to different pH levels (7.4–8.1) and temperatures (15.5–25.6°C) on mortality and net calcification rates have been assessed for Mediterranean scleractinian corals transplanted near a volcanic CO_2 vent off Panarea Island (Prada et al. 2017). Results of this *in situ* study show a synergistic adverse effect on mortality rates for all corals (up to 60%), suggesting that high seawater temperatures may have increased their metabolic rates which, in conjunction with decreasing pH, could have led to rapid deterioration of cellular processes and performance. The same study (Prada et al. 2017) suggests that symbiotic corals may be more tolerant to increasing warming and acidifying conditions compared to asymbiotic corals. Laboratory cultures of coralline algae under conditions of elevated temperature and pCO_2 revealed effects on photosynthesis, growth and calcification. Crustose coralline algae *(Neogoniolithon brassica-florida)* sensitivity to ocean acidification examined in CO_2 seeps confirmed that calcifying algae are likely to be threatened

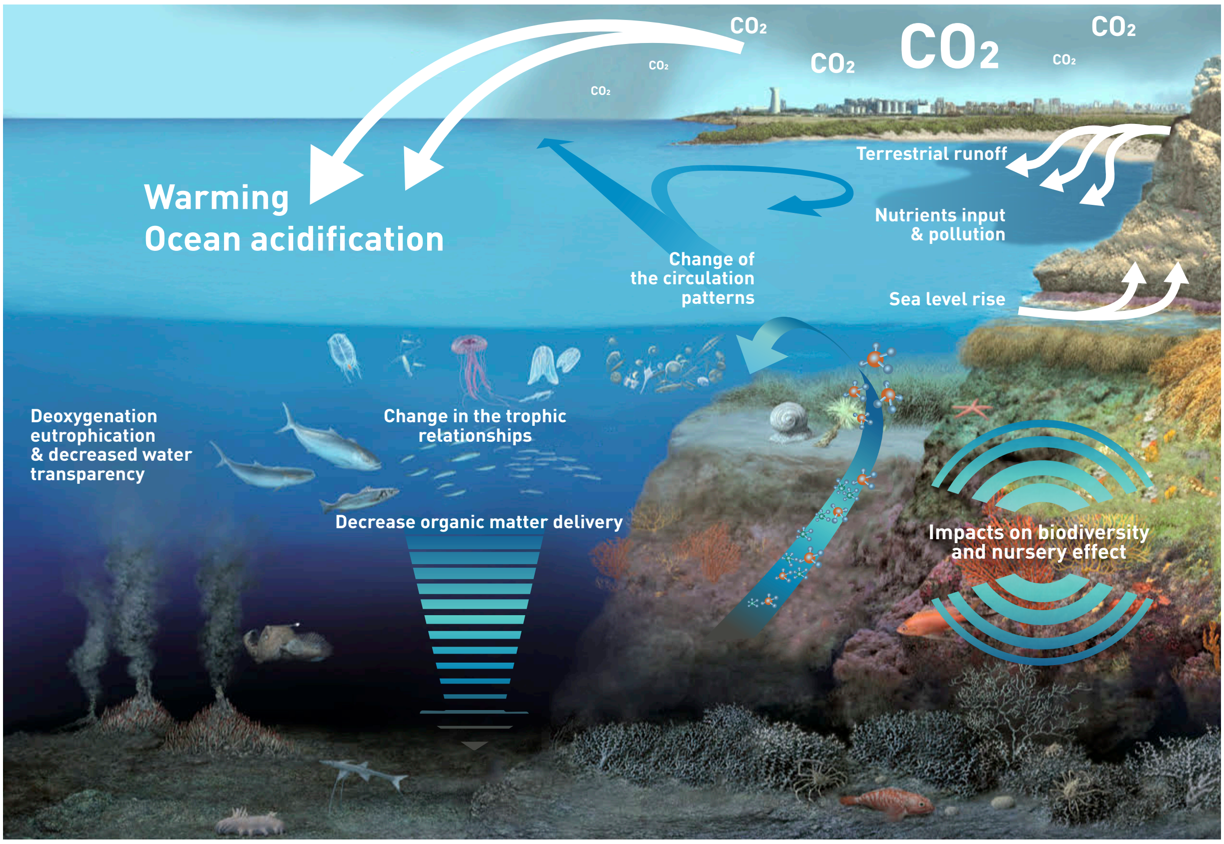

Figure 4.4 | Different drivers potentially affecting marine pelagos and benthos in the Mediterranean Sea (original diagram in Rossi et al. 2019, artwork by A. Gennari).

by ocean acidification, especially species living near their thermal limit. Further in situ and laboratory experiments indicate that *N. brassica-florida* may not be able to contribute to reef accretion under the levels of seawater warming and ocean acidification projected by the end of this century (Fine et al. 2017).

Seagrass

Warming can induce declines in abundance through increased shoot mortality in Mediterranean *Posionia oceanica* meadows. Younger life stages (i.e., seedlings) of *P. oceanica* may be particularly vulnerable to climate change. Insights into acidification effects on seagrasses have come from CO_2 vent surveys showing consistent loss of crustose coralline algal epiphytes on seagrass leaves, and greater seagrass density close to seeps with a lower pH (Hendriks et al. 2017). Lower epiphyte loads can have positive impacts for seagrass as it reduced shading and nutrient uptake by the epiphytes.

In the case of seagrass such as *P. oceanica*, projections show a negative impact due to the effects of global warming over the next century and to significant climate change challenges posed to an endemic system that is already suffering losses from anthropogenic impacts (Jordà et al. 2012). The trajectory of *P. oceanica* meadows under the warming expected in the western Mediterranean was studied through the twenty-first century and warming seems to likely lead to the functional extinction of *P. oceanica* meadows by the middle of this century (year 2049 ± 10) even under a relatively mild greenhouse-gas emissions scenario (Jordà et al. 2012). Similarly, the distribution of two seagrass species under different scenarios was forecasted (Chefaoui et al. 2018), and the results found that, in the worst-case scenario (RCP 8.5 scenario), *P. oceanica* might lose 75% of suitable habitat by 2050 and is at risk of functional extinction by 2100, whereas *Cymodocea nodosa* would lose around 46.5% of suitable habitat by 2050. The same study (Chefaoui et al. 2018) also predicts that erosion of present genetic diversity and vicariant processes can happen, as all Mediterranean genetic regions could decrease considerably in extension in future warming scenarios. The functional extinction of *P. oceanica* would have important ecological impacts and may also lead to the release of the massive carbon stocks these ecosystems stored over millennia.

Mussels

The Mediterranean mussel *Mytilus galloprovincialis* is particularly sensitive to warming. A significant decrease in growth (total weight, shell length, shell weight) has been found in warmer conditions as well as clear dissolutions of the shells exposed to low pH conditions (-0.3 compared to ambient). Mussels exposed to low pH showed a clear loss in the organic layer covering the shell in summer, explaining the clear dissolution signal measured on these mussels (Gazeau et al. 2014). Non-climate drivers, such as chemical pollution *(Section 2.3.3)*, are exacerbating the pressures on this important commercial mussel *(M. galloprovincialis)*.

Jellyfish

The sensitivity and specificity of the Mediterranean Sea to climate change and other human-related stressors have been unequivocally documented in recent years by a significant increase in the number and frequency of jellyfish outbreaks (Coll et al. 2010; Canepa et al. 2014). Ocean warming and acidification may favor the dissemination of the non-indigenous *Cassiopea andromeda* that seems to benefit from the changed conditions (Fuentes et al. 2018). Also, seawater temperature, together with the quantity and quality of available food resources, are known as major drivers of gonadal outputs (Harland et al. 1992; Ben-David-Zaslow and Benayahu 1999). Some studies showed that elevated temperature by itself or in combination with high feeding frequency (due to raised zooplankton prey abundance) increased the budding rate and bud size in Aurelia polyps populations worldwide (Hočvar et al. 2018). Thus, more food and warmer waters may be the key to understanding proliferation of jellyfish in general and non-indigenous tropical species in particular. In a sea highly impacted by the alteration of the trophic chains due to overfishing, seawater warming favors the successful dispersion and growth of jellyfish.

Winners and losers

The western basin is acidifying faster than the eastern basin (Goyet et al. 2016). A first tipping point has already been reached, since anthropogenic CO_2 is already over 82 μmol kg^{-1} in many Mediterranean areas (Hassoun et al. 2015). The exact timing of the tipping points *(Section 2.2.9.2)* will strongly depend on the policies controlling human activities, which will impact both global warming and the anthropogenic CO_2 increase both in the atmosphere and into the ocean. The results of these projections raise concerns about how marine organisms will respond in the context of each scenario, after reaching every tipping point.

Mean warming, acidification and associated non-climatic stressors will have varying impact across the Mediterranean marine ecosystems, and result in both potential winners and losers. Impacts of ocean acidification and warming may extend to several Mediterranean marine and coastal ecosystem services, food provision, recreational activities, carbon absorption, climate regulation, coastal protection, and ultimately affecting human health (Falkenberg et al. 2020). Marine areas with economic activities directly depending on marine resources may face serious impacts on employment and benefits in sectors like aquaculture, open sea fisheries and tourism, which is relevant to many Mediterranean countries. Tourism may be affected by acidification and warming through the impact of degraded marine ecosystems (loss of iconic coralligenous species, such as gorgonians - soft coral (Bramanti et al. 2013) from diving experiences and through jellyfish outbreaks). Sensitivity of shell-forming species such as bivalve mollusks to changes in temperature and acidity presents a threat to the aquaculture sector (Rodrigues et al. 2015).

A reduction in primary production linked to an increase in sea surface temperature could have negative impacts on fisheries catches and could exacerbate current overfishing trends (Cheung et al. 2010). Projections of biomass and fisheries catches across the Mediterranean under the high emission scenario RCP8.5 suggest a 5 and 22% increase in total fish and macroinvertebrate biomass , and a 0.3 and 7% in fisheries catches by 2021–2050 and 2071–2100, respectively, combined with changes in primary and secondary production (Moullec et al. 2019). Winners were mainly small pelagic species, thermophilic and/or exotic species, of smaller size and of low trophic levels. Loser species are generally large-sized, some of which are of great commercial interest. The bulk of the increase is expected in the southeastern part of the basin whereas significant decreases are most likely in the western Mediterranean Sea. Read more about projections for marine food resources and fisheries in *Sections 2.4.2.3* and *3.2.2.2*.

Since temperature seems to be a main environmental parameter driving the cnidarian community composition, abundance and spatial distribution patterns in the Mediterranean Sea, jellyfish are considered a possible group of winners under warming (Guerrero et al. 2018). The structure and phenology of the Mediterranean hydrozoan community displayed significant changes in species composition, bathymetric distribution, and reproductive timing over the last decades. When the Scyphozoa group is considered, *Pelagia noctiluca* (among the most abundant jellyfish in the Mediterranean Sea and Eastern Atlantic waters) has increasingly frequent massive outbreaks associated with warmer winters (Milisenda et al. 2018). Swarms of the Portuguese Man-of-War *(Physalia physalis)*, in summer 2010 were the result of an unusual combination of meteorological and oceanographic conditions during the previous winter and not a permanent invasion favored by climate changes (Prieto et al. 2015). However, many studies have attributed the increase in *Pelagia noctiluca* outbreaks to the alteration of the trophic structure of ecosystems due to overfishing and/or eutrophication on the one hand, and by sea warming and changes in surface hydrography on the other (Licandro et al. 2010; Canepa et al. 2014). Water temperature affects sexual reproduction through changes in the energy storage and gonad development cycles and it is still expected that the species composition and biogeography of jellyfish communities will change under global warming.

4.1.2.2 Vulnerabilities

Climate-related vulnerabilities

It is expected that the ocean's primary production will, in general, be reduced with environmental change. As a result, production zones may be redistributed and the natural habitat of commercially valuable species of fish may change (Izrael 1991). On the other hand, climate change can also lead to changes in the composition of the bottom of marine food webs. The rise in water temperature has already increased jellyfish population outbreaks in the Mediterranean Sea *(Section 4.1.2.1)*, such as *Pelagia noctiluca*, a planktonic predator of fish larvae and of their zooplankton prey. The outbreaks of this species, along with other jellyfish species, may become more frequent in the Mediterranean Basin in the future and extend over a longer period of the year than previously, causing changes to the pelagic food web and thereby reducing fishery production (Licandro et al. 2010). Rising seawater temperatures might also trigger the increased spread of pathogens throughout the Mediterranean in the future, affecting both marine organisms, and human health (Danovaro et al. 2009) (see *Section 5.2.3* on heat-related impacts).

Temperature has a major direct impact on the physiology, growth, reproduction, recruitment and behavior of marine organisms such as fish. Warming associated with climate change already affect the Mediterranean ecosystem for some benthic and pelagic species (Marbà et al. 2015). Warming combined with a decline in oxygen and resource availability reduces fish body size, with the average maximum body weight of fish expected to shrink by 4% to 49% from 2000 to 2050 (Cheung et al. 2013). Also, fish tend to adapt to local environmental temperatures. Therefore, among the most perceptible large-scale consequences of climate change is the shift in spatial distribution range of marine organisms, which will make some Mediterranean sub-basins more vulnerable to drivers than the others. Seawater warming will induce a loss of climatically suitable habitats for various organisms, causing distribution shifts, as well as species extinction. The diversity of fish assemblages is predicted to be severely affected due to their loss of suitable climatic niches. Demersal species will suffer regional impacts associated with the expected changes in primary production, thermohaline circulation, and the severity of winter weather *(Section 2.2.2)*. Warming and the expected increase in Atlantic water entering into the Mediterranean will likely affect migrations and spawning behavior in large pelagic fish (Barange et al. 2018). In recent decades, several mass mortality events of invertebrates have occurred in the Mediterranean which have been linked to the documented rise in seawater temperatures (Rivetti et al. 2014).

Projections for the global warming scenario (SRES A2) for the potential future distribution of 75 Mediterranean endemic fish species have shown that by 2041-2060, 31 species are projected to extend their geographic range, whereas the geographic range of 44 species is projected to reduce (Ben Rais Lasram et al. 2010). Also, 25% of the Mediterranean continental shelf is predicted to undergo an overall change to endemic assemblages by the end of the 21st century, where the survival of 25 species is threatened and six species would become extinct (for example, starry sturgeon *Acipenser stellatus* and European sturgeon *Huso huso*). For "narrow" endemic species found strictly in the Mediterranean Sea that do not reach the neighboring Atlantic Ocean and Black Sea, their extinction would be irreversible. By the middle of the 21st century, the coldest areas of the Mediterranean Sea, namely the Adriatic Sea and the Gulf of Lion, would act as a refuge for cold-water species, but by the end of the century, those areas are projected to become a "cul-de-sac" that would drive those species towards extinction (Ben Rais Lasram et al. 2010). Another study concludes that 54 species will have lost their climatically suitable habitat at the end of the century and that species richness will decrease across 70.4% of the continental shelf area (Albouy et al. 2013). Information about the trends of fisheries in the Mediterranean is detailed in *Sections 2.4.2.1* and *3.2.1.2*.

Anthropogenic vulnerabilities

Ship collisions and harmful fishing practices are among the non-climate drivers exacerbating the vulnerability of marine cetaceans in the changing Mediterranean. The previous analysis of ship collision records for the relatively isolated population of fin whales in the Mediterranean Sea from 1972 to 2001, indicated that the fatal collision rate increased from 1 to 1.7 whales per year during this period mainly in the Pelagos Sanctuary (the largest marine protected area created for marine mammals in the Mediterranean; see *Section 4.1.1)* due to high levels of traffic and whale concentrations (Panigada et al. 2006). Studies by Pennino et al. (2016, 2017) assessed the risk exposure for high intensity vessel traffic areas for the three most abundant cetacean species (*Stenella coeruleoalba, Tursiops truncatus* and *Balaenoptera physalus*) in the southern area of the Pelagos Sanctuary. They modeled both the occurrence of three cetacean species and marine traffic intensity, and identified two main hotspots of high intensity marine traffic in the area, which partially overlap with the area where the studied species are present. International shipping, although considered as an environment-friendly form of transportation, directly and indirectly impacts cetaceans in many ways, particularly in the Mediterranean Sea, one of the world's busiest waterways (Bray et al. 2016; Coomber et al. 2016). More recent data about maritime traffic in relation to cetaceans, investigated through direct observations (July 2013–June 2015) and along three fixed transects in western Mediterranean areas, showed seasonal maritime traffic intensity with the highest vessel abundance impacts on cetaceans in most offshore sub-areas in the spring and summer, especially for the species *B. physalus* and *S. coeruleoalba* (Campana et al. 2017).

4.1.3 Adaptation

4.1.3.1 Long-term monitoring and adaptation strategies

Temperature significantly affects eukaryotic phytoplankton metabolism, increasing the demand for nitrogen with consequences for the marine carbon cycle due to shifts towards N-limitation (Toseland et al. 2013). Experiments reveal that some taxa of marine phytoplankton may adapt to ocean acidification, and there are also strong indications from studies of variation and structure in natural populations that selection on standing genetic variation is likely (Collins et al. 2014).

To better evaluate the adaptation strategies of plankton communities to the diverse climate and non-climate related drivers, it is necessary to assess the vulnerabilities of the pelagic ecosystem, including both plankton and nekton communities, to the impacts of climate change, including temperature and pH variations. Taking into consideration the diversity of plankton communities' responses to climate change and other stressors in every Mediterranean sub-basin (Crise et al. 1999; Psarra et al. 2005; Vadrucci et al. 2008; Calvo et al. 2011; Marić et al. 2012; Ouba et al. 2016; Danovaro et al. 2017; Benedetti et al. 2018), wider monitoring coverage is needed to improve our knowledge about the different adaptation processes that characterize and best suit each geographical zone. Since each Mediterranean Basin represents a unique set of interrelated physical, biological and human components and processes, the extent and nature of impacts in one basin will differ between sub-basins as well.

Also, an assessment of the implications of accelerated temperature increase in the Mediterranean Sea and the identification of the types of problems that a marine area will face is crucial in order to anticipate the need for action (Lacoue-Labarthe et al. 2016). In their review about the biodiversity and ecosystem functioning, Danovaro and Pusceddu (2007) have recommended enhanced strategies for protecting the Mediterranean Sea, such as monitoring environmental quality, grey and black lists of chemicals, utilizing the best available technologies once they have been tested for their eco-sustainability, applying precautionary principles (e.g., reducing pollution emissions), monitoring biodiversity and long-term temporal changes in community structure. The suggestion has been made to assess not only the apparent changes, but also the potential biodiversity (cyst banks) while paying particular attention to species replacement in relation to functional biodiversity (Danovaro and Pusceddu 2007).

4.1.3.2 The role of Marine Protected Areas (MPAs) for adaptation

Marine Protected Areas cannot halt climate change and impacts such as ocean acidification, but they are an important tool for enhancing the resilience and adaptive capacity of ecosystems. A topical example in this sense are Mediterranean coralligenous reefs, critical for life-supporting and ecological functions and providing a natural capital like biomass production, erosion control, historical, economic and intrinsic value. Marine protected areas provide refuge and replenishment zones for this heavily exploited and vulnerable species. Moreover, they protect, aid recovery and are home to a large number of species (Rodríguez-Rodríguez et al. 2015; Pascual et al. 2016). Few MPA designs account for official MPA boundaries regardless of boundary overlaps and their ecological implications (Gabrié et al. 2012), whereas others account for MPA boundary overlaps and thus foster a more ecologically meaningful, functional spatial approach through "protected polygons" (Foster et al. 2014).

The effectiveness of MPAs can be improved if they form part of a system of protected areas geared towards ensuring ecological representativeness and creating networks. Nevertheless, subdividing an area into zones with varying intensities of use (zoning), ranging from total protection (marine reserves where extractive use is prohibited) to areas serving primarily to uphold sustainable and/or traditional use of marine resources, and areas that are closed to fishing activities, is increasingly recognized as a useful instrument for sustainable, ecosystem-based fisheries management, particularly artisanal fisheries (Pascual et al. 2016). MPA ecological effectiveness, defined as species self-replenishment and colonization through dispersal, depends, among other variables, on MPA design factors such as size, shape, spacing and location (Shanks et al. 2003; OSPAR Commission 2007; Roberts et al. 2010; Sciberras et al. 2013). Different categories of MPAs often sit side by side with core areas under strict protection and peripheral zones with fewer restrictions relating to use.

An example of these MPAs is the Mediterranean Marine Protected Area of Medes Islands, in the northwestern Mediterranean Sea. This area was recently the subject of an economic assessment, using monetary valuation, of changes in the quality of highly biodiverse coralligenous systems (Rodrigues et al. 2015). The Adriatic Sea, for example, has the largest number of MPAs and also the smallest, least spaced and least compact designated and functional MPAs. The design pattern in this ecoregion seems to have randomly followed a design approach of "several small" MPAs (Rodríguez-Rodríguez et al. 2015). The establishment of a transboundary Large Marine Protected Area (LMPA) and Fisheries Restricted Area (FRA) can reverse ecological and socio-economic losses in the Adriatic, one of the most exploited areas of the Mediterranean as shown in a study that presents current opportunities and expected benefits of LMPAs (Bastari et al. 2016). This demonstrates that the establishment of MPAs should take into consideration the structural and functional links between key organisms within the ecosystem and between ecosystems to guarantee a sustainable adaptation strategy.

The majority of MPAs are located along the basin's northern shores, highlighting the lack of MPAs in the south and east coasts (Abdulla et al. 2008). Coll et al. (2012) studied the interaction between marine biodiversity and threats (including climate change) across the Mediterranean and assessed their spatial overlap with current marine protected areas. They identified areas of conservation concern where future protection activities should be targeted through spatial prioritization. Spatial prioritization in conservation is commonly employed to direct limited resources to where actions are most urgently needed and most likely to produce effective conservation outcomes. Resilience is increasing through building MPA networks and setting priorities at the regional level. Examples for the conservation of three key Mediterranean habitats, i.e., seagrass *Posidonia oceanica* meadows, coralligenous formations, and marine caves, were determined through a systematic planning approach (Giakoumi et al. 2013).

4.1.3.3 Management of fisheries and adaptation

Fisheries is one of the main sectors related to resource-based growth activities in the Mediterranean area *(Section 5.1.1.3)*. Sustainable development of fishing activities and the management of their impacts require better constructive collaboration between scientists, industry and government agencies. The analysis of all available stock assessment and effort data for the most important commercial species and fleets in the Mediterranean Sea since 2003, demonstrated a significant decline for red mullet and giant red shrimp stocks (Cardinale et al. 2017). This latter study concluded that the European Common Fisheries Policies have failed to achieve the maximum sustainable yield before 2015 for the Mediterranean Sea and will face large difficulties to reach maximum sustainable yield and Marine Strategy Framework Directive targets before 2020 under the current management system, due to many factors, such as the ineffectiveness of the putative effort reductions to control fishing mortalities, the continuous failure to follow scientific advice, and the existence of ineffective national management plans as a primary management measure (Cardinale et al. 2017).

The establishment and implementation of management plans that could efficiently help fisheries to adapt relies on knowing each species properties and demographic features. For example, the local and isolated groups of the European anchovy *(Engraulis encrasicolus)* may have unique demographic properties and should be managed separately since they may react independently to exploitation (Jemaa et al. 2015a). The same conclusion has been highlighted for pelagic species (such as the European sardine, *Sardina pilchardus*) with high gene flow to ensure sustainable fishery benefits and efficient conservation as they also may have unique demographic properties and responses to exploitation (Jemaa et al. 2015b).

The current knowledge on Mediterranean fisheries and ecosystems is limited. In fact, the effect of poorly regulated fisheries, in combination with ongoing climate forcing and the rapid expansion of non-indigenous species, are rapidly changing the structure and functioning of ecosystems with unpredictable effects on the goods and services provided (Colloca et al. 2017). Although this would call for urgent conservation actions, the management system implemented in the region appears too slow and probably inadequate to protect biodiversity and secure fisheries resources for future generations. This is why some studies are encouraging the adoption of other management approaches such as the establishment of a transboundary Large Marine Protected Area (LMPA), specifically a no-trawl area LMPA or Fisheries Restricted Area (FRA), which is a promising and feasible approach for reversing ecological and socio-economic losses in some Mediterranean sub-basins such as the Adriatic (Bastari et al. 2016), as mentioned earlier in *Section 4.1.3.2.*

Maintaining ecosystem services (through efficient fisheries management, sustainable and ecofriendly aquaculture industry *(Section 3.2)* is crucial for the food security, economic growth and well-being of neighboring populations *(Section 5.1.1.3)*. Developing practical management actions that take into consideration the uniqueness of each species and their responses towards different drivers is crucial to increasing their resilience and plasticity in the context of climate change.

4.1.3.4 Adaptation strategies for ocean warming and ocean acidification in the Mediterranean Sea

Studies on adaptation to climate change in the Mediterranean Sea are still very limited. Actions considered are mostly supply-side oriented, aimed at restoring or protecting the production of marine goods and services harmed by ocean warming and acidification for example (Ziveri et al. 2017). The demand-side dimension can ultimately produce economic consequences of the same or greater magnitude than adaptation through supply-side strategies and actions.

The Mediterranean Sea is a marine biodiversity hotspot (Coll et al. 2010) and ecosystems with high biodiversity and/or redundancy of functional groups (for example, several species fill the role of algal grazers) tend to be more resilient and recover more quickly following disturbance. This implies that biodiversity preservation and improvement are logical methods for sustaining ecosystems responding to rapid environmental stressors. In practice this means, on the one hand, exploiting the acclimation potential of many calcifying species of the Mediterranean and, on the other hand, protecting other species. The recommendation of a drastic reduction of local drivers is strictly connected with mitigation and adaptation strategies, since reducing local stressors – such as land-based pollution, coastal development and overharvesting – is the most common strategy for improving or maintaining ecosystem resilience (read more on economic vulnerabilities/risks and the adaptation measures in *Sections 5.1, 6.10.2* and *6.11.2*).

In the Mediterranean, commercial fisheries are economically important on a regional and local scale or for some specific communities and user groups. Although there is still limited knowledge on the combined direct impacts of ocean acidification and warming on fish, there are indications of the physiological and behavioral effects of CO_2 on fish (Nilsson et al. 2012; Milazzo et al. 2016). However, the two phenomena could indirectly impact fisheries affecting phytoplankton community structures at the bottom of the food web (Nagelkerken et al. 2016). In general, when fishing activity is more "sustainable", it tends also to be more resilient to negative shocks. All the measures working in this direction are thus also suitable for mitigating the adverse economic effects of ocean acidification.

Aquaculture is a key economic sector of fisheries affected by ocean acidification and warming. In the Mediterranean, detrimental effects on bivalve mollusk species might arise from the associated increase in sea surface temperature, ocean acidification and possible synergies with other non-climate drivers (Gazeau et al. 2014). A study suggests that the increase in frequency and duration of summer heatwaves are perceived as the highest threat, having been observed in a majority of the studied production sites in past years, with effects on seed (spat), adult mortality and byssus attachment (Rodrigues et al. 2015). Ocean acidification knowledge transfer and monitoring programs are essential for the development of appropriate strategies to counteract the effects of these phenomena, which are still poorly known by stakeholders. Adaptation in this sector tends to be particularly expensive since it usually requires costly investment in new machinery or in modifying existing machinery so as to reduce negative environmental impacts. A recent study emphasizes that the cost of management and mitigation strategies and actions will be dependent upon the socio-economic context. Specifically, costs will likely be greater for socio-economically disadvantaged populations, exacerbating the current inequitable distribution of environmental and human health challenges (Falkenberg et al. 2020).

Some species are proven to improve the resilience of their habitat to various drivers. For example, *Paramuricea clavata* forests may enhance bioconstruction processes and increase the resistance and resilience of benthic assemblages in Mediterranean coralligenous habitats (Ponti et al. 2014b, 2018). The lack of available food, rising temperature and decreasing pH trends will be essential to understanding future population dynamics. Bioengineering as a possible adaptation strategy includes techniques to mitigate chemical effects of increased atmospheric CO_2 concentrations on the oceans. These chemical changes may have a variety of important biological consequences, including some potentially negative impacts, which are controversial and surely require further consideration. These ideas have never been tested *in situ* (Ziveri et al. 2017).

In conclusion, any kind of action that improves marine ecosystem health, resilience or biodiversity could delay and reduce the adverse effects of climate drivers. This includes the implementation of more sustainable fishing practices as well as reducing pollution from agricultural activity, sustainable tourism and developing more effective waste management. Marine protected areas can potentially have an insurance role if they are placed in locations not particularly vulnerable to ocean acidification and climate change. However, the detrimental effects of these global phenomena on certain habitats in vulnerable regions do not make MPAs easily effective in improving species resilience to environmental change when considering long-term strategies. Developing specific adaptation options, for example new practices in aquaculture or improving marine and coastal protection against storm surges and coastal erosion, could be effective but particularly costly (see *Sections 3.3.2.2* and *3.3.2.3* for more information about the use of marine energy as a renewable energy resource and the vulnerability of coastal energy systems to climate extremes).

Adaptation strategies must have medium- to long-term effectiveness. They thus require careful and anticipatory planning to enjoy their benefits reasonably soon, and especially to enable them to tackle problems while they are still manageable. Overall, adaptation strategies are a necessary to response to ongoing and expected Mediterranean environmental changes. However, the necessary strategy for reducing climate change impacts needs effective mitigation policies and actions to be implemented.

4.1.3.5 Regional observation networks as a tool for adaptation

Another aspect that might improve the effectiveness of managed adaptation strategies is the establishment of active regional and local observation networks. Local observation programs and regional networks that include scientists from different Mediterranean countries/sub-basins create a solid platform for peers to collaborate in monitoring climate change drivers and impacts, enhance data sharing policies and accessibility, and improve capacity-building among the members of their scientific community.

Furthermore, long-term active hubs would definitely help in deriving more robust findings about the different environmental trends in the Mediterranean, which will provide more comprehensive and conclusive results for decision makers. Within the Global Ocean Acidification-Observing Network (GOA-ON), a regional Mediterranean hub has been recently established, called the Ocean Acidification Mediterranean Hub[31] (OA Med-Hub). This hub could be an important platform for providing robust ocean acidification-related results for the scientific community, the general public and decisions-makers, which would help to create relevant future adaptation actions in Mediterranean countries.

Moreover, these regional networks could be an effective tool for improving public awareness and enhancing capacity-building among scientists who are not able or do not have the appropriate tools/equipment to monitor specific phenomenon. Thus, such hubs could unify the methodologies and tools adopted to measure and monitor short- and long-term climate change trends, and their effects on local and regional marine resources and ecosystems. They could also help obtain funds for laboratories that do not have the capacities to properly survey climate change drivers and impacts. For example, GOA-ON published recently an implementation strategy document[32] to provide guidance that will harmonize sampling and analysis procedures, to compare results and trends. Creating similar networks that could target other phenomena, such as deoxygenation, warming, etc., and good communication between these hubs will be crucial for developing suitable and holistic key messages that could be provided to policymakers.

4.2 Coastal ecosystems

4.2.1 Current condition and past trends

4.2.1.1 Observed changes

The coastal zone refers to the area in which the interaction between marine systems and the land dominate ecological and resource systems. These rather complex systems consist of coexisting biotic and abiotic components which interact with human communities and their socio-economic activities (UNEP/MAP/PAP 2008). In sensitivity studies concerning expected sea level rise, the term "Low-Elevation Coastal Zone" (LECZ) has been used for the specific area up to an elevation of 10 m (Vafeidis et al. 2011). Ecosystems in this zone are referred to hereafter as "coastal ecosystems". The natural coastal systems include distinct coastal features and ecosystems such as rocky coasts, coral reefs, beaches, barriers and sand dunes, estuaries, lagoons, and generally the land located at the lower end of drainage basins, where stream and river systems meet the sea and are mixed by currents and tides (i.e., deltas, river mouths, wetlands) (Convertino et al. 2013).

To evaluate the risks that could affect Mediterranean coastal systems, their natural habitats, or particular events that could occur on its shores, many indexes have been developed, such as the Environmental Sensitivity Indices (ESI) developed for the evaluation of oil spill risk in Mediterranean coasts (Gugliermetti et al. 2007), the participatory multicriteria analysis (MCA) for a multidimensional assessment of coastal erosion risks (Roca et al. 2008), and the coastal dune vulnerability index for Mediterranean ecosystems (Ciccarelli et al. 2017). Also, a Coastal Risk Index (CRI-Med) has been developed to assess coastal vulnerabilities associated with the physical and socio-economic impacts of climate change in all Mediterranean coastal zones (Satta et al. 2017; *Fig. 4.5*). By applying the CRI-Med on 21 Mediterranean countries, coastal risk hotspots are found to be predominantly located in the South-Eastern Mediterranean region. Countries with the highest percentage of extremely high-risk values are Syria (30.5%), Lebanon (22.1%), Egypt (20.7%), and Palestine (13.7%). Coastal hotspots are designated to support the prioritization of policies and resources for adaptation and Integrated Coastal Zone Management (ICZM).

Natural Mediterranean habitats under severe degradation

Climate change affects marine biodiversity, especially in coastal habitats (Gatti et al. 2015; Bertolino et al. 2016, 2017a; Betti et al. 2017; Longobardi et al. 2017). Mediterranean shores have unique and highly diversified landscapes, which harbor a high level of diversity in fauna and flora *(Section 2.4)*. Directly or indirectly, sea level rise *(Section 2.2.8)*, global warming *(Section 2.2.4)* and changes in

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[31] http://goa-on.org/regional_hubs/mediterranean/about/introduction.php

[32] http://goa-on.org/documents/general/GOA-ON_Implementation_Strategy.pdf

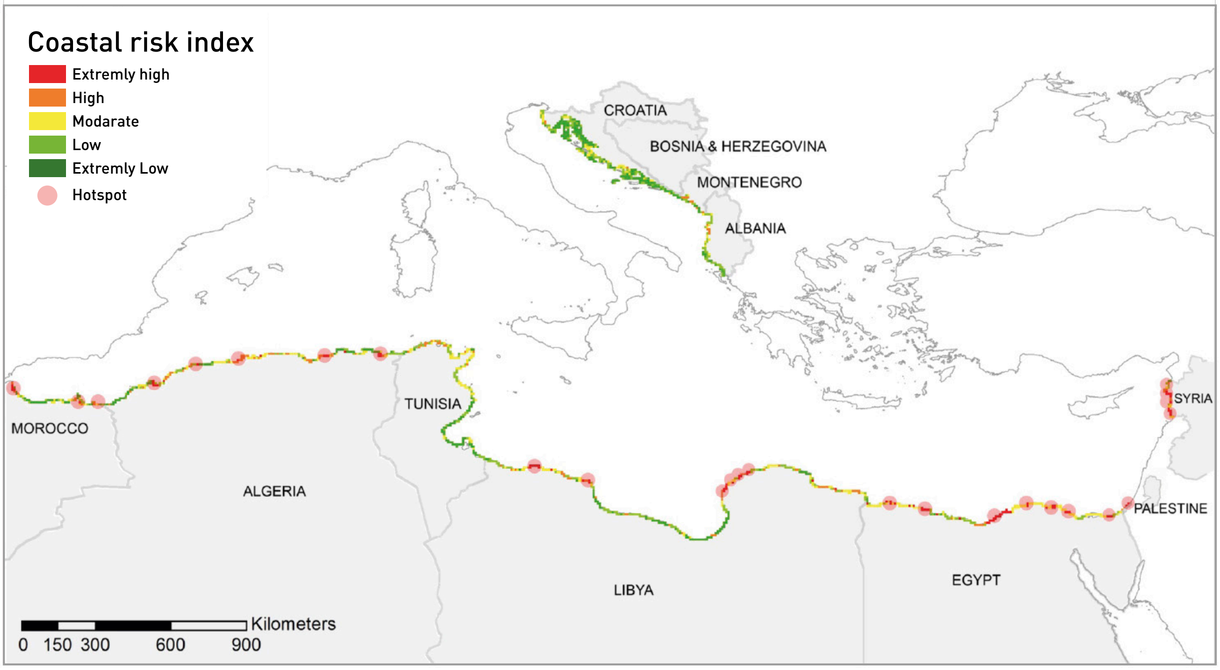

Figure 4.5 | Coastal Risk Index (CRI-MED) map of the Mediterranean, indicating five levels of vulnerability (Satta et al. 2017).

rainfall patterns *(Section 2.2.5)* would greatly modify coastal ecosystems and rivers with significant impacts on the way they function. For instance, in response to relative sea level rise, coastal wetlands and river mouths would be affected, while reduced precipitation and prolonged droughts will reduce the water discharge of Mediterranean rivers and catchments (Merheb et al. 2016). Dynamic coasts are likely to retreat or disappear because of the effects of erosion due to the accelerated rise in sea level. With the accelerated rise in sea level, the least mobile species will likely be the most severely impacted in contrast to mobile organisms such as fish and water-birds which are more able to adapt.

Coastal ecosystems function in a way that maintains the preservation of energy and matter transfer and plays an important role in global cycles (such as carbon and nitrogen global cycles) between the continental and marine realms. Furthermore, in addition of hosting a wide diversity of wild faunal and floral species, coastal ecosystems are also often used as aquaculture platforms (i.e., fish, shellfish cultures, etc.), and the pressures on them may have significant impacts on their uses.

Sandy beaches and sand dunes

Escalating pressures caused by the combined effects of population growth, demographic shifts, economic development and global climate change pose unprecedented threats to sandy beach ecosystems across the world (Velegrakis et al. 2016; Vousdoukas et al. 2016). From the sub- to the supra-littoral, sandy habitats are important in preventing coastal erosion and flooding, but their value may be enhanced by the many biological processes that complement or even increase their role in coastal defense. For example, in addition to their role in nourishing other sandy systems, shallow, sub-tidal sands also support seagrass beds, a habitat increasingly recognized as important for coastal protection due to their ability to stabilize and accumulate sediment, and attenuate and dissipate waves (Christianen et al. 2013; Ondiviela et al. 2014).

In addition to direct anthropogenic impacts (e.g., urban and agricultural development, *Sections 2.3* and *2.4*), climate change is predicted to have dramatic, widespread and long-lasting consequences on sandy coastal ecosystems. For instance, sea-level rise increases the phenomenon of "coastal squeeze", but increased storm intensity and frequency are likely to be the major challenges faced (Feagin et al. 2005; Harley et al. 2006; Velegrakis et al. 2016; Vousdoukas et al. 2016).

As ecosystems, sandy beaches play varying important roles, and interact closely with coastal dunes both physically and biologically. The typical coastal dune system is composed mainly of three components: the submerged beach, the emerged beach and the dune *(Fig. 4.6)*. For thousands of years, human activities have been impacting the sandy beaches and coastal sand dunes of the Mediterranean Basin through agriculture, husbandry and the deliberate use of fire (Lavorel et al. 1998; Cori 1999; Falcucci et al. 2007). In recent decades, tourism has caused important damages as the main driver of coastal urbanization, the increase of summer visitors, and the introduction of non-indigenous or exotic species (Tzatzanis et al. 2003). The pedestrian and motorized pathways all over dunes lead to vegetation destruction and therefore enhanced weathering and erosion. Waste and non-indigenous species introduction are also destruction factors among many other drivers highlighted in *Sections 2.3* and *2.5*.

The impact of human pressure on landscape patterns and plant species richness in Mediterranean coastal dunes was assessed and a general simplification was observed in the natural dune spatial pattern with a decline in plant richness where human pressure is important (Malavasi et al. 2018). Assessing the conservation status of coastal dune systems in Tuscany (Italy), Ciccarelli (2014) showed that the general spatial pattern of vegetation there was close to the natural zonation (Acosta et al. 2007; Forey et al. 2008; Miller et al. 2009; Fenu et al. 2013), with a variable sequence of coastal dune plant communities, ranging from the disappearance of the foredune habitats to the presence of the complete sequence. Vegetation of the driftline disappeared in this study's transects where erosion was significant, while embryonic shifting dunes with *Elymus farctus* were well represented in the area. However, embryonic dune habitat showed a decrease in coverage in transects belonging to coastal tracts affected by erosion. Although vegetation of the driftline and embryonic shifting dunes have few taxa with low coverage, they represent an important element that must be considered in conservation programs (Ciccarelli 2014).

Rocky coasts

Rocky intertidal shores play an important role for marine habitat functioning (Sugden et al. 2009). They are a destination for leisure, exploration and relaxation (Hall et al. 2002; Sugden et al. 2009), and are subject to extractive activities for food, bait or ornamental purposes (Murray et al. 1999; Hall et al. 2002). Hence, the benefits provided by the Mediterranean intertidal area, and the associated economic assets, are relevant in the perspective of integrated coastal zone management and under the current climate change scenario. Rocky shores are biologically rich and diverse habitats (Benedetti-Cecchi et al. 2003; Ceccherelli et al. 2005; Schembri et al. 2005; Mangialajo et al. 2008a). Their diversity is multiplied from the local scale up to the basin-wide level by the interplay of biotic and abiotic factors such as interaction among species, exposure, microtopography, island or mainland location and latitude. The presence of ecosystem engineering species also plays a crucial role here, where their disappearance is typically associated with radical changes in the structure of the assemblages. The genus *Cystoseira*, for example,

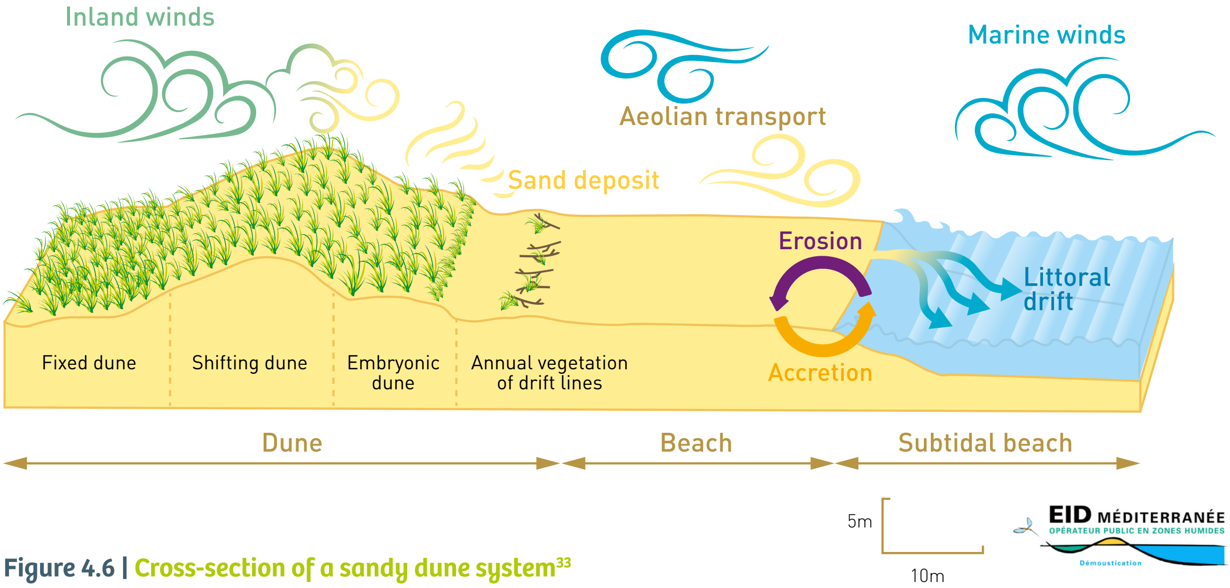

Figure 4.6 | Cross-section of a sandy dune system[33]

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[33] http://www.marinespecies.org/traits/wiki/File:Sand_dunes.JPG

includes low-shore canopy algae responsible for habitat formation for sessile invertebrates requiring high humidity and low light levels, such as sponges and tunicates (Benedetti-Cecchi et al. 2001; Ceccherelli et al. 2005; Mangialajo et al. 2008b). The loss of *Cystoseira* canopies results in disruptions to habitat complexity and species diversity patterns, and in the development of algal turfs associated with low-abundance invertebrate assemblages (Benedetti-Cecchi et al. 2001; Mangialajo et al. 2008b).

Mytilus galloprovincialis is an edible mussel, widespread in intertidal and shallow subtidal areas throughout the Mediterranean Sea, where it is also aquacultured. The loss or reduction of natural *M. galloprovincialis* populations (Sarà et al. 2011) and of another autochthonous element of bivalve fauna, *Mytilaster minimus* (Sarà and de Pirro 2011), has been shown to produce changes in the associated assemblages, enhanced when the contemporary reduction in canopy-forming algae occurs (Maggi et al. 2009). Although not an endangered species, its presence and abundance might be altered by the establishment of non-indigenous species like the mussel *Brachidontes pharaonis* (Sarà et al. 2008).

Mediterranean vermetid reefs are found where the temperature of surface coastal waters is no lower than 14°C (in winter) (Chemello and Silenzi 2011). A typical vermetid reef is the outcome of complex synergistic building activity by the vermetid mollusc *Dendropoma (Novastoa) petraeum* and the encrusting red algae *Neogoniolithon brassica-florida* (Chemello and Silenzi 2011). Other species, such as the red algae *Lithophyllum* spp., support the process of bioconstruction. Vermetid reefs develop in the lower mesolittoral and upper infralittoral, on rocky coasts only, and precipitate an aragonite shell (Silenzi et al. 2004; Sisma-Ventura et al. 2009). In addition to temperature and the type of substrate, the hydrodynamism of shallow water layers influences the distribution and size of these structures on a small scale, because vermetid platforms are rare along sheltered coasts (Chemello and Silenzi 2011). As for ocean acidification (Section 2.2.9), although *D. petraeum* were able to reproduce and brood at high levels of CO_2, recruitment success was found to be adversely affected (Milazzo et al. 2014).

Experimental work on the Mediterranean subtidal red alga *Peyssonnelia squamaria* shows that this species may benefit from ocean acidification, as its own nitrogen metabolism will be regulated (Yıldız 2018). Among the engineering species, although vermetids are resilient to near-future pCO_2 levels, it is likely that their reefs will not be able to withstand levels of acidification predicted for the end of this century, and the associated community will change as a result *(Section 2.2.9).*

Mediterranean subtidal rocky ecosystems have not been well studied. An initial current baseline and gradient of ecosystem structure was established for nearshore subtidal rocky reefs on a Mediterranean scale, at 8 to 12 m water depths (Sala et al. 2012). This baseline study showed remarkable variation in the structure of rocky reef ecosystems and suggested that the healthiest shallow rocky reef ecosystems in the Mediterranean have both large fish and algal biomass. Protection level and primary production were the only variables significantly correlated to community biomass structure. Fish biomass was significantly larger in well-enforced no-take marine reserves, but there were no significant differences between multi-use marine protected areas (which allow some fishing) and open access areas at the regional scale (Sala et al. 2012).

Overall, intertidal systems are poorly represented in the socio-economic literature, and there appears to be low awareness of their value among stakeholders. Subsequently, conservation efforts for intertidal communities are minimal.

Coastal wetlands

Mediterranean coastal wetlands include a wide variety of natural habitats such as river deltas, coastal lagoons and salt marshes, intertidal wetlands, and coastal aquifers. Global warming and direct anthropogenic impacts, such as water extraction (more on land and sea use changes and practices in *Sections 2.4* and *3.1.5.2*), largely affect water budgets in Mediterranean wetlands, thereby increasing wetland salinities and isolation, and decreasing water depths, water quality and hydroperiods (duration of the flooding period) (Mediterranean Wetlands Observatory 2018). These wetland features are key elements that structure waterbird communities for instance (Ramírez et al. 2018). However, the ultimate and net consequences of these dynamic conditions on key species assemblages are largely unknown, although recent work indicates that waterbird communities, for example, tend to adapt to climate conditions (Gaget et al. 2018).

Seagrass meadows

Seagrass meadows in the Mediterranean Sea cover 1.35 to 5 million hectares, between 5 and 17% of the worldwide seagrass habitat. The rate of loss of seagrass is above 1.2% each year and up to 5% in the Mediterranean (Marba and Duarte 2010). The Mediterranean Sea is home to four seagrass genera (*Cymodocea, Halophila, Posidonia* and *Zostera*) encompassing four indigenous species *(C. nodosa, P. oceanica, Z. marina* and *Z. noltii)* and one non-indigenous species *(H. stipulacea)* (Sghaier et al. 2011). The largest Mediterranean sublittoral area occupied by seagrasses is dominated by the endemic *P. oceanica* (neptune seagrass). It clonally reproduces in meadows and can spread up to 15 km while being hundreds to thousands of years old. In certain areas its populations are significantly declining due to a combination of human-induced factors (Vohník et al. 2016). *Posidonia oceanica* is the most threatened seagrass habitat: almost half of the surveyed sites in the Mediterranean have suffered net density losses of over 20% in 10 years. These *P. oceanica* losses are directly linked to human activities: eutrophication from nutrient pollution, alteration of coastal sediment balance and physical disturbances from trawling, anchoring of yachts, dredging, and other activities highlighted in *Sections 2.3* and *2.4.* Other non-human impacts include rising sea temperature *(Section 2.2.8)* and non-indigenous species *(Section 2.5)* (Claudet and Fraschetti 2010; Crooks et al. 2011).

The non-indigenous variety of *Caulerpa racemosa*, currently spreading in the Mediterranean Sea, was first discovered in the early 1990s near Tripoli Harbour in Libya (Nizamuddin 1991). It spreads rapidly, and is now found off the coasts of multiple countries around the Mediterranean Sea (Lebanon, Tunisia, Libya, Egypt, Cyprus, Turkey, Greece, Malta, Croatia, Italy, France and Spain), and has reached the Canary Islands in the Atlantic Ocean (Verlaque et al. 2004; Bitar et al. 2017). Recent work has shown that this non-indigenous variety is *C. racemosa* var. *cylindracea,* which was introduced from southwestern Australia (Verlaque et al. 2003). Long-range dispersal of the algae seems to be a result of human activities (e.g., dispersal by anchors, fishing). *C. racemosa* can inhabit a wide range of subtidal substrata (sand, mud, rocks, dead matte of seagrass, from 0 to 50 m depths), and has the potential to expand its range around the entire coastline of the Mediterranean Sea. *C. racemosa* modifies the density and diversity of benthic communities (Capiomont et al. 2005).

Early studies on spatial distribution and expansion of *H. stipulacea* had been focused on the northern Mediterranean - the spreading of *H. stipulacea* along the southern and southeastern Mediterranean coasts was only noticed later (Lipkin 1975; Bitar et al. 2000, 2017; Abboud-Abi Saab et al. 2003; Lakkis and Novel-Lakkis 2007; Verlaque et al. 2015).

Coastal lagoons and deltas

The small range of tides associated with low-speed currents has encouraged the establishment of lagoon or endogenic systems around much of the Mediterranean. Lagoons and deltas provide support for rich biodiversity, including vital habitats for bivalves, crustaceans, fish and birds. They provide a physical refuge from predation and are used as nursery and feeding areas for some endangered species (Franco et al. 2006; Le Pape et al. 2013; Escalas et al. 2015; Isnard et al. 2015). There are more than 100 coastal lagoons in the Mediterranean, holding an important ecological role, and also providing essential goods and services for humans (read how the effects of climate change on coastal ecosystems could affect livelihood, culture and human rights in *Section 5.3*). Over 621 macrophyte species and 199 fish species are present in Atlantic-Mediterranean lagoons (Pérez-Ruzafa et al. 2011).

Due to their location between land and open sea, coastal lagoons are subject to strong anthropogenic pressures in parallel with climate change. Habitat destruction, pollution, water withdrawal, overexploitation and non-indigenous species are the main causes of their degradation (Newton et al. 2018). These pressures are responsible for major ecosystem alterations such as eutrophication, bacterial contamination, algal blooms (toxic, harmful or not), anoxia and fish killings. Furthermore, additional problems arise from coastal erosion, subsidence and effects related to extreme meteorological events, typical for the Mediterranean (Aliaume et al. 2007).

In the Mediterranean, the largest coastal wetlands are found in delta areas like that of the Po (Italy), Nile (Egypt), Rhône (France) and Ebro (Spain) rivers *(Section 3.1.1.3).* Like most wetlands, deltas are diverse and ecologically important ecosystems (UNEP-MAP-RAC/SPA 2010). Deltas absorb runoff from both floods (from rivers) and storms (from lakes or the ocean). Deltas also filter water as it slowly makes its way through the delta's distributary network. This can reduce the impact of pollution flowing from upstream. Plants such as lilies and hibiscus grow in deltas, as well as herbs such as wort, which are used in traditional medicines. Many animals are indigenous to the shallow, shifting waters of a delta. Fish, crustaceans such as oysters, birds, insects are also part of a delta's ecosystem (UNEP-MAP-RAC/SPA 2010; Medi-

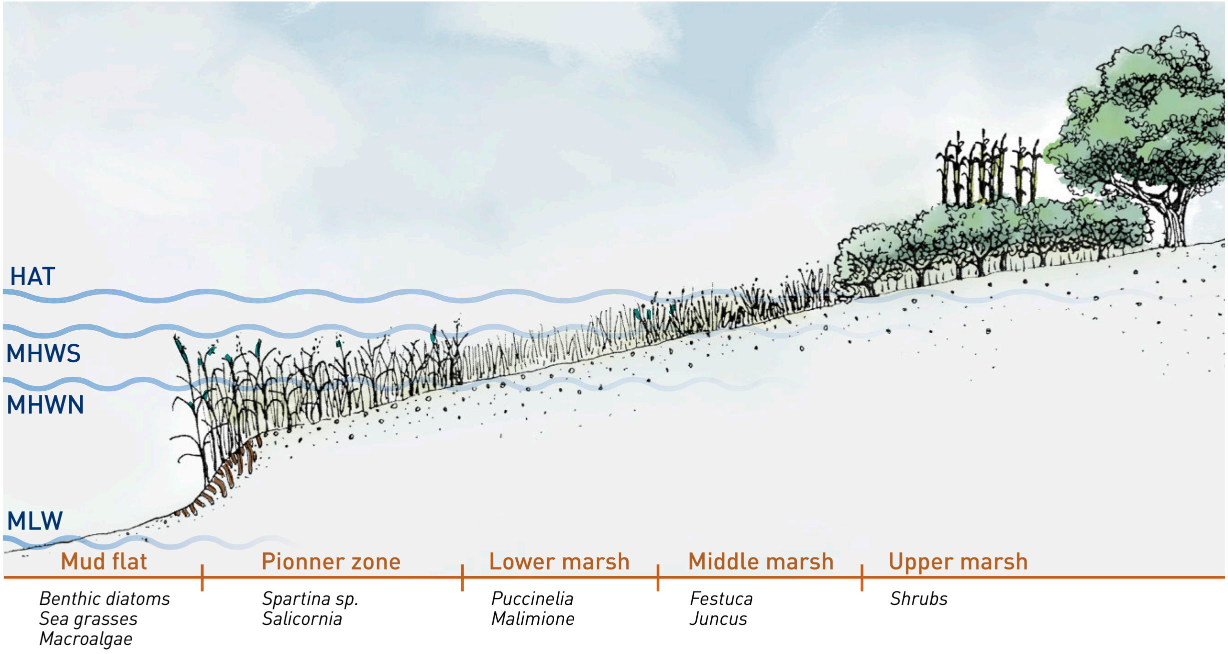

Figure 4.7 | Typical salt marsh zonation (modified from Bertness et al. 2002). Species along the tidal elevation gradient are adapted to the inundation frequency, including extreme flooding and storm events. MLW: Mean Low Water; MHWN: Mean High Water of Neap tides; MHWS: Mean High Water Spring tide; HAT: Highest Astronomical Tide.

terranean Wetlands Observatory 2012). In deltaic areas and low-lying coastal plains climate change, particularly sea-level rise, is already considered as an important issue (Nicholls and Hoozemans 1996), that significantly decreases the return periods of maximum water levels due to storm surges (*Section 2.2.8* and *Box 3.1.1*). This has been discussed by Sánchez-Arcilla et al. (2008) for the Ebro delta where other phenomena are affecting deltaic behavior such as increases in inundation/flooding, coastal erosion, salinity intrusion, and changes in wave climate (wave height, direction, and storminess).

Salt marshes

Salt marshes cover low-energy, intertidal shorelines worldwide and are among the most abundant and productive coastal ecosystems. Salt-marsh ecosystems provide a wide array of benefits to coastal populations, including shoreline protection, fishery support, water quality improvement, wildlife habitat provision, and carbon sequestration (Hansen and Reiss 2015). These are specialized habitats, characterized by high primary productivity and species diversity, which support a wide variety of native flora and fauna, and also constitute important areas for wintering aquatic birds (Simas et al. 2001). Salt marshes protect lowlands from marine flooding by damping storms and waves and by slowing flows pushing inland (Allen 2000).

In the Mediterranean Basin, coastal salt marshes *(Fig. 4.7)* include various Mediterranean plant communities of the classes *Juncetea maritimi* and *Salicornietea fruticosae* which are under the influence of saline seawater. The vegetation is dominated by perennial and shrubby halophytes growing on the extreme upper shores of low sedimentary coasts, sheltered from the mechanical action of waves. Their habitat is especially diverse in the Iberian Peninsula and in southern Italy (Sicily, Apulia, Calabria) (Molina et al. 2003; Cutini et al. 2010; Sciandrello and Tomaselli 2014). In these parts, the habitat forms a mosaic of tall rushes mixed with shrubby and other herbaceous species, often with succulent stems and/or leaves, forming halophytic shrublands and thickets. In soils with brackish water, beds of reed and other tall helophytes grow. The habitat further includes Mediterranean halo-psammophile meadows *(Plantaginion crassifoliae)*, humid halophilous moors with the shrubby stratum dominated by *Artemisia coerulescens*, halo-nitrophilous shrubby seablite thickets of *Suaeda vera* rarely inundated, shrub communities of *Limoniastrum* spp., and communities in the Dalmatian coastal region, in somewhat drier habitats with less salt, which are not directly affected by waves and tides. On intertidal muds, cord grasses *(Spartinion maritimae)* may grow, but these are relatively rare in the Mediterranean (Molina et al. 2003; Cutini et al. 2010; Sciandrello and Tomaselli

2014). Saltmarshes include a wide diversity not only of vegetation (Ayyad and El-Ghareeh 1982), but also of plankton, crustaceans and fish species. The zooplankton structure and dynamics in permanent and temporary Mediterranean salt marshes were investigated, and the results found that although temporary and permanent basins show no differences in the most abundant zooplankton species, they differ in their zooplankton diversity, temporal pattern and size structure (Brucet et al. 2005). The same study also found that the presence of a stable fish population in the permanent salt marshes may explain the high values of zooplankton diversity and the low densities of large zooplankton (Brucet et al. 2005).

In an assessment of the threat level of non-indigenous species on salt marshes of the southeastern Iberian Peninsula, the status of its habitats has been categorized as "particularly critical" as many of them were destroyed in the past, due to their transformation into cropland or by desiccation for fear of malaria (Al Hassan et al. 2016). In the Valencia region (Spain), the coastline supports virtually all farming, much of the region's industrial activity, and shelters large population centers. This, along with huge pressure from tourism (i.e., pressures related to water consumption, *Section 3.1.2.3*), have highly impacted salt marshes. These ecosystems house a specific flora of halophytes and their high specialization contributes to their vulnerability (Pétillon et al. 2005).

Coastal aquifers

In Mediterranean coastal systems, seawater intrusion is an important consequence of climate change and human action in coastal aquifers (Sherif and Singh 1999). Salinization alters the fundamental physicochemical nature of the soil-water environment, increasing ionic concentrations and altering chemical equilibria and mineral solubility (Herbert et al. 2015). Increased concentrations of solutes, especially sulfate, alter the biogeochemical cycling of major elements including carbon, nitrogen, phosphorus, sulfur, iron, and silica (Herbert et al. 2015), which has negative impacts on photosynthetic pigments and global biomass (Parihar et al. 2015). More about seawater intrusion in coastal aquifers can be found in *Section 3.1.2.2.* Three realistic scenarios (no change, sea rise of 0.5 m, land side lowered by 0.5 m by water pumping) were considered by Sherif and Singh (1999), who found that the Nile Delta aquifer is vulnerable to climate change and sea level rise. However, salinization tolerance can be found in some soil inhabitants like the spider *Arctosa fulvolineate* and the beetle *Merizodus soledadinus*, which survived salinity levels up to 70‰ (Pereira et al. 2019). Also, some littoral and terrestrial amphipod species can survive salinity levels up to 900 mOsm external concentration (Morritt 1988).

Risks from non-indigenous species

Phytoplankton

The Mediterranean Sea has experienced particularly strong algal bloom events over the past 50 years, mostly near the coast, in bays, lagoons, ports, beaches and estuaries, leading to deterioration in water quality, increasing the mortality of fish and risks to human health due to specific toxins that could be released into the marine environment and bio-accumulated through the marine trophic chain (Aligizaki 2009; Vlamis and Katikou 2015; Griffith and Gobler 2020). Climate-induced changes in water temperature, stratification and other physical properties appear to strongly impact the physiology and behavior of harmful algae bloom species, in terms of occurrence, physiology and toxin production *(Section 2.3.4)* in Mediterranean coastal areas where already more frequent Harmful Algal Blooms "HABs", and "novel" nuisance species have been recorded (Legrand and Casotti 2009).

The potential impact of climate-induced changes to phytoplankton, and especially HABs, has raised attention in the scientific communities and directed their research in this field, mainly driven by human health concerns due to the potency of some algal toxins that are transferred through the marine food web (Turki et al. 2006; Drira et al. 2008; Mabrouk et al. 2012; Estevez et al. 2019). In monitoring southern Mediterranean countries, more than 64 dinoflagellate species were identified with a remarkable increase in spring and summer (Feki et al. 2016). Dinoflagellate abundance between tidal periods was variable and the highest abundance was detected in the slack period in the Gulf of Gabès (southern coast of Tunisia), suffering from the pressure of high urbanization and industrialization rates, as well as rapidly increasing population growth rates. The dinoflagellates represent a major part of the eukaryotic primary production in marine ecosystems and the ability of several strains to cause shellfish poisoning and/or to form resting cysts has led to considerable attention being paid to the diversity and distribution of planktonic dinoflagellates in relation to environmental factors, hydrodynamism, nutrients and microalgae/biotoxins (Monti et al. 2007).

Ostreopsis (a dinoflagellate) blooms have become common in temperate areas as well, and regularly occur in the Mediterranean Sea in the summer and autumn (Vila et al. 2001; Selina et al. 2014). In these areas, *Ostreopsis* was well-known as its blooms were often associated with harmful effects on the health of both humans and benthic marine organisms (Vila et al. 2001; Aligizaki and Nikolaidis 2006). Additionally, *Ostreopsis* often appeared in association with other toxic or potentially toxic benthic dinoflagellates such as *Prorocentrum* spp., *Amphidinium* spp. and *Coolia monotis* in several Mediterranean areas (Monti et al. 2007; Mabrouk et al. 2012; Selina et al. 2014). The genus *Ostreopsis* includes several species producing various palytoxin-like compounds with harmful effects on humans and marine fauna (Scalco et al. 2012). Species of this genus are regular members of the epiphytic community in tropical seas but their geographic range has shown an apparent expansion towards temperate regions of the Mediterranean Sea.

Jellyfish

Cassiopea andromeda is a non-indigenous jellyfish species that possibly takes advantage of the warming tendency in the Mediterranean Sea. Recently detected in Malta, Sicily and other areas beyond the Eastern Mediterranean Sea, this benthic jellyfish seems to be well adapted to mesotrophic waters near harbors and closed bays in where water has low hydrodynamism (Yokeș et al. 2018). Due to the fact that many coastal areas all over the Mediterranean are no longer oligotrophic, the dispersion of this species may accelerate its path. The huge biomass reached in certain zones and its fast-growing features (Deidun 2018) may be a problem for fisheries, coastal tourism and management.

Other non-indigenous jellyfishes are also increasing their abundance in the warming Mediterranean Sea. The dreaded cubomedusa is typical of tropical seas, such as around the Australian Great Barrier Reef or the Philippines. Cubozoans, or "box jellyfish", are considered to be the cnidarian group's most dangerous, with an extremely painful sting that changes the lives of dozens of Australians every year. During the summer of 2008, a great abundance of a cubomedusa occurred along the Spanish coast, spotted off the beaches of Denia, Alicante, particularly *Carybdea marsupialis*, a small jellyfish species. It is rare in the Mediterranean Sea, so had never been considered to be a species that would form a major proliferation, yet during the summer of 2008 the Red Cross reported a high number of stinging incidents in this area due, no doubt, to this almost imperceptible, transparent and seemingly harmless jellyfish forming dense swarms in the breakers (Kingsford et al. 2018). It is possible that *C. marsupialis* appeared because of the changing conditions throughout the water column, but the information about its distribution or what factors influence its life cycle is still limited (Canepa et al. 2017). Sea warming seems to be one of the key factors explaining its acute proliferation, and is likely the reason of the already changing trophic interaction map of the Mediterranean Sea due, in part, to climate change. Water temperature, together with quantity and quality of available food resources, are known as major drivers of gonadal outputs (Harland et al. 1992; Ben-David-Zaslow and Benayahu 1999). In general, jellyfish sexual and asexual reproduction is known to be influenced by warming. Some studies have shown that elevated temperature by itself or in combination with high feeding frequency (due to raised zooplankton prey abundance) increased budding rate and bud size in Aurelia polyps populations worldwide (Hočvar et al. 2018).

Fish

The establishment of the lionfish (*Pterois* sp.) and the blowfish (*Lagocephalus* sp.) in Mediterranean waters can be envisaged as a paradigm of how climate change helps the dispersion of tropical species in a warm temperate sea *(Section 2.5.1).* The lionfish, for example, is a predator that has almost no controlling species (other fishes, sharks, etc.) and is a generalist, living in all shallow and mesophotic zones. The species has high reproductive and dispersal capacities, a massive production of well-protected eggs all year long and a fast spread and high larval survival rates (Betancur et al. 2011). In the Eastern Mediterranean Sea, these non-indigenous species have been introduced from the Red Sea, and have been documented in many areas (Bariche et al. 2013, 2017; Kletou et al. 2016). The blowfish *(Lagocephalus sceleratus)* is another example, with dispersion apparently faster in certain zones (Boustany et al. 2015; Kara et al. 2015). One of the first records indicate fast mobility from the original source (the Suez Canal) (Akyol et al. 2005; Kara et al. 2015), and since its first recorded sighting, it has been detected even in coastal waters in southern Italy (Azzurro et al. 2014). All the non-indigenous vagile fauna would have a very restricted dispersion if the water column temperature conditions were stable, with a clear marked low temperature during the autumn and winter, but changing conditions may be favoring its definitive establishment in Mediterranean waters (Bianchi and Morri 2003). The rapid spread of some of these species will be a serious problem for fisheries and trophic relationships in coastal areas, causing the likely local extinction of some species that may be preys of these generalist fish species (Coro et al. 2018).

Plants

Among numerous threats, the pressure of non-indigenous plants has strong effects in these fragmented and linear ecosystems. *Dittrichia viscosa* is a perennial, 40-130 cm high plant, very common in the western Mediterranean but also found in its eastern part (Al Hassan et al. 2016). The species shows a remarkable pioneering character, and in recent decades largely expanded its range in Mediterranean countries, possibly due to increased human disturbances (Wacquant 1990; Mateo et al. 2013). Its capability to colonize new habitats and threaten biodiversity has been well-documented (Wacquant 1990) and related to characteristics such as its phenotypic plasticity (Wacquant and Bouab 1983), high stress tolerance (Curadi et al. 2005) and resistance to chemical pollution (Murciego et al. 2007; Fernández et al. 2013), as well as to its allelopathic effects (Omezzine et al. 2011). In the last 50 years, *D. viscosa* has become an invader in the NW Mediterranean region, since it increased its ecological range under disturbance pressure and is colonizing new habitats (Wacquant 1990; Boonne et al. 1992; Wacquant and Picard 1992; Mateo et al. 2013). The species' recent expansion in the Iberian Peninsula has also been correlated to temperature increases due to accelerated global warming (Vesperinas et al. 2001). Although *D. viscosa* cannot directly compete with true halophytes in highly saline environments, it is nevertheless quite stress tolerant and therefore presents a threat to the vegetation located on salt marsh borders, where several endemic and threatened species are found in the area of study conducted by Al Hassan et al. (2016).

Other non-indigenous species

Some non-indigenous eco-engineering species are also favored by sea warming in the Mediterranean Sea *(Section 2.5)*. Sea forests are living three-dimensional structures, similar to terrestrial forests but basically comprised of seaweeds, seagrasses, sponges, cnidarians, bryozoans, ascidians and other sessile organisms in the ocean benthos (Rossi et al. 2017a). These forests are dominated by ecosystem engineering species, organisms which directly or indirectly modulate the availability of resources to other species, causing changes to the physical condition of biotic or abiotic materials (Jones et al. 1994). In the case of the non-indigenous species, we can highlight two different case studies of non-indigenous eco-engineering species that may be already changing the benthic seascape in many areas of the Mediterranean Sea due to the suitable conditions for their expansion. The first case is represented by the seaweed *Caulerpa cylindracea.* This chlorophyte has been identified as one of the most successful bioinvaders (Montefalcone et al. 2015). This species has been much more successful with respect to *Caulerpa taxifolia,* the so-called killer algae. In several areas, it is replacing other algae, phanerogams and sessile animals creating a new seascape in which the biodiversity and biomass are rapidly changing (Alomar et al. 2016).

A different case study is that of myxotrophic scleractinians that are more present toward the northern and western Mediterranean Sea. *Oculina patagonica* has been recorded in many Mediterranean areas but was not present in northern Spanish coastal areas until recently (Leydet et al. 2018). This species seems to be rapidly adapting to new temperature trends, a factor that drives new populations to quickly move north. Originating from the south, this species is now an invader that proliferates, replacing other native species in shallow waters, where sea urchin barrens may be essential to understand their capability to cope with new spaces (Coma et al. 2011). The presence of this species in northern areas seems to be correlated with sea warming, but has clear photobiological limits due to temperature factors that have to be considered (Rodolfo-Metalpa et al. 2014).

4.2.1.2 Past changes

Although human activity is considered as a major driving force affecting the distribution and dynamics of Mediterranean ecosystems, the full consequences of projected climate variability and relative sea-level changes on fragile coastal ecosystems for the next century are still unknown. It is unclear how these waterfront ecosystems, as well as the services they provide, can be sustained, when relative sea-level rise and global warming are expected to exert even greater pressures in the near future (drought, habitat degradation and accelerated shoreline retreat) (Kaniewski et al. 2014). The most suitable archives for such paleoreconstructions are located in coastal wetlands that are highly vulnerable to global warming and the rapid rise in sea level, as they are highly exposed to processes such as flooding, subsidence, sediment scarcity and coastline erosion (Anthony et al. 2014; Wong et al. 2014) *(Chapter 2).*

Response of coastal ecosystems to past changes in sea level

During the Holocene period, sea level worldwide exhibited significant fluctuations, mostly responding to the advance and retreat of the continental ice sheets (Lambeck et al. 2010). In the Mediterranean, regional sea level has risen continuously for the whole Holocene with a sudden slowdown at ~7.5 ka BP and a further deceleration during the last ~4.0 ka BP, after which time observed regional sea-level changes have mainly related to variability in isostatic adjustment (Galili et al. 2005; Vacchi et al. 2016). This mid-Holocene sea level stabilization had a major influence on fluvial sedimentation in coastal regions, and the formation of many coastal wetlands such as flood plains, coastal lagoons and deltas can be traced back to this period (Pavlopoulos et al. 2006; Fouache et al. 2008; Carmona et al. 2016). Although the stabilization of sea level and availability of sediment are important variables in this process, the palaeogeography of the lagoon environment and specific fluvial and marine sedimentary dynamics are also important variables in each case study (Huntley 2001).

Coastal wetland-based archives have an exceptional scientific potential to observe past ecosystem changes and identify key thresholds for particular ecosystems facing sea-level rise. In northeastern Spain, a reconstruction of past ecosystems was presented for the Castelló lagoon using ostracods, diatoms, and pollen and non-pollen palynomorphs as bio-indicators of marine vs freshwater influences (Ejarque et al. 2016). This study pointed out the strong link between the lagoon ecosystem, changing sea-level and the historical anthropogenic pressure. From the late Neolithic to the medieval period, dynamics of the lagoon ecosystem were mainly driven by changing marine influence. From ~1,550 and ~150 cal BC maximum marine flooding hampered agropastoral activities. After the Medieval period, societies actively controlled lagoon dynamics and became a major agent of landscape transformation. The removal of littoral woodlands after the 8th century was followed by the expansion of agrarian and industrial activities. The expansion of the milling industry and of agricultural lands led to the channelization of the river Muga into the lagoon after ~1,250 cal AD, which caused its transformation into a freshwater lake ecosystem (Ejarque et al. 2016).

In the Corsican back-barrier wetlands, a study of the fossil Coleoptera in two sediment cores supplemented by pollen and geochemical data show that 60% of past wetland beetle fauna at the Grecu pond became locally extinct because of the increase in salinity caused by marine intrusions (Poher et al. 2018). Most of this diversity loss occurred 3,700 years ago, when relative sea-level reported in the region rose. Regarding the Cannuta marsh, results of the same study show evolution from a brackish lagoon to a freshwater environment marked by diversification of wetland beetle fauna 1,000 years ago, which is possibly due to relative sea-level stability and floodplain progradation (Poher et al. 2018).

In the Eastern Mediterranean, the rapid response of the Alikes Lagoon of Zakynthos Island ecosystem has been attributed from 8,540 and 3,400 BP to climate-related events such as storms or tsunamis where marine characteristics dominate (Avramidis et al. 2013). Furthermore, the study of Kaniewski et al. (2014) shows that Haifa Bay underwent a landward sea invasion, with a maximum sea penetration 4,000 years ago. The main consequences of the sea invasion were a retreat of the coastal forest, a loss of resilience and disappearance of the initial local biogeographic zonation. The forest replacement by a thorny shrub-steppe and then by an open-steppe appeared to follow, rather than cause, failure of tree regeneration. Due to the intrusion of the saline water table in freshwater streams, the freshwater wetland associated with the Na'aman River was deeply impacted after 4,000 cal. years, with a fall in hygrophilous-hydrophilous herbs. The subsequent coastal progradation that started at 3,400-3,300 cal yr BP left an eroded sandy-salty area, colonized by a steppe vegetation that became dominant until the end of the shoreline retreat (2,900 cal yr BP). A similar process was observed in the Salt Lake of Larnaca, Cyprus, where a shift from sheltered marine to lagoon environments produced an ecological change with a strong increase in xerophytic vegetation-types colonizing the shores that were no longer washed by seawater (Kaniewski et al. 2013b). The 3.2 K yr BP drought event (Schilman et al. 2001a; Kaniewski et al. 2013a) caused a dramatic demise in wooded ecosystems unrecovered until after 2,850 cal yr BP. Due to human-induced modification during the last ~200 years, it retreated by 15 m (Zviely et al. 2009). This new phase of sea-level invasion is well attested by high values of steppe vegetation and a renewed drop in hygrophilous-hydrophilous herbs. This suggests that similar stresses generate analogous biological processes, whatever the period under consideration.

Mediterranean coastal ecosystems, including fauna and flora components, are very sensitive to sea-level changes. The mid- to late Holocene changes in sea-level caused strong biological stresses and major ecological alterations providing a foreshadowing of potential future diversity and community changes along Mediterranean coastal wetland ecosystems and a model to understand the consequences of sea-level rise for the next century (Marcos and Tsimplis 2008). This retrospective approach encompassing historical anthropogenic pressure also clearly indicates that for efficient management of coastal habitats, anthropogenic pressures linked to urban development *(Section 5.1.1.3)* must be reduced in order to mitigate the predicted effects of global change.

Response of coastal ecosystems to past climate variability

In addition to eustatic sea level curves and coastal geomorphological dynamics, recent research has revealed that the climate variability of the Holocene impacted the Mediterranean coastal ecosystems particularly through storms and floods (Carmona et al. 2016). Storm surges, leading to catastrophic coastal flooding, are amongst the most feared natural hazards due to the high population densities and economic importance of coastal areas. Strong evidence has been provided for enhanced periods of storms that caused coastal flooding over the last 4,500 years as a result of solar activity, acting on cycles of around 2,200-yr and 230-yr (Kaniewski et al. 2016). These storm surges were characterized by inland intrusion of ostracods and dinoflagellate cysts, while the intrusion of saline water into the freshwater-fed plains greatly affected terrestrial ecosystems leading to land fragmentation by salt encroachment (Kaniewski et al. 2016). An important part of paleoenvironmental Holocene research has focused on identifying phases of high frequency and magnitude of floods related to climate variability (Thorndycraft and Benito 2006; Benito et al. 2008, 2015). In the Western Mediterranean region, periods with more frequent heavy-rain flooding events coincide with transitions to cooler and wetter climates, while flood frequency in northern Africa is linked to drier climate and in the eastern Mediterranean, to wetter conditions (Benito et al. 2015). Some studies hypothesized that these have been driven by internal modes of atmospheric and oceanic changes such as the East Atlantic pattern, the NAO, and thermohaline circulation (Degeai et al. 2017). However, the effect of these flood episodes on coastal ecosystems is much less documented and needs to be further addressed in high time-resolution studies.

Based on these findings, short-term climate events, which are driven by high frequency external and internal forcing factors, are superimposed on anthropogenic-driven factors. This complex interaction may either accentuate or attenuate the effect of current and future global warming. For instance, climate models are predicting a decrease in Mediterranean storms in the second half of the 21st century while the study by Kaniewski et al. (2016) suggests that a decrease in solar activity will increase and intensify the risk of frequent flooding in coastal areas.

4.2.2 Projected vulnerabilities and risks

4.2.2.1 Projections and risks based on biological groups

Phytoplankton

Climate change consequences, particularly increasing temperatures *(Section 2.2.4)*, decreasing nutrient replenishment *(Section 2.3)*, and ocean acidification *(Section 2.2.9)*, are expected to cause changes in plankton communities at different levels, from phenology and biomass to community structure. For example, a shift in phytoplankton community, dominance of smaller species (picophytoplankton and nanoflagellates) and a decrease in diatoms, with an expected decrease in the biomass of calcifying organisms such as coccolithophorids are some of the expected outcomes (Dias et al. 2010; The MerMex Group et al. 2011). There are still many uncertainties when it comes to the impact of sea warming and acidification on primary production in the Mediterranean, but it is clear that physico-chemical changes will affect the magnitude, timing and composition of phytoplankton blooms, with associated changes in the seasonal distribution of zooplankton (Moullec et al.) *(Section 4.1.2)*. Ocean acidification combined with warming and deoxygenation, has been shown to cause negative effects on marine animals and to stimulate the production of primary producers, particularly in coastal waters that do not experience stratification or nutrient limitation (Gao et al. 2020). The associated decreased predatory pressure has the potential to further increase primary production. The increased primary production will stimulate the respiration of bacteria and thus intensify the hypoxia and low pH zone (Gao et al. 2020).

To understand how climate variation controls phyto-and zooplankton dynamics and possibly affects artisanal and small-scale fisheries exploiting areas near the coast, Goffart et al. (2017) used a unique long-term (1979-2014) time series obtained from a Mediterranean coastal area unbiased by local anthropogenic pressure in the Bay of Calvi, Corsica. They identified threshold values of physical variables below and above which they strongly impact nutrient availability, phyto- and zooplankton bloom characteristics and seasonality succession of plankton functional groups, stressing the importance of winter conditions in determining the state of Mediterranean pelagic

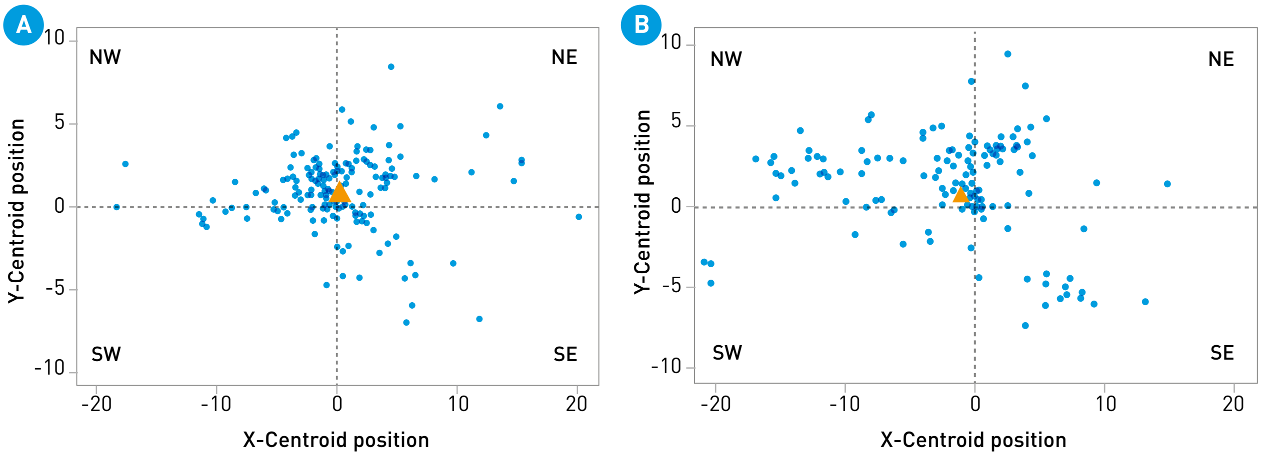

Figure 4.8 | Expected geographical species shifts for the 288 coastal Mediterranean fish species for both periods (a: 2040–2059; b: 2080–2099). Shifts were calculated from geographic range centroids and are expressed in degrees (NW: North West, NE: North East, SE: South East, SW: South West). Triangles represent the overall displacement of the fish assemblage calculated as the average centroid geographical shift (Albouy et al. 2012).

ecosystems, and highlighting that the thresholds obtained from their long-term time series provide key information for improving model scenarios of the impact of climate change on Mediterranean ecosystems.

The functional traits and geographic distribution of 106 copepod species were used to estimate the zooplankton functional diversity of Mediterranean surface assemblages for the 1965–1994 and 2069–2098 periods (Benedetti et al. 2018). Multiple environmental niche models were trained at the global scale to project species habitat suitability in the Mediterranean Sea and assess their sensitivity to climate change predicted by several scenarios. A relatively low decrease in species richness is predicted for 97% of the Mediterranean Basin, with higher losses in the eastern regions (Benedetti et al. 2018). The results of the same study show that climate change is not expected to alter copepod functional traits distribution in the Mediterranean Sea, as the most and the least sensitive species are functionally redundant. Such redundancy should buffer the loss of ecosystem functions in Mediterranean zooplankton assemblages induced by climate change. Since the most negatively impacted species are affiliated with temperate regimes and share Atlantic biogeographic origins, the results of Benedetti et al. (2018) are in line with the hypothesis of increasingly more tropical Mediterranean communities (*Section 2.6.2.3).*

Fish

In the Mediterranean Sea, a reduction in primary production linked to an increase in sea surface temperature (see previous sub-sections in this chapter and *Section 3.2.2.2*) could have negative impacts on fisheries catch and could exacerbate current trends of overfishing. Projected changes in primary and secondary productions suggest that trophic mismatches between fish pre-recruits and their prey could increase in the future, with negative consequences for recruitment success, sustainable fisheries and conservation of biodiversity (Lejeusne et al. 2010; Stergiou et al. 2016). Also, jellyfish outbreaks (e.g., *P. noctiluca*) may become more frequent in the Mediterranean Basin (see previous sub-sections) and may extend over a longer period of the year than previously, causing alteration of the pelagic food web and thereby reducing fishery production (Licandro et al. 2010).

Using Bioclimatic Envelope Models (BEMs), the potential future climatic niches of 288 coastal Mediterranean fish species were projected based on a global warming scenario, then the species-level projections were geographically aggregated to analyze the projected changes in species richness and composition (Albouy et al. 2012). The results show that projected changes in assemblage composition are caused by different processes (species replacement vs. nestedness) in several areas of the Mediterranean Sea, and that the coastal fish fauna in several regions of the Mediterranean Sea could experience a "cul-de-sac" effect if exposed to climate warming (Albouy et al. 2012) *(Section 4.1.2.2.).*

Fish species ranges are expected to move northwards and eastwards, and most of the Gulf of Lion as well as the Adriatic and Aegean sub-basins are projected to experience a net decrease in species richness resulting from a loss of thermal niches for numerous fish that are not balanced by the arrival of other species from the south by the end of the 21st century *(Fig. 4.8).* In a best-case scenario, remaining or arriving species in local assemblages after global change impact would share combinations of functional traits with lost species, thereby maintaining ecosystem functioning, while in the worst-case scenario, lost species would have functional traits distinct from those of remaining or arriving species, hence the functions they support would go extinct and would imperil ecosystem functioning. Overall, the joint exploration of changes in species richness and composition coupled with the distinction between species replacement and nestedness bears important information for understanding the nature of climate change impacts on biodiversity (Albouy et al. 2012).

Lionfish (*Pterois* sp.) and blowfish (*Lagocephalus* sp.) in Mediterranean waters reflect how climate change helps the dispersion of tropical species in a warm temperate sea *(Section 4.2.1.1).* The question is when these species will migrate to the Western Mediterranean Sea. Johnston and Purkis (2014) argue that this is unlikely to happen. The connectivity between different areas is not the same as in the Caribbean for example, and the shifts in temperature need to be much more dramatic to make this invasion possible during the coming decades. However, the generalist behavior of this species may be one of the essential points to understanding its future success if a shift of 1 to 1.5 °C occurs in surface waters in some areas. This alien species from warm tropical waters may present a problem for other species because of the sea warming tendency *(Section 2.2.8).* It is not only a problem of the alien species per se, but a problem of shift from warm temperate to tropical trophic chain structures. The rapid spread of some of these species will be a serious problem for fisheries and trophic relationships in coastal areas, as the local extinction of some species that may be preys of these generalist fishes is very likely (Coro et al. 2018).

All the above-mentioned projections highlight the pressures that could increase the risk to fish and their habitats, namely for commercially valuable euryhaline coastal fish species (i.e., sole, seabass, seabream, mullet, eel) in coastal nursery sites such as lagoons, estuaries, and deltas. These pressures vary from rising temperatures that could exacerbate the occurrence of HABs (i.e., ciguatoxins, produced by dinoflagellates) and thus the distribution of biotoxins and pathogens (i.e., *Vibrio* bacteria) (Lloret et al. 2016), to the depletion of oxygen that may cause suffocation, which kills fish, to plastic pollution (Barange et al. 2018). A likely decrease in connectivity between neighboring ecosystems within the Mediterranean is expected because of a decrease in the size of spawning areas and an increase in larval retention on smaller areas of the continental shelf (Barange et al. 2018). In addition to warming and ocean acidification, changes to fisheries' structures will contribute to the disappearance and modification of fragile and long-lived species that create biogenic structures or seagrass meadows, which provide important ecosystem services as well (Jordà et al. 2012).

Seaweed

Other non-indigenous species are also favored by sea warming in the Mediterranean Sea. For the non-indigenous seaweed *Caulerpa cylindracea (Section 4.2.1.1),* the effects on the quality and quantity of available seston may be positive, also changing biogeochemical cycles and benthic-pelagic coupling relationships (Rizzo et al. 2017). Warming and acidification may be a perfect match for these fleshy algae (Comeau and Cornwall 2017), promoting its proliferation, in part, by the resistance to sedimentation processes, increased in many areas due to direct human impact (Alomar et al. 2016). Several algae species' dispersal may be thus enhanced not only by direct climate change effects but also by direct human impacts in coastal areas.

Corals

As for myxotrophic scleractinians, such as *Oculina patagonica,* projected global warming is likely to cause a gradual contraction in their distribution zones, where temperatures are too high due to their temperature constraints (Rodolfo-Metalpa et al. 2014). Higher transparency of water and rising temperatures in surface waters may also be the key to understanding its successful proliferation. Myxotrophy needs a photosynthetic component that is not present in Mediterranean waters as it is in tropical waters: light (water transparency) and temperature, combined, are the key to understanding high photosynthetic performance (Schubert et al. 2017). Some of these species from tropical or subtropical waters, may be favored by the new conditions of the water column in the Mediterranean Sea, but not all of them. It is possible that Indo-Pacific species (Lessepsian species), adapted to higher temperatures, have more potential of spreading over Mediterranean shallow areas over the coming decades.

The reproductive features and the larval release strategy of octocorals species make them highly sensitive to global climate change (especially in shallow areas, above 40 m depths). Recent models highlight that water stratification in the Mediterranean Sea may last for longer periods and warmer waters may stress non-mobile organisms (Galli et al. 2017). Whether the food availability for benthic suspension feeders would be affected by elevated temperatures is not clear, but it has been shown that under anomalous warming episodes in shallow water adults of *P. clavate, E. singularis* and *C. rubrum* suffer from partial or total tissue loss (Garrabou et al. 2001; Linares et al. 2005, 2008; Rossi and Tsounis 2007). Also, the new recruit mortality in shallow populations is very high when compared to deeper populations (Bramanti et al. 2005; Linares et al. 2008; Coma et al. 2009). Furthermore, mother care (i.e., the energy invested by mother gorgonian colonies to the offspring) will be crucial to understanding the potential survival in a warmer and less productive ocean (Viladrich et al. 2016, 2017). Within the context of global change, there is a risk that the period of trophic crisis might be significantly prolonged to the point that the capacity of energy reserves in lecitotrophic larvae would not last until the arrival of favorable feeding conditions in early autumn. This situation could be even worse if the spawning of these species is triggered earlier by the increase in temperature. Asexual reproduction may enable some individuals to survive catastrophic mortality events such as warming episodes and then expand following the disturbance (Lasker and Coffroth 1999). However, chronic stress that reduces recruitment will have less obvious effects on these clonal taxa and may be the key to understanding future composition of benthic communities. Climate change could lead to partial recruitment failure in the affected species, with major changes in the population structure and dynamics, and a drastic change in ecosystem functioning. These combined factors may be crucial to understanding how seascapes will change in shallow Mediterranean benthic communities.

Non-indigenous species in the Mediterranean Sea may be invasive or simply immigrant species *(Section 2.5)*. The new suitable conditions are key to understanding the transition observed in coastal and offshore areas. Higher temperatures that may be bad for native species (adapted to clear seasonal trends and certain limits of temperature and light), may be positive for the incoming species that are stressed by the same rising temperature phenomenon in their native areas.

4.2.2.2 Projections and risks based on key natural habitats

Sandy beaches/dunes

The impacts from reshaped coastlines as a result of sea level rise and changes in wave climate were assessed via regional climate models, indicating that beaches of the Balearic Islands (western Mediterranean) would suffer a coastal retreat of 7 to 50 m, equivalent to half of the present-day aerial beach surface, under the RCP4.5 and RCP8.5 climate scenarios (Enríquez et al. 2017). Also, beach erosion due to sea level rise in the Aegean archipelago (eastern Mediterranean) was evaluated: under a mean sea level rise of 0.5 m (RCP4.5), a storm-induced sea level rise of 0.6 m is projected to result in complete erosion of 31 to 88% of all beaches (29 to 87% of beaches are currently fronting coastal infrastructure and assets), at least temporarily (Monioudi et al. 2017). The projections of the same study suggest a very considerable risk, which will require significant effort, financial resources and policies/regulation in order to protect/maintain the critical economic resources of the Aegean archipelago (Monioudi et al. 2017). Biodiversity loss will be the outcome of the negative pressures driven by climate change consequences, which would hamper beach ecosystem resilience (Scapini et al. 2019). The specificity of sandy beaches as narrow ecotones between sea and land may be lost under climate change pressure, adversely affecting fine-tuned macrofaunal adaptations and therefore ecosystem functioning (Scapini et al. 2019). In comparing two coastal plant communities, one in Montenegro and another in Albania, it is demonstrated that the less disturbed beach had zonation very similar to potential vegetation, while plant communities of the touristic beach were fragmented or even substituted by replacement communities (Šilc et al. 2016).

The way habitat distribution will be altered under the effects of two climate change scenarios were analyzed, and the efficiency of the current Italian network of protected areas in the future after distribution shifts was evaluated in Prisco et al. (2013). According to this latter study the range of habitats is currently sufficiently covered by protected areas, achieving the conservation target. However, according to their predictions, protection levels for mobile and fixed dune habitats is predicted to drop drastically under climate change (Prisco et al. 2013).

After combining a digital terrain model with 5 years of nest survey data describing location and clutch depth, Varela et al. (2019) identified (a) regions with the highest nest densities for the loggerhead *(Caretta caretta)* and green turtle *(Chelonia mydas),* (b) nest elevation by species and beach, and (c) the estimated proportion of nests inundated under each sea-level rise scenario. On average, green turtles nested at higher elevations than loggerheads. However, because green turtles dig deeper nests than loggerheads, these were at similar risk of inundation. For a sea-level rise of 1.2 m, a loss of 67.3% for loggerhead turtle nests and 59.1% for green turtle nests were estimated (Varela et al. 2019). Existing natural and artificial barriers may affect the ability of these nesting habitats to remain suitable for nesting through beach migration.

Rocky shores

The prolonged desiccation events on the southeastern rocky shores of the Mediterranean were characterized, and their potential ecological impacts on the unique intertidal Mediterranean Sea ecosystem of vermetid reefs were examined (from 2012 to 2014) by Zamir et al. (2018). This study shows that desiccation stress has already increased on southeastern Mediterranean vermetid reef ecological communities, and if this trend continues, further increases in aerial exposure and desiccation stress could be expected, which could have long-term impacts on this fragile ecosystem (Zamir et al. 2018). For the vermitid *Dendropoma petraeum,* long-term exposure to acidified conditions predicted for the year 2100 and beyond caused shell dissolution and a significant increase in shell Mg content. Unless CO_2 emissions are reduced and conservation measures taken, these reefs are in danger of extinction within this century (Zamir et al. 2018), with significant ecological and socio-economic ramifications for coastal systems (Milazzo et al. 2014).

The narrow range of the intertidal in the Mediterranean has particular implications for its resilience to climate change and sea level rise. For example, in the Mediterranean, the potential harsh effects of tidal aerial exposure on the ecological responses of intertidal organisms is, in fact, usually buffered by wave splashing (Sarà et al. 2011). This might help limit the otherwise detrimental impacts of increasing aerial temperature and dryness on organisms. However, the limited amplitude of the Mediterranean intertidal area implies a very small optimal range of environmental features. As such, some species may be able to adapt and migrate as sea levels rise, but others will not. This knowledge is not definitive as historical exploitation of the Mediterranean Sea and the absence of rigorous baselines makes it difficult to evaluate the current health of these ecosystems and the efficacy of conservation actions at the ecosystem level (Sala et al. 2012).

Coastal wetlands

The extent of wetland salinization and thus its effect on Mediterranean wetlands are still poorly known. Typically, increased salt and sulfide concentrations induce physiological stress in wetland biota and ultimately can result in significant shifts in wetland communities and their associated ecosystem functions (Herbert et al. 2015). In a large-scale outdoor mesocosm experiment, the effects of salinity on successional patterns, diversity, and relative abundance of Camargue (southern France) temporary pool crustaceans were studied (Waterkeyn et al. 2010). Salinity significantly altered crustacean communities hatching from the resting egg bank through a number of direct and indirect effects. Salinity had a significant negative effect on the establishment of large branchiopods and copepods. Both the diversity and density of cladocerans, especially chydorids, were positively related to salinity, possibly due to the absence of biotic interactions with large branchiopods at the highest salinity values (Waterkeyn et al. 2010). In the same study, the authors hypothesize that the salinity-mediated presence of the large branchiopod keystone group can shift the whole wetland regime from a zooplankton-rich clear-water state to a zooplankton-poor turbid state. Crustacean succession was significantly altered by salinity, by slowed development rates, population growth or maturation rates of some species. This suggests that in addition to salinity changes, any alteration of wetland hydroperiod (e.g., through aridification or poor water management) could have a synergistic effect on community structure and the diversity of invertebrate communities, including some keystone species.

Based on Multi-Criteria Decision Analysis techniques, it is documented that wetlands and terrestrial ecosystems have the highest relative risk scores in the Tunisian coastal zone of the Gulf of Gabes (Rizzi et al. 2016). A combination was made for regular sampling of waterbird presence through one annual cycle with in-situ data on relevant environmental predictors of waterbird distribution to model habitat selection for 69 species in a typical Mediterranean wetland network in southwestern Spain (Ramírez et al. 2018). Species associations with environmental features were subsequently used to predict changes in habitat suitability for each species under three climate change scenarios (encompassing changes in environmental predictors that ranged from 10% to 50% change as predicted by regional climate models). Waterbirds distributed themselves unevenly throughout environmental gradients and water salinity was the most important gradient structuring the distribution of the community. Environmental suitability for the guilds of diving birds and vegetation gleaners will decline in future climate scenarios, while many small wading birds will benefit from changing conditions. Resident species and those that breed in this wetland network will also be more negatively impacted than those using this area for wintering or stopover (Ramírez et al. 2018).

Seagrass meadows

Considering the rapid loss of seagrass habitat in the Mediterranean Basin and its capacity to capture carbon, preventing seagrass degradation by developing blue carbon projects is a major opportunity for financing seagrass protection. The avoided degradation of *Posidonia oceanica,* for instance, could provide an extra source of CO_2 capture of 4 tons per hectare per year (Sifleet et al. 2011). More importantly, avoiding their destruction would also prevent the washing away of carbon stored in the sediments under the seagrass beds and thus avoid the release of more than 500 tons of CO_2 per hectare, stored over millennia (Chefaoui et al. 2018).Temperate seagrass ecosystems as the thermal regime of the Mediterranean Sea, are sensitive to ocean warming and will exceed the upper thermal limit of the endemic *P. oceanica* in some areas (Marba and Duarte 2010; Jordà et al. 2012).

Using *Cymodocea nodosa* as a model species, Ontoria et al. (2019) assessed the joint effects of warming (at 20°C, 30°C and 35°C) with two potential outcomes of eutrophication. They found that in addition to the possibility of the persistence of *C. nodosa* being directly jeopardized by temperature increase, the joint effects of warming and eutrophication may further curtail its survival (see projected impacts on seagrasses in *Section 4.1.2.1,* whereas the drivers "Eutrophication" and "Warming" are detailed in *Sections 2.2.7* and *2.3.2*).

Coastal lagoons

Coastal lagoons are sentinel systems that are highly vulnerable to potential impacts associated with climate change, particularly, as these systems have a key role in regulating the fluxes of water, nutrients and organisms between land, rivers and the ocean (Newton et al. 2018).

The effects of seawater acidification were assessed on a number of biological responses for one mussel and two clam species, including growth and calcification, at two locations, namely a coastal lagoon in southern Portugal and in the Northern Adriatic Sea (Range et al. 2014). In this study, the CO_2 perturbation experiments produce contrasting responses depending on the species and location. Whereas the effects of acidification on growth and calcification in water of the Adriatic Sea were significant, in the coastal lagoon, these effects were much less evident, probably buffered by a high carbonate content in the water (Range et al. 2014). The same study reveals major variations in macroinvertebrate response to the imposed changes (in temperature and pH, respectively), underpinning the need for species-specific and location-specific adaptation measures. A reflection on threats to integrated management of the Thau coastal lagoon (France) due to climate change and the multi-scalar water scarcity adaptation strategy underlines that although water uses are currently secured thanks to the regional transfer of water, they are not coherent with local water management and create new vulnerabilities in the context of climate change (La Jeunesse et al. 2016). Climate change scenarios predict intensified terrestrial storm runoff, providing coastal ecosystems with large nutrient pulses and increased turbidity, with unknown consequences for the phytoplankton community. In the same lagoon (Thau), a 12-day mesocosm experiment shows that pulsed terrestrial runoff can cause rapid, low quality (high carbon: nutrient) diatom blooms (Deininger et al. 2016). However, bloom duration may be short and reduced in magnitude by fish. Thus, climate change may shift shallow coastal ecosystems towards famine or feast dynamics.

Covering most of the bottom of the Mar Menor lagoon (southeastern Spain), *Caulerpa prolifera* has probably increased the resistance of the lagoon to eutrophication processes through the high uptake of nutrients from the water column and their retention in the sediments, avoiding high phytoplankton densities (Lloret et al. 2008). Nevertheless, if climate change predictions prove true, the current status of the lagoon is likely to collapse, since future environmental conditions could make *C. prolifera* unable to reach values of net photosynthesis greater than zero, and eutrophication processes are expected to appear (Lloret et al. 2008).

Deltas

A comprehensive overview of the status and sustainability of the Ebro, Rhône, and Po Deltas and Venice Lagoon has been published by Day et al. (2019), showing that all of these systems have been strongly modified by human activities. However, each system has a unique combination of impacts that informs management and restoration approaches (see the interaction among drivers in *Section 2.6)*.

As an example, the Ebro Delta is a diverse area in terms of wetland habitat types and has high ecological (e.g., it is the second most important "Special Protection Area" for birds in Spain) and economic value (e.g., third largest producer of rice in Europe) (Fatorić and Chelleri 2012). In the last 150 years, the Ebro delta has been largely transformed into rice fields, which now cover 70% of the total area (Cardoch et al. 2002) and have both direct and indirect effects on the ecology of the area, such as salt infiltration in ground water. The main impact is the destruction of natural habitats, but even the remaining deltaic ecosystems have been affected by rice production, through alteration of the natural hydrological cycle as a result of freshwater inputs during the rice growing season (April to September). In addition, large amounts of nutrients and pesticides are delivered for the fertilization and care of the rice paddies (Forès 1992). The planned construction of 49 new reservoirs mainly for irrigation purposes and withdrawal of water upstream from the delta are forecasted to have drastic ecological consequences such as reductions in sediment and freshwater inputs into the delta and detrimental side effects on deltaic ecosystems fauna and flora (Prat and Ibáñez 1995). Overall, because of its morphology, relative sea-level rise will become the most important climate-induced potential hazard for the Ebro delta (Sánchez-Arcilla et al. 2008).

Sea level rise may severely threaten many key coastal ecosystems such as the Nile delta and may cause the loss of important habitats such as the loggerhead *(Caretta caretta)* nesting beaches (UNEP/MAP-RAC/SPA 2009). Projection of averaged sea-level rise trends by El Sayed Frihy et al. (2010) indicates that the coastal plain of the Nile Delta and Alexandria is vulnerable to accelerated sea-level rise but not at the same level due to wide variability of the land topography, which includes low-lying areas, high-elevated coastal ridges and sand dunes, accretionary beaches, and artificially protective structures. Similarly, based on Earth System model simulations, the sea-level variation along the Egyptian coasts is significantly affected by other factors such as sea-level variation West of the Gibraltar Strait, steric sea level, and sea-surface temperature (Shaltout et al. 2015).

Coastal aquifers

Several recent studies have considered the possible impacts of climate change and seawater level rise on seawater intrusion in coastal aquifers (Sefelnasr and Sherif 2014). All have revealed the severity of the problem and the significance of the landward movement of the dispersion zone under seawater level rise. Most of the studies did not consider the possible effects of seawater rise on the inland movement of the shoreline and the associated changes in the boundary conditions at the seaside and the domain geometry. Such effects become more evident in flat, lowland, coastal alluvial plains where large areas might be submerged with seawater under a relatively small increase in seawater

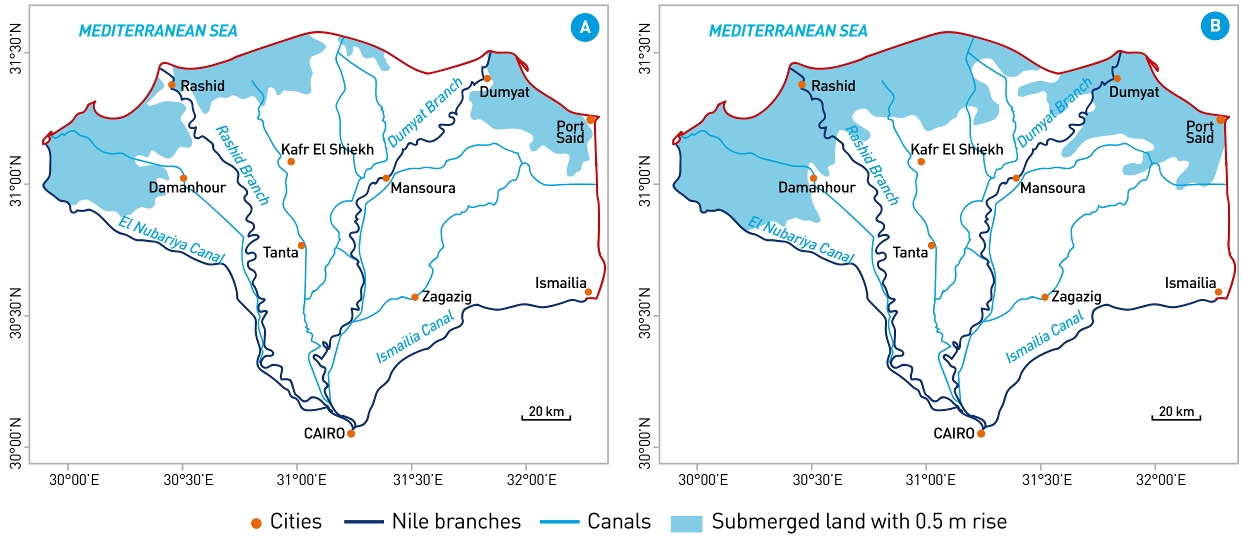

Figure 4.9 | Nile Delta, Egypt, A) Submerged land in the coastal zone under 0.5 m seawater rise. (B) Submerged land in the coastal zone under 1.0 m sea-level rise (Sefelnasr and Sherif 2014). Red line indicates the border of the basin.

level. None of the studies combined the effect of increased groundwater pumping, due to the possible decline in precipitation and shortage in surface water resources, with the expected landward shift of the shoreline. Using a two-dimensional horizontal model, the study of Sefelnasr and Sherif (2014) investigated the possible effects of seawater level rise in the Mediterranean Sea on the seawater intrusion problem in the Nile Delta Aquifer. They concluded that large areas in the coastal zone of the Nile Delta will be submerged by seawater, and the coastline will shift landward by several kilometers on the eastern and western sides of the Delta *(Fig. 4.9)*. By using an equivalent porous continuous medium to represent a karstic Apulian aquifer (southern Italy), an evident piezometric drop was confirmed for the past period (until 1999) and a likely similar dramatic drop in the future was projected (Romanazzi et al. 2015). All phenomena considered in this study's models (e.g., sea level and sea salinity) showed non-negligible effects on coastal groundwater (Romanazzi et al. 2015).

The effects of salinization on coastal aquifers' biogeochemistry typically include decreased inorganic nitrogen removal (with implications for water quality and climate regulation), decreased carbon storage (with implications for climate regulation and wetland accretion), and increased generation of toxic sulfides (with implications for nutrient cycling and the health/functioning of wetland biota) (Herbert et al. 2015). In agriculture, studies on the salinization effects on soil organisms are scarce, but negative effects of saline conditions on survival and reproduction of soil invertebrate species (Owojori et al. 2008, 2014) or on avoidance behavior of earthworms (Bencherif et al. 2015) have been reported. Deleterious effects of soil salinization on diverse life stages of agriculture plants have also been described (Wichern et al. 2006), including decreased and/or delayed germination and/or effects on seedling physiognomic state, deficient growth, as well as a decrease in photosynthetic pigments, and global biomass (Parihar et al. 2015). However, some littoral and terrestrial amphipod species can survive salinity levels of up to 900 mOsm external concentration (Morritt 1988), as along with other spiders mentioned earlier (Pereira et al. 2019).

4.2.2.3 Vulnerabilities

Coastal urbanization

The Mediterranean bioregion is currently suffering severe disturbance due to intensive urbanization and climate change effects (Adloff et al. 2015)[34]. The situation is expected to worsen as land availability decreases (due to the global warming and infrastructure impairment), while demographic growth and migration flows are likely to pursue (Burak and Margat 2016) (read more on land and sea use changes in *Section 2.4*, water management and infrastructure in *Box 3.1.1*, and the vulnerability of coastal energy systems to climate extremes in *Section 3.3.2.3*). In the future, hydroclimatic hazards, probably more frequent and intense, will have adverse impacts on ecological balances and human health and well-being, particularly in coastal Mediterranean cities where almost one-third of the population lives (Hallegatte et al. 2009; Magnan et al. 2009; Adloff et al. 2015; Im et al. 2018). However, Mediterranean coastal cities seem to lack a long-term vision (i.e., establishing smart cities, green cities, etc.) for planning future urban development and valuable policies and social-economic resources for establishing participative governance (Mazurek 2018) *(Section 5.1.3.1)*.

Social-economic contexts and urban growth rates, trends and phases are quite variable from North to East and South and even across each country (Im et al. 2018). While the size of these urban settlements varies from North to South, most have a historic urban center developed around a harbor near the sea, which makes the different biological species living in or near these areas highly vulnerable not only to human stressors, but also to global phenomena like climate change *(Chapter 2)*.

The survey of juvenile fish populations across various infrastructures and natural sites along a 100 km shoreline of the French Mediterranean coast demonstrated that anthropogenic structures can play an important role as potential juvenile fish habitats, particularly in harbors where highly variable densities were found, with densities on ripraps or jetties that were equivalent to those of natural sites (Mercader et al. 2018). This is the case of the herbivorous fish *Siganus rivulatus* in Lebanon-Eastern Mediterranean where it settled in protected shallow areas offering hard substrates and algal communities such as muddy harbors (Bariche et al. 2004).

One of the most frequently documented negative impacts of the high density of harbors and boats, are the collisions and disturbance of large mammals (dolphins, whales, sea turtles). In particular, the destructive impact of fishing practices on dolphin populations has reached international news

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[34] http://www.medqsr.org/

headlines (see *Section 4.1.2.2* for more information about ship collision effects on cetaceans). Another threat for marine mammals in harbor areas is marine dredging with high concern and impact on the marine life of cetaceans, pinnipeds, and sirenians with effects largely unknown (Todd et al. 2015). The leisure activities, habitat degradation, noise, contaminant remobilization, suspended sediments, and sedimentation may impact marine mammals indirectly through changes to prey. Dredging has the potential to impact marine mammals with specific species and location effects, depending on the type of dredging equipment. In harbor areas, marine mammals continue to be impacted by many anthropogenic activities and almost all marine mammal species have been reported to face at least one threat in the Mediterranean (Laran et al. 2017; Avila et al. 2018).

Reduced primary production *(Section 4.1.2.2)* and the possible increase of local blooms of toxic algae in some urbanized coastal areas could have many repercussions on marine ecosystem services such as tourism and fisheries, and ultimately on human health (read how the effects of climate change on coastal ecosystems could affect livelihood, culture and human rights in *Chapter 5.3*). The impact of eutrophication is largely observed in many Mediterranean systems, namely in harbors. For example, in Punic harbors of Carthage, the oldest and most well-preserved in the Mediterranean Basin (Gulf of Tunis, South Mediterranean Sea), the harmful blooms of *Dinophysis sacculus, D. acuminata, Alexandrium* spp., *Gymnodinium aureolum, Gymnodinium impudicum, Akashiwo sanguinea, Scrippsiella* spp. and *Prorocentrum gracile* were identified in correlation with water temperature and orthophosphate concentrations (Aissaoui et al. 2014) *(Section 2.3.3).*

The Mediterranean Basin is particularly exposed to biological invasions through shipping from maritime traffic and the high number of harbors constitute large areas for the extension of several non-indigenous species (Izquierdo-Muñoz et al. 2009). The species *Pseudonereis anomala* (Gravier 1900) (Polychaeta, Nereididae) first recorded in Alexandria (Egypt) by (Fauvel 1937), was recorded in several harbor areas in the Mediterranean within the period (2003 and 2005) (Kambouroglou and Nicolaidou 2006), indicating shipping transfer of benthic species (read more on biological pollutants in *Section 2.3.4*, on non-indigenous species in *Section 2.5,* and on future risks associated with non-indigenous species in *Section 6.12*).

In harbor systems, where macrofauna is scarce and difficult to sample, the study of meiofaunal assemblages is proposed as the most suitable instrument for monitoring purposes since, ports, ranging from large commercial harbors to small tourist marinas, are the main link between anthropized and natural coastal ecosystems, and should be taken as primary sources of coastal disturbances (Sedano Vera et al. 2014). Other Mediterranean species associated with marine fouling harbors have been described by Khedhri et al. (2016). The brachyuran decapod is associated with marine fouling in Egyptian Mediterranean harbors and nine species of 9 genera affiliated with 5 families have been recorded so far.

The spatial and temporal changes in climate attractiveness in the Mediterranean could have major impacts on the sustainability of tourism development as suggested by Amelung and Viner (2006), who used a Tourism Climate Index based on future climate change scenarios for the Mediterranean region. This intense tourism activity is harming the Mediterranean shores. Based on the type of garbage on 13 Mediterranean beaches, there are indications that most Mediterranean coastal litter is land-based (Gabrielides et al. 1991). In fact, based on beach cleanups organized over the summers of 2016 and 2017 in Cyprus, Loizidou et al. (2018) suggest that although these initiatives are quite successful at collecting large pieces of marine litter, small pieces of litter (such as cigarette butts and small pieces of plastic items related to recreational activities) remain, accumulating or buried over time, with some items becoming a nuisance to beach goers and a potential source of marine litter. This issue is already influencing coastal organisms such as loggerhead sea turtles *(Caretta caretta)* where, according to a survey by Tomas et al. (2002), the most frequent type of debris in their gastrointestinal tract is plastics (75.9%). Furthermore, the environmental impacts of sunscreen chemicals are likely to be exacerbated in the Mediterranean waters due to the massive influx of tourists and its densely populated coasts, the basin's limited exchanges with the ocean, the high residence time of surface waters, and its oligotrophic waters, which raises significant concerns about its toxicity on marine biota and its bioaccumulation in the marine trophic chain (Tovar-Sánchez et al. 2019) *(Section 2.3).*

Coastal cities with a sandy ground are often exposed to massive sand extraction. An investigation on the short-term effects of sand extraction on macrozoobenthic communities before and after beach dredging along the Emilia-Romagna coast (northern Adriatic Sea) showed no significant settlement of opportunistic species (Simonini et al.

2005). The same study suggested that the limited impact of sand extraction operations on the physical characteristics of sediment and hydrological-sedimentary characteristics in the relict sand area should aid its rapid recovery and the restoration of the original community in a short period of time (2–4 years after dredging). The same pattern was documented in the coastal ecosystems of the Bay of Blanes on the Catalan coast (Sardá et al. 2000) where recolonization in these dredged habitats was fast, and no changes in seasonal trends were detected after dredging. However, this latter study documented that the filter-feeder *Callista chione* and the carnivorous polychaetes Protodorvillea kefersteini and *Glycera* spp., were still significantly reduced after two years, suggesting that a longer period is needed to restructure dredged bottoms to their initial situation (Sardá et al. 2000).

Sea level rise

Similar to the impacts of sea level rise elsewhere (Bernstein et al. 2019; Mullin et al. 2019; Murfin and Spiegel 2020), many Mediterranean regions will be increasingly exposed to a major risk of submersion and erosion, affecting several parts of the coast (with extreme cases being Venice, Kerkennah archipelago in Tunisia, Alexandria and the Nile delta) (UNEP/MAP/PAP 2015; UNEP/MAP 2016). Future risks associated with sea level rise are detailed in *Section 6.9*. The main consequences on coastal ecosystems include more frequent and/or intensive flooding along low-lying coasts, particularly in delta areas, lagoon coasts, tideland and some islands (*Sections 2.2.8.1* and *6.9.1*). Slight increases in mean sea level will lead to relatively quick inundation, deterioration and displacement of significant areas of wetland vegetation. Severe losses of coastal wetlands are expected in the Mediterranean (McFadden et al. 2007). Apart from the actual loss of land area, these wetlands support rare and localized habitats containing highly specialized organisms, the degradation or loss of which will in turn impact migratory bird populations, particularly along main migratory routes (Cyprus, Malta, Palm Islands Nature Reserve in Lebanon). Mediterranean waterbird communities already show changes in community composition based on the recent changes in temperature and whether or not they have a strict protection status, greatly improves the adaptability of species and communities (Gaget et al. 2018). Future breeding suitability maps indicate that the little tern *(Sternula albifrons)* and the common tern *(Sterna hirundo)* could potentially face a drastic decrease in suitable breeding grounds even in protected areas (Ivajnšič et al. 2017).

A modelling study from the island of Zakynthos-Greece for the loggerhead sea turtle *(Caretta caretta)* suggests that even under the most conservative 0.2 m sea-level rise scenario, about 38% (range: 31 to 48%) of total nesting beach area would be lost, while an average of 13% (range: 7 to 17%) of current nesting beach area would be lost (Katselidis et al. 2014). For a sea-level rise of 1.2 m, they estimated a loss of 67.3% for loggerhead turtle nests and 59.1% for green turtle nests although suitability of nesting sites for future migration will also be dependent on existing natural and artificial barriers (Varela et al. 2019).

Accelerated cliff and beach erosion will result in habitat and species loss. For example many cliffs host chasmophytic endemics while many coastal habitats of priority importance at the European/global level (i.e., coastal Junipers, *Posidonia* meadows) (Gubbay et al. 2016; Janssen et al. 2016). In the western Mediterranean, seagrass could reach functional extinction under warming scenarios (Jordà et al. 2012; Telesca et al. 2015). The effects of sea-level rise on competition and the subsequent plant diversity decrease in Mediterranean-climate marshes (Noto and Shurin 2017). Increased salinization in the estuaries will result in species changes/structure, function, and occurrence of eutrophication (EEA 2004; Bernes 2005; Robinson et al. 2005; Smayda 2006).

4.2.3 Adaptation

4.2.3.1 Adaptation of different coastal systems

When it comes to adaptation strategies for coastal systems to environmental changes, different zones require specific actions. For example, shorelines are mainly affected by deterioration of engineering species such as corals, and vermetids forming reefs that protect coasts from erosion, regulate sediment transport and accumulation and provide habitat for other species. Estuaries are particularly vulnerable to pollution, including plastic from nearby human settlements and require different adaptation strategies. Thus, suitable adaptation policies include (i) reducing pollution runoff, both from agriculture and industry and waste management, (ii) policies to limit or prevent acidification and (iii) moving aquaculture operations to areas protected from critical acidification levels (*Sections 3.1.5* and *6.11*).

Keystone Mediterranean benthic species are vulnerable to ocean acidification and warming (Rodolfo-Metalpa et al. 2011, 2014; Milazzo et al. 2014;

Zunino et al. 2017; Verdura et al. 2019). Therefore, spatial planning for these areas should include plans for coastal protection and different urbanization schemes (infrastructure sector), plans to enhance the attractiveness of these zones for tourists, and different regulations for recreational boats. The most likely mechanisms by which ocean acidification refugia (OAR) can mitigate ocean acidification impacts are reducing exposure to harmful conditions or enhancing adaptive capacity (Kapsenberg and Cyronak 2019). While local management options, such as creating OAR, can help coastal ecosystems to adapt, they present unique challenges, and reducing global anthropogenic CO_2 emissions remains a priority. Given the scale of ocean acidification impacts on human health and well-being, recognizing and researching these complexities may allow the adaptation of management such that both the harms to human health are reduced and the benefits enhanced (Falkenberg et al. 2020).

Deep waters are mainly impacted by changes in wild harvests so adaptation measures should focus on fisheries indirectly impacted by changes in phytoplankton production at the surface as well as ocean warming. Shallow coastal zones are exposed to changes in availability of fish and shellfish. Hence, here the most effective adaptive measures involve the management of both fisheries and aquaculture, and the wise use of coastal habitats. The resilience of socio-ecological systems to sea level rise, storms and flooding can be enhanced when coastal habitats are used as natural infrastructure since they provide similar services and added benefits that support short- and long-term biological, cultural, social, and economic goals (Powell et al. 2019). Better integration across policy and planning instruments is needed to enhance adaptive capacity at the interface of climate change adaptation, marine and aquaculture planning and management. This requires holistic and cooperative management tools, such as aquaculture management areas, that could support adaptation across wider spatial scales (Greenhill et al. 2020). This could be enabled by establishing links between existing and proposed collaborative groups to enhance development of adaptation responses and through co-ordination of monitoring and review processes to promote learning across scales (Kapsenberg and Cyronak 2019; Powell et al. 2019; Greenhill et al. 2020). Economic and financial tools to promote environmental management are detailed in *Section 5.1.3.2.*

4.2.3.2 Harmful algal bloom monitoring

In the last two decades, Harmful Algal Bloom (HAB) events have increased, with many species suddenly emerging in regions previously free from such toxic or potentially harmful algae. Along the Mediterranean coastline, several phytoplankton toxic networks have been established such as the French REPHY network[35]. The recent observations are quite atypical for phytoplankton blooms, and may be partially explained by exceptionally favorable new environmental conditions related to climate change (Draredja et al. 2019; Jenhani et al. 2019; Ninčević Gladan et al. 2020). Coastal HABs appear to have increased on a global scale and several reasons have been suggested: better knowledge of toxic species, better monitoring and alerting systems, the transport of algal cysts in ballast waters, the development of aquaculture, the stimulating effect of urban and industrial activities and/or atypical climate conditions (Glibert et al. 2005). The same trend has been observed in the Mediterranean (see *Sections 2.3.4* and *4.2.1.1*). Thus, national and regional water quality assessment efforts and routine coastal monitoring programs intended to detect species, and the study their toxicities have increased worldwide and in the Mediterranean area as well (Nastasi 2010).

Similar to programs elsewhere around the Mediterranean, the Tunisian national monitoring network of phytoplankton and phycotoxins, has been implemented since 1995 to ensure public safety by establishing tools for early warning of bloom events. Also, a regional project "Risk-Monitoring, Modelling and Mitigation (M3-HABs) of benthic microalgal blooms across the Mediterranean regions" found that better awareness of the risks associated with the Ostreopsis blooms could be achieved, including appropriate diffusion of cautionary measures, the production of common monitoring protocols, the development of new technologies for species-specific identification, species counting, and the build-up of prediction models in order to prevent and reduce risk factors for the environment, human health and economic activities. Despite the efforts in management and monitoring work, predicting the impact of climate

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[35] http://www.ifremer.fr/envlit/surveillance/phytoplancton_phycotoxines

change on HABs in the Mediterranean is very challenging as it involves many combining factors. Thus, the calls for increased awareness in both HAB and seafood monitoring programs remain a high priority in the Mediterranean region (Turki et al. 2014; Visciano et al. 2016; Estevez et al. 2019; Ordoñez et al. 2019).

4.2.3.3 Early detection of potentially dangerous species

An updated list of introduced alien species in the Mediterranean (November 2018) shows that the non-indigenous species (NIS) number is close to 1,000 species *(Section 2.5.1.1)*. Adaptation to NIS requires protecting the coastal population against the possible risks associated with the establishment of NIS *(Section 2.5)*. In fact, in the past two decades research interest in NIS has increased, mostly stimulated by evidence about their ecological and socio-economic impacts in the Mediterranean region. This has also raised the urgency of innovative approaches to forecast, track and manage these species (Corrales et al. 2018) *(Section 6.12)*. For example, the Early Detection and Rapid Response (EDRR) has been recognized as a key aspect for NIS management and acknowledged by the European Commission, and has been included in the new European regulation (EU) No 1143/2014 on the prevention and management of the introduction and spread of NIS. Efficient public awareness campaigns disseminating information to local communities, also through "specific alerts", was adopted as the key driver to quickly detect unwanted NIS and are still used in the last few years with several theoretical frameworks developed through formalized early warning systems (Azzurro et al. 2014).

The silver-cheeked toadfish *Lagocephalus sceleratus* (Gmelin, 1789) (Tetraodontidae) has expanded rapidly through the Western Mediterranean (Streftaris and Zenetos 2006; Jribi and Bradai 2012; Kara et al. 2015). Due to its toxicity, many Mediterranean countries have quickly responded by informing the general public about the risks associated to the consumption of this species. These awareness initiatives, necessary to limit the impacts of this invasion (Nader et al. 2012), have been carried out in countries such as Egypt, Turkey, Lebanon, Cyprus, Greece and Tunisia (Ben Souissi et al. 2014). The same strategy is being adopted for the common lionfish *Pterois miles (Section 2.5.1.3)*. Hence, early detection and continuous monitoring of these species is a successful example of positive interaction between citizens, researchers, and policymakers (Azzurro et al. 2016).

The current list of NIS provides a reliable updated database and basis to continue monitoring the arrival and spread of NIS in the Mediterranean, as well as to provide counsel to governmental agencies with respect to management and control. The current geographical, taxonomical and impact data gaps can be reduced only by instituting harmonized standards and methodologies for monitoring alien populations in all countries bordering the Mediterranean Sea.

4.2.3.4 Adaptation management strategies for the jellyfish *Pelagia noctiluca*

Long-term climate fluctuations have been correlated with jellyfish abundance in Mediterranean waters as revealed by (Molinero et al. 2005, 2008). The *Pelagia noctiluca* represents the most important jellyfish species in the Mediterranean Sea (an oceanic scyphozoan that has become very abundant along the coasts) with negative interaction and toxicity (Condon et al. 2013). In order to better monitor and track the dispersion of jellyfish in the Mediterranean and raise awareness about these species, many networks have been established. The CIESM JellyWatch Program was set up in 2009 to gather baseline data on the frequency and extent of jellyfish outbreaks across the Mediterranean Sea (CIESM 2009b, 2009a). The Medusa Project set up in Catalonia set out to understand the spatio-temporal dynamics of the jellyfish populations in the NW Mediterranean Sea by carrying out daily sampling during summer (May to September) of 243 beaches, covering more than 500 points. The recommendations of Medusa were to enhance similar sampling programs for all Mediterranean coasts to better understand changes in the distribution, abundance, and blooming patterns of dangerous jellyfish species (Canepa et al. 2014). The MED-JELLYRISK project "towards an early warning system to detect jellyfish swarms", started with a campaign to better understand the movement of jellyfish blooms. Three sea drifters were deployed off the coast of Mellieha Bay. Based on satellite tracking, the information gathered by the sea drifters - including sea surface currents (direction and strength) and temperature allowed scientists to validate numerical models that can simulate the dispersion of jellyfish blooms and predict their incidence on coastal areas. These jellyfish dispersion models constituted the basic element of a prototype system intended to act as an early warning of jellyfish swarms impacting Mediterranean beaches. The mission of the Italian, Maltese, Spanish and Tunisian scientists behind the MED-JELLYRISK project (2014-2015) was making public authorities, local businesses and beachgoers ready to live together with jellyfish and adapting solutions to address the growth of such fascinating creatures (Lucas et al. 2014). The possible relationships between climate change and blooms of *P. noctiluca* have been studied and it has been proposed that *P. noctiluca* may be an indicator of climate variability in the Mediterranean Sea (Daly Yahia et al. 2010; Condon et al. 2013; Rosa et al. 2013).

Despite these studies and monitoring surveys, additional studies and long-term surveys are needed to improve knowledge of the eco-physiology of the marine species, which will help to better manage and maybe take advantage of NIS, harmful microalgal and jellyfish biomasses and/or their bioactive molecules as a resource for biotechnological applications, from biofuels to pharmacology, cosmetics, health products, food for humans and feed for livestock or aquaculture farms (de Domenico et al. 2019).

4.2.3.5 Ecosystem-based adaptation management

Given the already poor conditions of exploited resources, there is a need for fisheries management to adapt to future changes and to incorporate climate change impacts into future management strategy assessment (Moullec et al. 2019) *(Section 3.2).* Ecosystem-based adaptation is gaining attention as a cost-effective method for protecting human and ecological communities against the impacts of climate change. This approach has been supported by many studies for various Mediterranean habitats to improve their resilience against the consequences of various drivers. For example, an initial assessment of vulnerability to sea-level rise to help decision makers, and other relevant stakeholders, to develop appropriate public policies and land-use planning measures has been provided (Demirkesen et al. 2008). Also, potential strategies to ameliorate the impact of seawater inundation have been proposed, such as: wetland preservation, beach nourishment at tourist resorts and the afforestation of dunes (Snoussi et al. 2008). Protected areas can play an important role in safeguarding coastal dune plant communities against land-use transformations (Prisco et al. 2016). In this context, functional traits can guide conservation planning, helping to identify groups of species most at risk of population declines. Future conservation interventions need to be mindful to ensure that the natural disturbance regime of dune ecosystems is not disrupted. At the water body management level, scientific cooperation is necessary to deal with the conceptual and ecological difficulties derived from inter and intra-lagoon variability in hydrology and biological assemblages, which are inherent factors in the functioning of these complex ecosystems (Pérez-Ruzafa et al. 2011).

The multiple levels of land-sea interactions (Fang et al. 2018) require a new approach to Integrated Coastal Zone Management (ICZM) and marine spatial planning. The Mediterranean includes hotspots of global priority for land-sea integration (Halpern et al. 2009) and there are emerging Mediterranean case studies which embrace such an approach (Ramieri et al. 2019). Conservation planning and management should focus on cross-realm processes and building resilience between realms. In this respect, connectivity between processes and structural elements is of the utmost importance. Single realm connectivity is inadequate (Fang et al. 2018) since it cannot account for cross-system threats (Beger et al. 2010) and multi-realm species (Giakoumi et al. 2019). Interaction between realms should be translated into structural connectivity (see for example the framework proposed by (Beger et al. 2010) or functional connectivity (Magris et al. 2018) where multi-realm species are taken into consideration. In addition, integrating connectivity and climate change (Magris et al. 2014; Keeley et al. 2018) can be used in various spatio-temporal scales and could be fully applied to maintain and restore land–sea processes. Case studies and innovative approaches are highlighted in *Sections 6.9.3* and *6.9.4.*

4.2.3.6 The role of institutions/ actors and local communities: recommendations

Adaptation efforts often focus on one species, or species group (e.g., jellyfish, algae) or on a specific land-sea ecosystem (e.g., sandy beaches). A more holistic approach is required when trying to establish adaptation methods for the entire Mediterranean, which could include:

- Ecosystem Based Management (EBM) of coastal areas: ecosystem-based approaches (the integrated management of land, water and living resources) to climate change adaptation and mitigation.
- Identify adaptation and mitigation interactions (synergies and conflicts) and assumptions related to adaptation/mitigation.
- Building institutional capacity (governance - adaptive management/monitoring) to improve governance over land/sea natural resources and climate

change adaptation. A Nexus approach has been proposed by the IUCN Commission on Ecosystem Management - coastal ecosystem group (CEM/CEG) based on three complementary approaches: (i) sectoral adaptation, (ii) cross-sectoral governance and (iii) territorial strategic planning (Krchnak et al. 2011; Ozment et al. 2015).
- Adaptation and coastal community resilience: Impacts will directly affect coastal communities. A participatory research approach may assist in assessing vulnerability of socio-economic groups, their current adaptation strategies and their adaptive capacity to cope with the impacts of climate variability and extremes and sea-level rise. Such an approach may identify barriers and opportunities for community response to climate change and place emphasis on any existing knowledge/practices promoting adaptation.
- Integrating local knowledge and institutions with respect to risk management and adaptation is part of an ecosystem-based approach (Colls et al. 2009).
- At a practical/management level, adaptation to coastal risks can be achieved via hard structures but also soft protection including beach nourishments and dune rehabilitation, in addition to improved spatial planning regulations, and anticipatory and reactive adaptation.

Overall, information, data, adaptation techniques and networks do exist, but collaboration can be enhanced. Also, public involvement in the development and implementation of adaptation strategies for these ecosystems can be improved. Awareness campaigns on the importance of adaptation measures for these ecosystems may help policymakers to make the necessary steps to ensure their protection and conservation against potential climate change impacts.

4.3 Terrestrial and freshwater ecosystems

4.3.1 Current conditions and past trends

The Mediterranean region is recognized as a global biodiversity hotspot (Myers et al. 2000; Mittermeier et al. 2005), representing one of the Earth's most geologically, biologically, and culturally rich and complex regions (Blondel and Aronson 1999; Blondel et al. 2010; Visconti et al. 2018). More than 50 plant refuges during recent ice ages (Médail and Diadema 2009) have allowed plant diversity to be exceptionally high (Mittermeier et al. 2005), with about 25,000 plant species today (Myers et al. 2000) and 60% endemism (Thompson 2005). There are 290 tree species (Noce et al. 2016), of which 200 are endemic (Quézel and Médail 2003; Gauquelin et al. 2018). Two thirds of Mediterranean amphibian species, 48% of reptiles, a quarter of mammals, 14% of dragonflies, and 3% of birds are endemic (Mittermeier et al. 2005; Lefèvre and Fady 2016; Paine and Lieutier 2016). However, the diversity of several taxa has not been analyzed in detail under the taxonomic and ecological angles (Azam et al. 2016).

4.3.1.1 Past climate variability and its impact on terrestrial ecosystems

Regional temperatures in the Mediterranean Basin are now ~1.4°C higher than during the 1880-1920 period, higher than the increase in global temperature of 0.85°C *(Chapter 2)*. During the Holocene (especially in the second half of this period), periods of precipitation deficits have occurred, but in contrast to the 21st-century situation, temperatures did not rise above the present average. These periods of precipitation deficits (~6 to ~5.2, ~4.2 to ~4, and ~3.1 to ~2.9 thousand yr BP) have been identified as possible causes of declines or collapses in civilization in the eastern Mediterranean region (Guiot and Kaniewski 2015).

Information from tree rings from different tree species growing at high elevation can provide annually-resolved, absolutely dated climate information across the Mediterranean covering the past centuries. Reconstructions from locations across the Mediterranean reflect different climate conditions during different times of the year. Recent tree ring-based climate reconstructions reflect not only seasonal temperatures but also parts of the hydrological cycle including drought stress. Only few tree-ring based climate reconstructions go beyond the past 600 years and this limits our understanding of drought variability, the magnitude and timing of long-term trends and centennial-scale variability across the Mediterranean back to medieval times.

The most detailed depiction of Mediterranean drought variability over the last 900 years is presented in the Old World Drought Atlas (OWDA), a tree-ring-based field reconstruction of warm-season drought severity

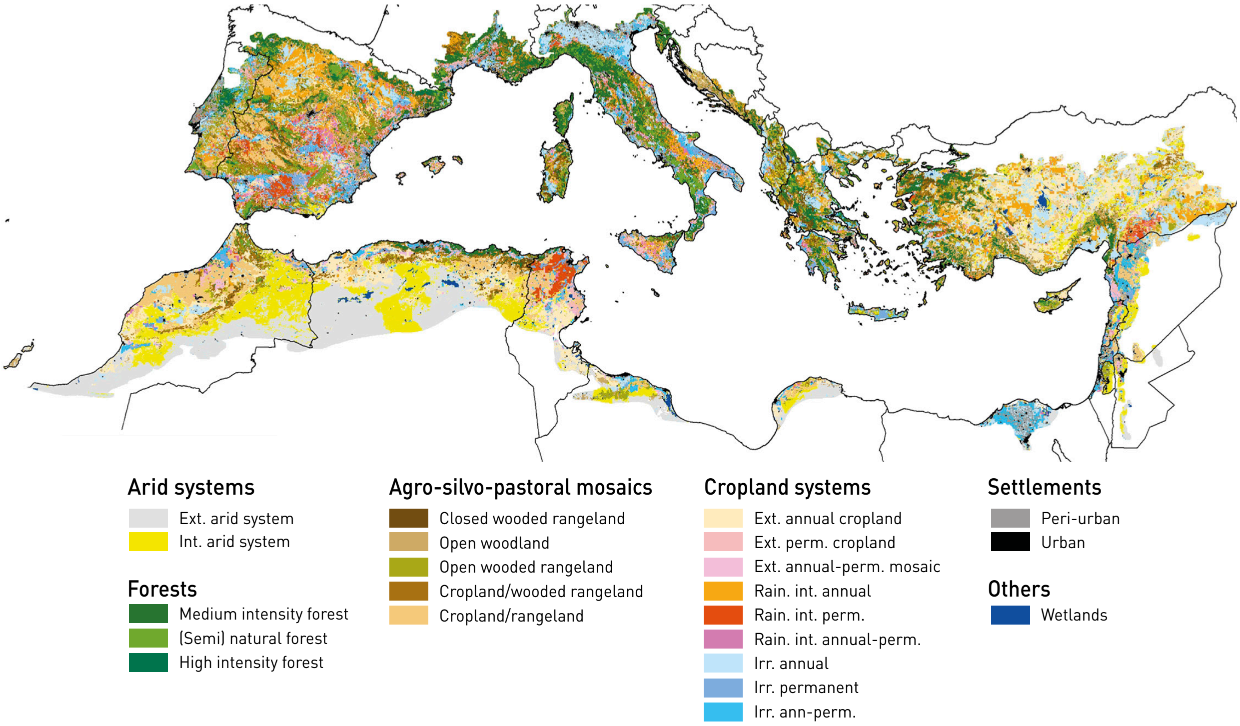

Figure 4.10 | Mediterranean land systems (Malek et al. 2018).

(Cook et al. 2015). Summer drought reconstructions from high-elevation sites from Mount Smolikas in the Pindus Mountains (Northern Greece) go back to AD 730 (Konter et al. 2017; Klippel et al. 2018). Drought variability displays significant East-West coherence between the western (Spain, Morocco, Algeria, and Tunisia) and eastern (Balkans, Greece, and Turkey) Mediterranean Basin on multi-decadal to centennial timescales (Cook et al. 2016). There appears to be a north-south contrast in the eastern Mediterranean, with a tendency for wet anomalies in Greece, Anatolia, and the Balkans while Libya, the southern Levant, and the Middle East are dry and vice versa associated with North Atlantic Oscillation (NAO) and other atmospheric circulation dynamics (Cook et al. 2016). The recent droughts in north-western Africa (Morocco) and the Levant are unusual in the context of the past 900 years (Esper et al. 2007; Cook et al. 2016). In the Pyrenees, the Alps, the northern Apennines, the Balkans, the north-western and southern Carpathians long tree ring width formation are mostly controlled by summer temperature (Buntgen et al. 2007; Büntgen et al. 2009, 2017; Popa and Kern 2009; Panayotov et al. 2010). Reconstructions from the Iberian Peninsula and northern Africa for the past 900 years reflect overall warmer conditions around 1200 and 1400, and again after around 1850. Cooler conditions are reconstructed for the mid 13th century and between the 15th and 18th century.

The only winter/spring $\delta^{13}C$ from tree ring-derived temperature reconstruction from southwestern Turkey indicates warmer conditions during the early 12th century and the late 15th century and lower temperatures from the early 16th century to the late 19th century (Heinrich et al. 2013). Tree ring-based climate reconstructions account for a maximum of 35% explained variance and thus are associated with large uncertainties.

Pollen-based reconstructions for the entire Holocene confirm the picture that significant switches between drier and wetter conditions have occurred around the Mediterranean Basin, even if temperatures have never reached current levels. Vegetation has switched between major biome categories in up to 10% of the land area from one century to another, with only slightly higher values during the particular shifts identified above (Guiot and Cramer 2016).

4.3.1.2 Direct human impacts on ecosystems in the past

The Mediterranean Region is also one of the regions with the longest and most intense human occupation in the world (Underwood et al. 2009), and its diversity is the result of co-evolution between human societies and their environment, characterized by constantly evolving land use practices over at least the past 300 generations of human occupation (Blondel 2006). The

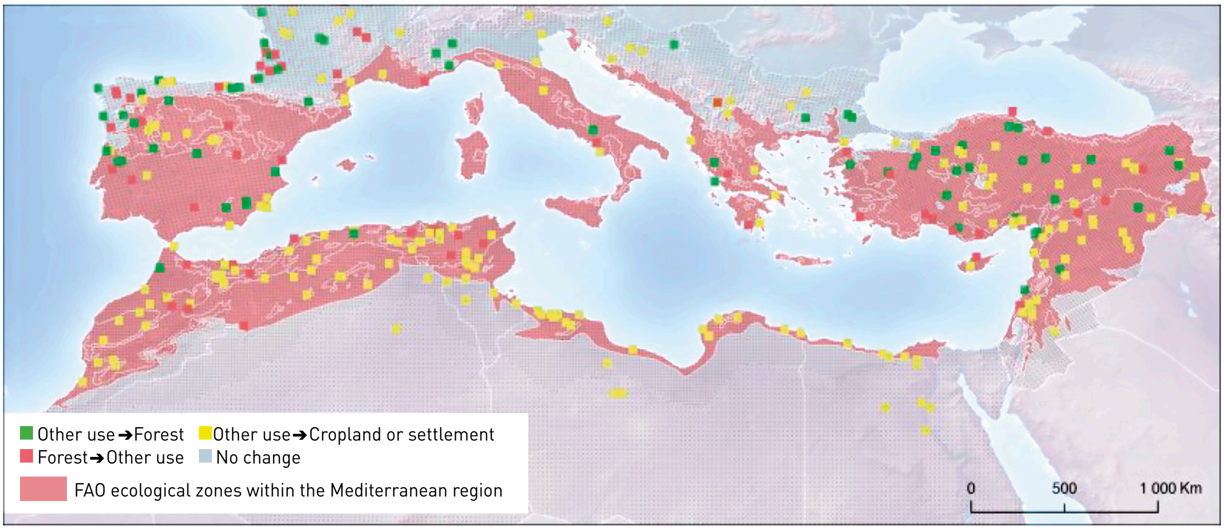

Figure 4.11 | Map of Global Dryland Assessment (GDA) plots showing main changes in land use over the years 2000 to 2015. Non-forest land uses are shown in green. Land use shifting from forests to other uses is shown in red. Changes from other land to cropland and settlements are shown in yellow. Plots that did not change are shown in black (Martín-Ortega et al. 2018).

presence of many endemic species is closely related to extensive use of Mediterranean landscapes, particularly agro-silvo-pastoral mosaic systems (Médail and Quézel 1999) and wetlands (Cuttelod et al. 2009). Reconstructing landscapes and ecosystems over the course of time remains difficult. Knowledge of the human history of the region is therefore still limited. Most changes in land cover appear to have been due to change in human activities, often inducing diversity through changes in different taxonomic groups and their interactions (Sirami et al. 2010). Throughout the Holocene, Mediterranean ecosystems appear to have been rather resilient to perturbations (Blondel 2006; Underwood et al. 2009). Together with urbanization and agriculture intensification (Myers et al. 2000), land abandonment and the decrease in open habitats are key trends in several countries of the northwestern part of the Mediterranean Basin (Portugal, Spain, France and Italy) (Mazzoleni et al. 2004).

Since about 1980, biodiversity changes are faster and greater across different Mediterranean taxonomic groups and habitats (Blondel et al. 2010; Vogt-Schilb et al. 2016; Delpon et al. 2018). Species loss is marked by a general trend of homogenization (loss of vulnerable and rare species) recorded in several taxonomic groups and by a general simplification of biotic interactions (loss of specialized relationship) (Blondel et al. 2010; Visconti et al. 2018).

The most detailed land use map of the Mediterranean indicates a highly heterogeneous spatial structure of land use systems *(Fig. 4.10)* (Malek and Verburg 2017; Malek et al. 2018). In a coarser reconstruction of land use change during recent decades, cropland was found to be the dominant land use (35.2%), grassland was the second most common land cover (26% of plots), followed by forest (20.7%) and other lands (13.4%). Settlement and wetlands accounted for the smallest number of plots, with 3.3% and 1.4% respectively (Martín-Ortega et al. 2018).

During the period 2000-2015, human activities have intensified in the Mediterranean region, particularly in Spain, France, Turkey and most North African countries *(Fig. 4.11)*, where an increase in cropland was recorded. An intensification of agricultural activities in the region is associated with marked transitions from non-irrigated or heterogeneous cropland to permanently irrigated cropland (Ruiz-Benito et al. 2012), leading to an increased use of freshwater resources, with similar projections being made for the future (Malek et al. 2018). New areas containing settlements occurred concurrently with this regional expansion in cropland because of urbanization and tourism, indicating an important trend of urbanization across the region (Martín-Ortega et al. 2018), impacting landscape character, resources use and ecosystem services capacity (Martínez-Fernández et al. 2009; Ruiz-Benito et al. 2012; Balzan et al. 2018).

Forests

In the Mediterranean region, the term "forest" comprises a variety of vegetation types interleaved with one another in complex patterns created by variations in soil, topography, climate, human use and fire history, among other factors. This includes dense stands with a closed canopy, as well as pre-forest or pre-steppe structures with lower tree density and tree height (Gauquelin et al. 2018) such as the human-shaped Mediterranean mosaic landscapes, including dehesas or montados, and multifunctional agro-silvopastoral systems of pastures with scattered oaks, typical of the Iberian Peninsula. The forests of the Mediterranean Basin cover more than 48.2 million ha of which 35 million are in southern Europe, 8.8 in the Middle East and 4.4 in North Africa (Quézel and Médail 2003; Fady and Médail 2004). However, based on the FAO definition of forests ("Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%"), there were an estimated 88 million ha of forest area in Mediterranean countries in 2015, representing 2.2% of the world's total forest area (FAO and Plan Bleu 2018).

Despite the small extent of the Mediterranean forest area compared to rest of the world, it is a floristic global hotspot with ca. 25,000 flowering plant and fern species (4.5% of the world´s endemics), which represent approx. 10% of the world's flowering plants (Myers et al. 2000). It is also the world's second highest region in terms of in plant endemism, with 50-60% of the plants being found nowhere else, including emblematic species such as cork oak *(Quercus suber)*, argan *(Argania spinosa)*, cypresses such as *Tetraclinis articulata* or, *Juniperus thurifera,* or fir species such as *Abies pinsapo, A. marocana, A. nebrodensis,* many of them endemic to the different mountain ranges across the Mediterranean (Thompson 2005; Blondel et al. 2010). The Mediterranean Basin hosts 290 indigenous woody species and subspecies (in comparison to 135 for non-Mediterranean Europe), 201 of which are endemic (Fady-Welterlen 2005). Intra-region variability in climate, soil and human factors result in a mosaic of forest types (Masiero et al. 2013). The relatively harsh climate conditions in arid zones prevent the existence of tall forests and lead to the formation of *maquis* and *garriga* shrublands, dominated by evergreen shrubs such as *Pistacia lentiscus, Quercus coccifera, Q. calliprinos* and *Cistus sp.* The semiarid zones are dominated by *Pinus halepensis* in the western part and *Pinus brutia* in the eastern areas. Sub-humid areas are the typical habitat for evergreen oaks such as *Quercus* ilex or *Q. suber,* but also *Pinus pinea* and other accompanying species such as *Arbutus unedo* or *Erica arborea.* Deciduous and marcescent oaks appear in the sub-humid to humid Mediterranean areas, with oak species such as *Quercus pubescens, Q. cerris, Q. pyrenaica, Q. faginea* or *Q. macrolepis*, among others, accompanied by conifers such as *Cedrus* sp. or by Mediterranean firs (*Abies pinsapo* or *A. cephalonica*). In mountain areas pines become the dominant species including *P. nigra* and *P. sylvestris,* and it is also possible to find islands of oceanic climate with *Q. robur, Q. petraea, Fagus sylvatica* or *Abies alba.* Along the rivers, forests of *Fraxinus* sp., *Populus alba* and *P. nigra* can prosper (FAO and Plan Bleu 2013). The wildlife diversity associated with this variety of forest environments is also high: 786 of 1,601 vertebrate Mediterranean species live in forest habitats and 792 of 1,184 terrestrial insects assessed by the IUCN Red List (as in 2018) are recorded as living in forests, 364 of which are endemic to the Mediterranean region (FAO and Plan Bleu 2018).

The human footprint in Mediterranean forests

The current composition, structure, dynamics and biological diversity of Mediterranean forests cannot be understood without considering the long history of uses and changes induced by human activities, which have contributed to shaping the Mediterranean landscapes as we know them today (Blondel 2006). Human influence in the Mediterranean dates back several thousand years, to the point that some authors argue that a "coevolution" has shaped the interactions between these ecosystems and the human societies that inhabited them (Blondel 2006).

Transformation into agricultural fields, over-exploitation, the prevalence of livestock grazing within forests, and the repeated occurrence of natural and human-caused fires led to a progressive reduction and fragmentation of vegetation cover, and forests are mainly confined into the less fertile slopes and occupy less than 15% of their potential area (Quézel and Médail 2003). In some areas, the loss of forest canopy on slopes and their associated understory after fire events has led to important soil erosion (Cerdà and Mataix-Solera 2009; Shakesby 2011). Nevertheless, most soil degradation in forests of the Mediterranean Basin is associated with overgrazing and trampling of the forest understory (Le Houérou 1990; FAO 2016; FAO and Plan Bleu 2018).

In many areas, however, the combination of forests, pastures and fields, together with the high variability in climate, relief and soil resulted in a mosaic-type landscape that greatly contributed to maintaining the biological diversity of Mediterranean landscapes. These landscapes are highly dependent on human stewardship to maintain their resilience to disturbances (e.g., by reducing fire risk through browsing the forest understory (Blondel 2006). The population increase and industrial development from the 18th century onwards led to an increase in the pressure on forests for wood and charcoal on the northern shore of the Mediterranean Basin (Nocentini and Coll 2013). Forests were intensively cut and transformed into coppices, some species were overexploited, and many forests were transformed into uniform, even-aged systems managed through clearcutting or uniform shelterwood (Puettmann et al. 2008).

At the beginning of the 20th century, extensive reforestation plans were implemented in many European countries to reverse the trend. For example, 3.3 million ha were reforested between 1938 and 1984 in Spain, 460,000 ha in Portugal and around 1.3 million ha in Italy during the 20th century (Pemán and Serrada 2017). These large national reforestation programs mainly used conifers (mostly pines) due to their ability to grow in degraded soils and harsh environments. Many reforested areas contributed to a general improvement of environmental conditions, but the use of a single species over vast areas, together with the lack of subsequent management led to very homogeneous forests, often at excessive densities, with associated expansion of pests and a high risk of wildfires (Nocentini and Coll 2013; Guijarro et al. 2017; Martín-Alcón et al. 2017).

Since 1990, overall forest area has increased by 0.67% yr^{-1} across the Mediterranean Basin (FAO and Plan Bleu 2018). Despite this generally increasing trend, forest loss and degradation still prevail around most of the Mediterranean Basin, especially in coastal areas, due to population increase and urban expansion (FAO and Plan Bleu 2018). Sharp differences can be observed between sub-regions. Almost all countries in the North experienced a huge increase in forest area, with rates around 1% yr^{-1} in Italy, France and Spain (Masiero et al. 2013), to which afforestation only contributes 0.23% yr^{-1}. The major part of this trend is due to the decline of agriculture and grazing and the consequent abandonment of marginal lands that are colonized by forests, a process that has been stimulated by European Common Agricultural Policy subsidies (FAO and Plan Bleu 2013, 2018). In contrast, on the southern Mediterranean shore, forest ecosystems are still at risk of fragmentation or disappearance due to human pressure from clearing and cultivation, overexploitation of firewood and overgrazing (Gauquelin et al. 1999; Croitoru 2007; Palahi et al. 2008; Djema and Messaoudene 2009; Masiero et al. 2013; FAO and Plan Bleu 2018). For example, Algerian forests decreased at a rate of 0.5% from 1990 to 2010 (FAO and Plan Bleu 2013) and a decrease rate of ~126,000 ha yr^{-1} across North Africa has been estimated over the last 25 years (Keenan et al. 2015). This degradation continues despite forest representing 22% of the protected land area in North African countries (FAO and Plan Bleu 2018). However, many of these protected areas generally lack management plans or the resources to implement them (IPBES 2018).

Ecosystem services provision by Mediterranean forests

Mediterranean forests are complex and biodiversity-rich socio-ecological systems, resulting from the coevolution of plants and societies through millennia of human perturbations and management (Blondel 2006; Doblas-Miranda et al. 2015; Gauquelin et al. 2018). Currently, Mediterranean forests play a key role in the livelihoods of diverse communities across the Mediterranean by providing people with ecosystem services, food and products for home consumption and income generation. In particular, the provision of non-wood forest products (NWFPs) and other services (e.g., watershed protection, soil erosion mitigation) (Merlo and Croitoru 2005; Croitoru 2007) stands out from the provision of wood forest products (WFPs) (FAO and Plan Bleu 2018). Removal of WFPs represents about 20 to 40% of the estimated total economy value in most northern countries, but less than 15% in most southern and eastern countries (Croitoru 2007). Northern Mediterranean countries dominate all areas of wood production, especially roundwood, pulpwood and derived products, with countries in eastern Mediterranean making a significant contribution to fiberboard production (Turkey produces 50% of the fiberboard products in the region) (FAO and Plan Bleu 2013). Production is low in the southern Mediterranean countries except for wood fuel, which constitutes one-third of the total production in the sub-region (FAO and Plan Bleu 2013), with firewood reaching 80 to 100% of total removals in Tunisia, Morocco and Lebanon (Croitoru 2007). In any case, the overall production of WFP in the Mediterranean is insufficient to meet regional demands, making the region a net importer of wood and wood forest products (FAO and Plan Bleu 2013).

The main NWFPs of Mediterranean forests include cork, pine cones and pine nuts, mushrooms, chestnuts, honey, truffles, berries, acorns, carob, myrtle, rosemary, and other products. Most of these NWFPs are generally harvested, stored and consumed by local communities or constitute their main source of income (FAO and Plan Bleu 2018). There is a significant geographical variation in production and consumption of NWFPs, largely dependent on the tree species available in each country. Portugal is the main producer of cork (50 percent of total production), followed by Spain (30%), Morocco (6%), Algeria (5%), Tunisia (4%), France (3%) and Italy (3%) (APCOR 2015). In 2016, the estimated annual export value of cork by Mediterranean countries was €1,295.8 million (APCOR 2015). Cork production is mostly concentrated in cork-oak savannas (also called dehesas or montados) that result from an intentionally induced simplification (both in terms of structure and species diversity) of the Mediterranean forest: human intervention reduces tree density, removes shrub cover and fosters the growth of grass. These are considered "biodiversity-based product systems" by the Convention of Biological Diversity and have a multi-functional character, contributing to the provision of other services such as fuelwood, acorns (to feed animals), carbon storage and pasture, while supporting important habitats for biodiversity (Bugalho et al. 2011).

Pine nut extraction (from stone pine *Pinus pinea*) generates an income of about €50-60 ha^{-1} yr^{-1} (for a cone yield of 200 kg ha^{-1} yr^{-1}), which is higher than the revenue from timber (€20–30 ha^{-1} yr^{-1}), fuelwood, and other products or uses (FAO and Plan Bleu 2013), where the most productive areas are Portugal and Lebanon, producing 4–7 t ha^{-1} yr^{-1}. In Mediterranean Europe, mushroom picking is a recreational activity and mushrooms are marketed according to origin (e.g., France, Italy and Spain) rather than used solely as a direct food source for local communities (FAO and Plan Bleu 2018). The saffron milk cap *(Lactarius deliciosus)* and porcino *(Boletus edulis)* are the most important species commercially traded, along with the highly-valued black truffle *(Tuber melanosporum)* which is increasingly artificially inoculated on purposefully cultivated oak trees. In Turkey, where 90% of the total pine honey is produced (*Pinus brutia* and *P. halepensis*), the beekeeping sector is the main source of income for nearly 10,000 families in the region (Croitoru and Liagre 2013). In Morocco, for example, argan forests contribute to 7% of regional GDP and ensure subsistence for 14% of the rural population (Croitoru and Liagre 2013). Grazing in forested areas remains the main source of subsistence for local populations in Algeria, Morocco, Tunisia, Lebanon and Turkey (Daly Hassen 2016). One the most recent marketed values of Mediterranean forests is their attraction for tourism, sometimes to the detriment of other forest services (García-Nieto et al. 2013) or to the forest itself (Kuvan 2010).

Mediterranean forests also hold many important non-marketed values, mostly regulating services. Among these, one of the most relevant is watershed protection: forests regulate watershed hydrological regimes and protect against erosion and extreme flooding events while filtering and purifying water for its local consumption (Palahi et al. 2008; Guerra et al. 2016). Watershed protection is the single most valuable benefit from forests in Syria, for example, accounting for more than 50% of the total economic value of forests (US$100 ha^{-1} yr^{-1}). In the Maghreb countries, it is second in value only to grazing, varying within US$26-32 ha^{-1} yr^{-1} (Croitoru and Liagre 2013). Mediterranean forests play an important role in regulating micro-climatic conditions, atmospheric composition, water and biochemical cycles (Peñuelas et al. 2017). They also represent a net carbon sink, helping mitigate climate change impacts *(Section 4.3.3)*. In 2005, the economic value of carbon storage in Mediterranean forests ranged between US$ 37 billion and US$ 63 billion, i.e., 13% of the forests' total economic value, when assuming the SRES IPCC scenarios A1 and B1, respectively, for the 2050 horizon (Ding et al. 2010). However, carbon storage capacity by Mediterranean forests is strongly modulated by management (Seidl et al. 2014; Bravo et al. 2017). In fact, forests can act as carbon sources if disturbed, poorly managed, overexploited or burnt (Ding et al. 2010; Peñuelas et al. 2017).

Other societal values of Mediterranean forests include their cultural, spiritual and religious importance (especially for the few remaining ancient forests) (Mansourian et al. 2013) and their attractiveness (aesthetics) for recreational activities and tourism (FAO and Plan Bleu 2013; Bernetti et al. 2019; Raviv et al. 2020). Recreational uses of Mediterranean forests can lead to trade-offs with other services: for example, in Tunisia, the number of visitors to parks demanding recreational services from forests increased from 93,000 to 110,000 between 1998 and 2014 (Daly-Hassen et al. 2017). In these areas, limiting the access to the public also limits soil erosion, one of the main explicit concerns of Tunisian forests (Daly-Hassen et al. 2017).

Mountains

According to the UNEP definition, Mediterranean mountains cover some 1.7 million km². Seven Mediterranean countries are among the top 20 mountainous countries in the world, and half of the countries in the region have at least 50% of their land classified as mountain areas (Regato and Salman 2008). Mediterranean mountains exhibit similarities in their biotic, ecological, physical and environmental characteristics but also significant differences (floristically, human colonization patterns, historic land uses and current anthropogenic pressures). Mediterranean mountains host many regional and local endemic species, some of which are relicts of past biogeographical patterns. Médail and Diadema (2009) identified 33 mountainous areas within 52 refugia in the Mediterranean Basin. Some of these mountains had already been identified as regional biodiversity hotspots (Médail and Quézel 1999) and global centers of plant diversity (Davis et al. 1994).

Historically, Mediterranean mountain forests have been crucial for the development of all civilizations and countries in the region. Most of the prehistoric populations of the Near East originated in Mediterranean mountain areas with very high plant and animal diversity, year-round water, shelter and suitable conditions for survival. Early mountain farmer-herders in the eastern Mediterranean and North African mountains changed pastoral and cropping patterns leading to the domestication of major livestock and domestic species but also important crops, including barley and wheat.

Land use changes in mountain regions

The long history of human intervention has modified land cover and resulted in numerous land use changes over time. Although Grove and Rackham (2003) support the resilience of modern Mediterranean landscape to changes since ancient times, McNeill (1992) argues that for most of the mountains, the changes that destroyed the environment and left behind skeletal landscapes are comparatively recent (past 200 years). Major land uses included woodcutting, pastoralism, agriculture and mining. Drivers of land use changes (north vs. south) included socio-political, economic, environmental expansion vs. population decline, urbanization and industrialization. The beginning of the 20th century, marked the start of rural emigration from the mountains of northern Mediterranean countries that peaked after the Second World War, resulting in land abandonment and the remarkable increase of forest cover seen in recent years. In southern Mediterranean countries, in contrast, an opposite trend is recorded due to the substantial increase in the rural population and consequent pressure on the mountains for arable and grazing land.

Recent land use changes have disrupted the traditional agro-silvopastoral equilibrium of the Mediterranean mountains. The increased forest cover in the northern Mediterranean has resulted in a decline in species and especially of habitat diversity and an increase in natural hazards, especially forest fires, but increased carbon sequestration and decreased soil erosion and sediment transport to the lowlands. The decrease in forest cover in the southern Mediterranean, on the other hand, has led to severe soil erosion.

The intensity and therefore impact of the principal human activities, i.e., agriculture, grazing and tourism, vary significantly from north to south of the basin. For example, agriculture was historically more important in the Sierra Nevada, the Lucanian Apennines of Italy and the Rif mountains than in Taurus mountains or the Pindos mountains (McNeill 1992). In addition, in Morocco the extensive deforestation of mountains has been reported as a result of an increasing rural population, intensive grazing and the end of traditional pastoral nomadic migrations (Rejdali 2004). Regional differences have also been demonstrated in the case of Lefka Ori and the Psiloritis mountains in Crete where the opposite pattern was observed with abandonment mainly due to different grazing practices and number of stock density (Papanastasis 2012). This reflects the impacts of cultural practices (tradition) even within the same region (Regato and Salman 2008; Papanastasis 2012).

Land use change is still considered a more imminent threat in the short to medium term for mountain areas compared to climate changes (Tasser et al. 2017). Abandonment of agricultural activities (including grazing) emerges as a common trend that can be identified in most of the Euro-Mediterranean mountains as a result of rural depopulation which started in the 1950s, with plenty of examples from Spain, Italy and Greece (Papanastasis 2012). Typical countryside structures such as terraces and stonewalls are collapsing, soil erosion is increasing while secondary succession is taking place in addition to reforestation activities carried out to mitigate the effects of torrential floods within rivers and ravines and to reduce the siltation of reservoirs within the valley bottoms (López-Moreno et al. 2008). Abandonment continues to date with farmlands abandoned as a consequence of migration to urban settlements in lowland areas, resulting in significant reduction in cultivation in the northern Mediterranean (Vicente-Serrano et al. 2004; Lasanta-Martínez et al. 2005). However, reports from Turkey support the argument that 'people are still in the mountains' since the decline in forest cover is small compared to other areas in the Mediterranean (Kadioğullari and Başkent 2008; Günlü et al. 2009) while in the Taurus, livestock husbandry is still very active (Kaniewski et al. 2007).

Mountain biodiversity changes

Mediterranean mountains located on the borders of different biogeographical regions, and three continents, are biodiversity hotpots with a flora which comprises different phytogeographical elements ranging from Euro-Siberian to Arctic-Alpine, and Irano-Turanian in the eastern Mediterranean. This is particularly demonstrated in the mountain flora of Crete, Cyprus and Turkey. In the Mediterranean Basin, with its long history of human activity, mountains are considered to be some of the last remaining wilderness areas with high landscape and biodiversity value providing a wide range of ecosystem services within and beyond their boundaries. Geology, tectonic activity, isolation and limited human activity explain the current biogeographical patterns occurring in Mediterranean mountains. These patterns conform to theory, with mountains displaying low species richness but high endemism along altitudinal gradients. In recognition of their importance, a high number of protected areas and many mountainous areas are part of the UNESCO World Network of Biosphere Reserves (Sierra Nevada, Mount Olympus and Lefka Ori-Crete).

Community composition changes have been recorded both because of land use as well as climate change. The increased forest cover in the northern Mediterranean has resulted in a decline in species and especially of habitat diversity (Papanastasis 2012). Altitudinal shifts have been already reported from the Montseny mountains (Peñuelas and Boada 2003), as well as changes in the abundance of endemic species (Fernández Calzado et al. 2012). Community-level studies in Mediterranean mountain ranges indicate that there will be colonization of high altitudes by subalpine species (Stanisci et al. 2005; Kazakis et al. 2007) or what Gottfried et al. (2012) have termed "thermophilization". There is already evidence in Mediterranean mountain areas of an increase in the frequency of extreme events, a direct result of climate change, manifesting itself as droughts and, sediment transfer (Maas and Macklin 2002).

Drylands and shrublands

Drylands are characterized by low precipitation levels which do not compensate for the evaporative demands imposed by high temperatures and solar radiation, thereby exhibiting high aridity levels (MEA 2005; Reynolds et al. 2007). Dryland ecosystems have low productivity, which is often exacerbated by the highly irregular, low predictable pulses of rain, resulting in a long period during which soil moisture depletion with no restoration prevails. Low productivity generates relatively low plant biomass, which produces only small amounts of plant litter and leads to low soil organic contents (Safriel 2006).

Drylands are classified using the aridity index (AI related to the average ratio of annual precipitation over potential evapotranspiration) developed by the United Nations (Middleton and Thomas 1997) into four classes: hyper-arid (AI<0.05), arid (0.05<AI<0.20), semi-arid (0.20<AI<0.50), dry sub-humid (0.50<AI<0.65). In the Mediterranean, drylands represent almost 80% of its area *(Fig. 4.15a)* from which 12.3% are classified as hyper-arid, 16.5% arid, 36.7% semi-arid and 14.5% dry-sub-humid (considering the boundaries of the Mediterranean SREX region defined in the 5th IPCC Assessment Report). Climatic constraints limit the productivity of drylands, increasing their susceptibility to wind and water erosion. These climatic limitations, coupled with intense human activity (e.g, agriculture, grazing and deforestation) has been leading to desertification and land degradation particularly in the Mediterranean (Olsson et al. 2019) *(Fig. 4.12)*.

The Mediterranean domain has undergone an overall increase in arid area of almost 15% (from 64% to 78%) at the cost of the more humid aridity classes (Daliakopoulos et al. 2017; Elsen et al. 2017). Changes in land cover in drylands have both human-driven and climate variability as underlying causes and have resulted in extensive land abandonment especially after 1960 (Moreira et al. 2011; Stellmes et al. 2013). The depopulation of marginal areas includes the abandonment of extensively used agricultural areas, the discontinuation of traditional forms of land use, e.g., dehesas (wooded pastureland) and a decrease in livestock grazing (Delgado et al. 2010; Rescia et al. 2010). Moreover, extensive active afforestation measures resulted in an increase in forested areas (Valbuena-Carabaña et al. 2010).

Despite their relative levels of aridity, drylands contain a great variety of biodiversity, much of which is highly adapted to water-limited conditions. As a result, there are many animal and plant species and habitats found only in drylands: some semi-arid and dry sub-humid areas are among the most biodiverse regions in the world (Gudka et al. 2014). Diversity is also high in drylands, for example between ecotones, areas of different aridity, temperature or altitude. Species have adapted to these factors in many unique ways, creating a variety of habitats that are essential to the survival of species as well as to the livelihoods of people.

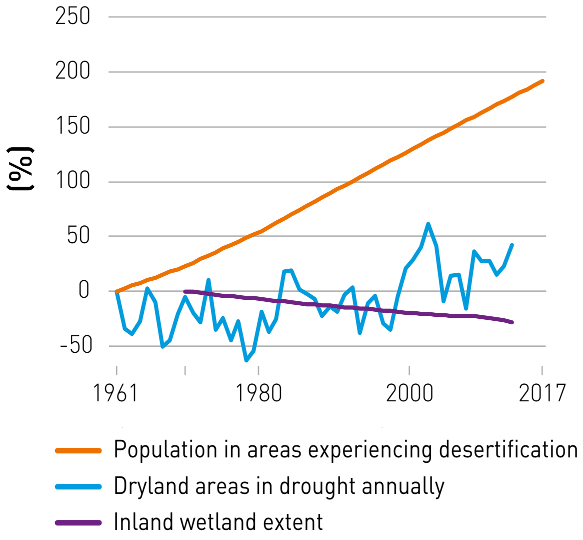

Figure 4.12 | Change in the percentage of land-use change from 1961 to present in relation to desertification and land degradation. Dryland areas were estimated using TerraClimate precipitation and potential evapotranspiration (1980–2015) to identify areas where the Aridity Index is below 0.65. Population data are from the HYDE3.2 database. Areas in drought are based on the 12-month accumulation Global Precipitation Climatology Centre Drought Index. The inland wetland extent (including peatlands) is based on aggregated data from more than 2,000 time series that report changes in local wetland area over time (IPCC 2019).

Steppes occupy important areas (630,000 km²) of the arid zones of the Mediterranean Basin, from the Red Sea to southeastern Spain (Maestre and Cortina 2005). Subjected to strong human impact for millennia, they have been greatly modified. Moreover, some of them, especially the graminean steppe of *Stipa tenacissima,* are the consequence of the degradation of the former open forests. In the past, particularly at the end of the last glacial episode and during the following glacial-interglacial transition, steppes were important biomes representing a significant part of the global continental carbon reservoir.

Shrubland ecosystems account for a substantial part of total land cover and are particularly relevant in arid, semi-arid, and dry-subhumid areas (Reynolds et al. 2007). Shrub-dominated ecosystems are increasing worldwide, a process with important implications for the structure and functioning of terrestrial ecosystems (Van Auken 2000; Berlow et al. 2002; Anthelme et al. 2007). In shrublands, the dominant maquis has many local names reflecting indigenous and local knowledge, such as macchia in Italy, matorral in Spain, phryganae in Greece or bartha in Israel. It is characterized by hard-leaved shrubby evergreen species of genera *Cistus, Erica, Genista, Juniperus, Myrtus, Phillyrea* and *Pistacia.* The term "garrigue" is restricted to the limestone, semi-arid, lowland and coastal regions of the basin and is maintained by grazing and fires.

Biological soil crusts are complex topsoil microbial assemblages composed of eukaryotic algae, cyanobacteria, mosses, liverworts, fungi and lichens (Velasco Ayuso et al. 2017). They cover the uppermost mm of the soil surface in most arid and semi-arid ecosystems throughout the globe and are one of the most conspicuous and important biotic components of these areas (Belnap and Lange 2013). They exert a strong influence on key ecosystem processes such as runoff (Alexander and Calvo 1990; Belnap 2006), soil respiration (Maestre and Cortina 2003), nitrogen fixation and transformations (Belnap 2002; Castillo-Monroy et al. 2010), establishment and performance of vascular plants (Defalco et al. 2001; Escudero et al. 2007) and act as habitats for a dependent food web of arthropods, fungi, bacteria, and other soil organisms (Belnap and Lange 2013).

Dryland biodiversity also provides significant global economic values through the provision of ecosystem services and biodiversity products. Many cultivated plants and livestock breeds originate in drylands, providing a genetic reservoir whose importance is increasing as climate change drives the demand for new adaptations and extinctions of wild breeds. These services, such as cultural identity and spirituality are central to dryland cultures and can be integral to the protection of dryland ecosystems. There has been an observable correlation between land degradation and cultural degradation in drylands demonstrating their interconnectedness (Davies et al. 2012).

Agroecosystems

Agroecosystems support high levels of biodiversity and then a rich diversity of habitats and landscapes because of traditional, low-intensity and diverse agricultural systems (Levers et al. 2016). However, this biodiversity has declined dramatically since the early 1950s due to the intensification of agriculture, leading to an increase in highly modified agroecosystems and simplified and agricultural landscapes (Poláková et al. 2011). The common farmland bird index indicates a reduction in agricultural biodiversity by 34% over the time period

1989-2016[36]. In agricultural landscapes, intensification of agricultural systems has generally induced decreased crop diversity, decreased coverage of natural and semi-natural areas (hedgerows, isolated trees, ponds, permanent grasslands) and lower connectivity between the remaining natural and semi-natural habitats (Stoate et al. 2001, 2009).

Agroecosystems provide important ecosystem services to society, but these are threatened by agricultural abandonment and intensification of agricultural practices. These threaten multifunctional landscapes and erode the capacity to deliver ecosystem services, particularly regulating, and cultural ecosystem services (Nieto-Romero et al. 2014; Balzan et al. 2020). Despite the increasing availability of literature about the topic, there are disparities in the availability of research about agroecosystem services within the Mediterranean region, in particular north-south trends. The limited availability of social research on the topic was identified in a review of Nieto-Romero et al. (2014). Most scientific studies focus on provisioning ecosystem services from intensely managed agroecosystems, whilst regulating and cultural ecosystem services were primarily studied in extensive agroecosystems (Nieto-Romero et al. 2014). These results are supported by recent literature, and a parallel can be drawn with the land-sparing vs. land-sharing debate (Phalan et al. 2011). Intensive agricultural districts, characterized by high landscape homogeneity, were shown to provide food products but are relatively poor in terms of capacity to deliver other services in Barcelona (Baró et al. 2017). Extensive agriculture and semi-natural habitats in Malta and in Sardinia were associated with ecosystem service synergies indicating high landscape multifunctionality (Bagella et al. 2013; Balzan et al. 2018).

Approaches that maintain farmland biodiversity have been linked with an improvement in the delivery of regulation ecosystem services in Mediterranean climates. There is evidence that habitat management through the provision of non-crop plant resources (e.g., floral) and conditions can contribute to increased abundance and diversity of natural enemies, biological control and suppression of crop pests when compared to lower biodiversity controls (Shackelford et al. 2017).

Agroecosystem development in different regions

The ongoing changes in Mediterranean agricultural ecosystems are driven by the dynamics of the global market of food, energy and technology (e.g., seeds, feeds, fertilizers and agrochemicals) and by regional societal changes (Debolini et al. 2018). A summary of these dynamics is necessary to understand and frame the ongoing changes of Mediterranean terrestrial ecosystems associated with agricultural systems *(Section 3.2.1.1)*.

Agricultural systems of northern and southern Mediterranean countries face contrasting challenges in relation to their diverse historical backgrounds and ecological constraints. On one side, particularly in southern Europe, farm abandonment in marginal land is associated with the bias introduced by the implementation of the Common Agricultural Policy (CAP) and post-socialism dynamics (Lasanta et al. 2017). Both external (migration, socio-economic model, public policies) and internal (local factors and characteristics of the agricultural holdings) factors trigger and control the land abandonment process, respectively. Biophysical and socio-economic drivers are interlinked, and the outcomes are therefore very site-specific, depending on local contexts. Abandonment of agricultural activities has many landscape, ecological and socio-economic implications particularly during the transition process, which is still under way in many mountainous areas of Mediterranean Europe (Sirami et al. 2010; Alary et al. 2019). In Mediterranean Europe, the agricultural subsidies related to the CAP and the agro-environmental measures had contradictory effects on land abandonment over the years, which in the long run resulted in a sharp decrease in the number of farms and the increase in average farm size (Papadopoulos 2015; Lowder et al. 2016). In contrast, between 1960 and 2000, average farm size in North Africa decreased, becoming less than 2 ha in around 70% of the farms operating less than 10% of farmland, as 50% of the land is farmed by holdings above 10 ha in size. This is consistent with a global trend of farm size reduction in low- and middle-income countries (Lowder et al. 2016).

The contrasting evolution of agriculture between the northern and southern Mediterranean shores indicates the profound differences in socio-economic and biophysical conditions driving agroecosystem change. While in northern Mediterranean countries abandonment of mountain and marginal land and intensification of lowland and coastal areas is clear, in southern countries there is still high pressure from agricultural and grazing systems on lands that are vulnerable to land degradation and desertification. In northern countries

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[36] European wild bird indicators, 2018 update: https://pecbms.info/european-wild-bird-indicators-2018-update/

the role of grazing livestock is strategic to mitigate the negative impacts of abandoned farmland (e.g., wildfire prevention). In southern countries, overgrazing is still a core issue (Lasanta et al. 2015) with important impacts on biodiversity (Plieninger et al. 2013) and related ecosystem services (Hurni et al. 2015).

In many marginal agricultural areas of Mediterranean countries, particularly in the north west, the abandonment of agriculture and livestock activities and the consequent forest transition is leading to the rapid expansion of wild fauna (e.g., wild boars, wolves, wild dogs) which is in turn negatively impacting farming (e.g., increased production costs and lower competitiveness of the agricultural business) (Otero et al. 2015), and soil degradation (Mauri et al. 2019). The conservation of biodiversity and ecosystem services can emerge from the implementation of adaptive management approaches, including monitoring of population dynamics and related environmental indices (Katona and Coetsee 2019). Abandonment is also generating a loss of plant biodiversity and cultural landscapes associated with grasslands and farmland fields (Malavasi et al. 2018) and the loss of valuable plant and animal germplasm selected over centuries for their adaptive capacity to these marginal lands (Bullitta et al. 2017), that is not of interest for intensive farmland and hence is at risk of loss. The encroached abandoned croplands and grasslands become particularly vulnerable to wildfires, particularly during the transition from grassland to forest, which in Mediterranean countries is represented by pyrophilous shrubby vegetation, particularly in oligotrophic soils (López-Poma et al. 2014; Bagella et al. 2017). In southern Mediterranean countries, overgrazing still prevails with impacts on soil degradation (Martínez-Valderrama et al. 2018) that are compensated by the increasing import of feed for animal food supplementation, which has doubled in Northern African countries in the past two decades (FAO 2017).

A key issue related to the ongoing changes to Mediterranean agriculture is the impact of these changes on ecosystem water resources and the related hydrological cycle (Milano et al. 2013; Martínez-Valderrama et al. 2018). In silvopastoral ecosystems, the transition from grass to woody vegetation exacerbates the negative effects of increasingly frequent drought events and extreme heatwaves associated with ongoing climate changes (Rolo and Moreno 2019). Deep-rooted tall evergreen trees increase actual evapotranspiration beyond the expected increase of reference evapotranspiration due to increased temperatures. Land use abandonment therefore results in the loss of ground and surface water resources, which is expected just when more water is needed both for civil and agricultural uses (García-Ruiz and Lana-Renault 2011).

Agriculture absorbs 80% and 60% of total water demand in African and European countries surrounding the Mediterranean Sea, respectively. Under business-as-usual trends, this demand is expected to rise as a consequence of temperature rise and higher drought frequency, resulting in higher evapotranspiration, while at the same time, groundwater recharge and runoff are expected to be reduced as a consequence of the altered water balance due the above-mentioned land use changes in northern Mediterranean countries (García et al. 2017).

The intensification of agricultural activities in lowland and coastal lands is also impacting biodiversity and ecosystem services as is the abandonment of marginal land. The impact of such intensification processes goes beyond provisioning services and the impact on agricultural biodiversity and multiple regulating and cultural ecosystem services is one of the main focuses of the CAP reform debate in Europe (Nieto-Romero et al. 2014). In the following paragraphs we describe the dynamics and drivers of different Mediterranean agroecosystems to understand the implications for biodiversity and ecosystem services.

Perennial crops

In 2017, over 80% of the 10 Mha of olive harvested area in Mediterranean countries was located in Spain (25%), Tunisia (17%), Italy (13%), Morocco (10%), Greece (9%), and Turkey (8%). The harvested area is steadily increasing at a rate of some 140 kha yr^{-1} because of the area increments in the MENA and North African countries, where many new plantations are increasing their productivity under introduced irrigation. However, the sustainability of such irrigated croplands is sometimes questioned in the arid lands of North Africa by the use of non-renewable deep groundwater and the high cost of non-conventional treated wastewater or seawater desalinization (Mualla 2018). Crop yield of perennial crops is instead stable and relatively high in European Mediterranean countries (Tanasijevic et al. 2014). In the case of grapes, the harvested area has declined from 200 kha to 150 kha in the past 2 to 3 decades, but production is stable as crop yield increased from 7.5 t ha^{-1} in the 1990s to some 8.0-8.5 t ha^{-1} in recent years, again as a consequence of the improvement of agronomic techniques and the use of irrigation (data from FAOSTAT).

Olives and vineyards are a fundamental part of the agricultural landscape and cultural heritage of Mediterranean croplands. In the traditional cropping systems, often based on some sort of agroforestry systems or, sometimes, agro-silvo-pastoral systems, are designed for a mix of provisioning services (food, wine, cork etc.), but they also provide unique habitats for agrobiodiversity and contribute to multiple ecosystem services (Cohen et al. 2015; Brambilla et al. 2017; Assandri et al. 2018). Almonds and other traditional fruit Mediterranean orchards, and agroforestry systems in many cases represent a traditional and cultural landscape (Moreno et al. 2018).

Vegetables

The production of fresh vegetables is increasing in some Northern African and Western Asian countries, particularly Egypt, Algeria, Israel and Turkey. In Egypt the area harvested has doubled in the last 10 years and now represents over 20% of the total harvestable area of fresh vegetables in the Mediterranean area, with just over 140 kha, slightly higher than Italy, traditionally the first country in the Mediterranean. In all other southern European countries, the harvestable area of fresh vegetables has remained stable during the past three decades. The cultivation of vegetables is related to a wide range of farming systems, ranging from very small family farms for subsistence, mainly in the northern African and Near East countries, to very well-organized industrial horticulture value chains. An extreme example of industrial vegetable production is that of Almeria, in Southern Spain, where some 30-40 kha of greenhouses for vegetables and ornamental plants in a very arid area (200 mm yr^{-1} rain) are producing a gross value of some €1.5-2.0 billion, 75% is generated through the export of fresh vegetables, primarily to northern Europe. These systems were developed relatively recently (the first greenhouse in Almeria was built in the 1960s) and rely on groundwater (80%), with potential overexploitation and salinization of aquifers under way (Custodio et al. 2016). However, a novel bioeconomy model is being developed in Almeria, to increase its sustainability (Egea et al. 2018). Such systems are increasingly growing in other countries, pushed by the demand for out-of-seasons vegetables across Europe, which is sometimes considered more sustainable than domestic production (Tobarra et al. 2018).

Intensive vegetable cropping systems increase the supply of provisioning ecosystem services but impact biodiversity and may lead to trade-offs with other regulating and cultural ecosystem services (Balzan et al. 2020). For example, the introduction of irrigation in arid and semi-arid agroecosystems generates a deep transformation of habitat, species composition and related ecosystem services. The mismanagement of irrigation can lead to soil salinization and impacts on agricultural biodiversity (De Frutos et al. 2015; Juárez-Escario et al. 2017). Intensive production sometimes includes the intensive use of agrochemicals with almost total control of weeds, pests and diseases. Furthermore, the industry includes investments in the development of new varieties characterized by tolerance or resistance to biotic and abiotic stress, reduction of harvesting costs, adaptation to long shelf-life and post harvest packaging, which in practice are reducing the diversity of varieties being grown. On the other hand, old varieties are often more suitable for organic farming systems and can provide valuable germplasm for future needs. Small holders therefore still represent a residual source of valuable germplasm that is at risk of extinction and deserves political attention. This is particularly true for Mediterranean germplasm that had been selected by farmers over centuries. Such farming systems therefore provide a valuable ecosystem service in terms of germplasm in situ conservation which is often linked to the cultural values of the traditional rural societies of the Mediterranean Basin.

Winter cereals

In Mediterranean countries, winter cereals often cover more than 50% of the arable land. Their impact on agroecosystems and ecosystem services is therefore very relevant. However, the winter cereals harvested area in the Mediterranean is generally declining, particularly in southern Europe (e.g., Italy) and is increasing in MENA countries (e.g., Egypt). In contrast, the grain yield is steadily increasing almost everywhere at an average rate ranging from less than +20 kg ha^{-1} yr^{-1} in North African countries to +40 to 60 kg ha^{-1} yr^{-1} in southern and eastern Europe (FAOSTAT). Schils et al. (2018) have shown that the yield gap between actual and water limited yield potential for wheat is relatively low in central western Europe and is increasing in Mediterranean countries and eastern Europe, where crop stresses other than just water are still limiting actual yield. This decline in harvested area and increase in yield indicates that, in the past, winter cereals were grown on marginal land. This is certainly the case of EU countries where the CAP subsidies were coupled with winter cereal crops until the CAP reform in early 2000, with farmers also "growing the subsidies" in unsuitable areas (Balkhausen et al. 2007).

In Mediterranean agroecosystems, winter cereals are sown between early and late autumn and harvested in early summer. This guarantees soil cover and protection from erosion in winter and spring but as most winter cereal fields are tilled, soils are exposed to water erosion during the early stages of the crop, corresponding to the heavy rains that are frequent in the Mediterranean climate at the start of the season. Furthermore, with intensive crops the capacity of cereal seedlings in the early growth stages to uptake nitrate nitrogen is low, hence either nitrates derived from the natural mineralization of organic matter or from mineral fertilizers distributed before seeding can contribute to the contamination of groundwater. These processes are expected to increase due to increased temperatures leading to higher mineralization rates, and the higher frequency of heavy storms.

Grasslands and grazing systems

Mediterranean grasslands of the "old world" cover over 1 billion ha of land, mostly in the MENA regions. They host some 240 million dairy and meat sheep, 100 million dairy goats and 95 million beef cattle, mostly based on livestock-cereal, agricultural and agro-silvopastoral systems (Porqueddu et al. 2016). Large-scale grazing systems in southern Europe have almost completely abandoned the traditional transhumant system and only few short-distance vertical movements between lowland and upland pastures are maintained (Caballero et al. 2011). Large-scale grazing systems in rangelands and common grasslands are always associated with specific grazing institutions, regulating grazing management and different arrangements between landowners and pastoralists. Such arrangements shape the cohesion of the local rural society, thus generating complex relationships between biophysical and socio-economic processes leading to more or less desirable outcomes at environmental and social scales (Caballero et al. 2011). In MENA countries, the grazing systems are still shaped by such dynamics and overgrazing is among the main drivers impacting land degradation and desertification, with site-specific issues that call for the development of integrated policy implementation frameworks (Middleton 2018).

In Mediterranean countries, livestock grazing systems are often well integrated with winter cereal cropping systems. Grazing can stimulate tillering and hence contribute to increasing the number of cereal heads per unit area. This practice is coupled with early seeding, which can contribute to preventing soil erosion and nitrate leaching. Grazing is suspended before heading and resumed after grain harvest, when grains losses and straw greatly contribute to animal feeding.

Ecosystem services related to pollination

The decline of pollinators is largely seen across Europe (Biesmeijer et al. 2006; Potts et al. 2010; IPBES 2016), but it strongly contrasts with the steadily growing demand for pollination in crop production (Klein et al. 2006; Aizen and Harder 2009; Garibaldi et al. 2013; Breeze et al. 2014; IPBES 2016). Over the last five decades, agriculture has become increasingly pollinator-dependent, with a three-fold increase in the number of crops requiring the intervention of pollinators (Aizen and Harder 2009). The recommended number of honeybees and hives required to provide crop pollination (by considering the natural presence and action of wild pollinators) across 41 European countries rose 4.9 times faster than honeybee stocks between 2005 and 2010 (Garibaldi et al. 2013). As a result, 90% of the demand for honeybee stocks is not met in 22 out of the 41 countries studied (Breeze et al. 2014). The Mediterranean climate zone has the highest bee species richness in Europe, with the Iberian, Italian and Balkan peninsulas being the most important areas of species richness. Southern Europe also has the highest concentration of endemism, and threatened species. The high diversity of bees in the Mediterranean region is a consequence of the climate of the region and the associated resource heterogeneity, which provide optimal conditions for bee diversity. Petanidou et al. (2008) provide evidence of high temporal plasticity in species composition and interaction identity, indicating that even flower visitation networks show high temporal variation. The main threat to European bees is habitat loss as a result of agriculture intensification and urban development, increased frequency of fires and climate change (Nieto et al. 2015). Fires considerably change vegetation and land cover conditions, and can therefore have an important effect on pollinators and plant pollination (IPBES 2016). For example, fires in Mediterranean oak-pine forests lead to an initial reduction of bee diversity in recently burnt areas. However, these areas recover in the following years, and this recovery is highly correlated to floral diversity (Potts et al. 2003). In Europe, 179 non-threatened species and two threatened species are regarded as under threat from an increased susceptibility to fire, whilst 113 non-threatened species and 23 threatened species are regarded as threatened by climate change (Nieto et al. 2015).

Traditional and non-intensive agricultural practices have a positive impact on agricultural biodiversity in the Mediterranean region (Sokos et al. 2013; Balzan et al. 2020). Similarly, several studies indicate a positive effect of diversified farming systems and organic management related to conventional monocultures (Kennedy et al. 2013). In the meta-analysis by Kennedy et al. (2013), Mediterranean organic fields were estimated to harbor 68% and 56% higher bee abundance and species richness respectively when compared to conventional fields. This study also recorded a significant positive effect of landscape composition, with average increases of 129% and 41% in bee abundance and richness, respectively, for each 0.1 unit increase in the Lonsdorf Landscape Index (an ecologically scaled index of landscape composition) (Kennedy et al. 2013). The Middle East and Mediterranean Europe recorded higher monetary benefits in crop production that is directly linked with pollination services in comparison to other regions. This is mainly due to the cultivation of a variety of fruit and seed crops (IPBES 2016).

Freshwater ecosystems

Freshwater ecosystems, including streams, rivers, lakes, riparian areas and terrestrial wetlands, offer many important ecosystem services such as water supply for drinking, agriculture and industries (Brauman et al. 2007), water purification, erosion control (MEA 2005; de Groot et al. 2010), recreation, tourism and flood mitigation (Mediterranean Wetlands Observatory 2018). Humans have used these services for thousands of years, and in the process, have severely degraded these ecosystems (Zaimes and Emmanouloudis 2012; Geijzendorffer et al. 2019b). This is particularly true for the Mediterranean region that has been inhabited for thousands of years. The region is characterized by limited water resources and strong population growth (+70% increase in population since 1970 (UN 2013) and +30% in the last 20 years (Abis 2006). Furthermore, substantial increases in seasonal tourism are forecasted in many Mediterranean countries (Burak et al. 2004; Gober 2010), particularly in coastal regions, which can triple in population during the summer (Abis 2006; Collet et al. 2014). Overall, water demand has doubled in the second half of the 20th century in the Mediterranean (Blinda and Thivet 2009; Collet et al. 2013). Accelerated population growth, tourism and globalization are expected to further exacerbate agriculture, urbanization and subsequent pressures leading to an increase in water demand and to significant changes in water use patterns, thus affecting surface waters in the decades to come (Sala et al. 2000; Ferreira et al. 2019; Mack et al. 2019).

River regulation

The highly irregular rainfall patterns and strong seasonal and annual variability of the flow regimes of Mediterranean rivers and streams (Garofano-Gomez et al. 2011), along with the high topographic relief of many of its river (Grantham et al. 2013) have led to the building of more than 3,500 dams in rivers during the 20th century (Cuttelod et al. 2009; Lobera et al. 2016). Large dams regulate river flow hydrology and influence water chemistry, sediment dynamics, channel form and biotic communities, act as barriers to sediments, fish migration and vegetation propagules (Brierley and Fryirs 2005; Charlton 2008), change the thermal regime, water quality and biogeochemical fluxes, thus impacting habitat availability and connectivity along the fluvial continuum (Van Steeter and Pitlick 1998; Gasith and Resh 1999; Brierley and Fryirs 2005; Nilsson et al. 2005; Garde 2006; Garofano-Gomez et al. 2011; Bernal et al. 2013; Bonada and Resh 2013; Mediterranean Wetlands Observatory 2018). Reservoirs can reduce the sediment load up to 90% and change the flow from a flashy Mediterranean river to a more constant flow regime below the dam. Downstream, the main consequences of water with reduced sediment supply from upstream include: i) river channel degradation (e.g., bed incision), coarsening of the surface layer and channel narrowing; ii) ecological degradation, damaging the availability and quality of habitat for both the aquatic and riparian biota; and iii) reduction of the sediment supply to the development of the river delta and hence accelerated coastal erosion (Kondolf 1997; Liébault and Piégay 2001; Simon and Rinaldi 2006; Vericat and Batalla 2006; Gendaszek et al. 2012; Lobera et al. 2016). The decline in river sediment inputs can be the result of human activities such as the stabilization of mountain slopes because of rural agriculture decline, rural exodus, reforestation and engineered torrent control (Provansal et al. 2014).

When considering all rivers, the total quantity of freshwater discharged into the Mediterranean each year (not including precipitation) has declined by about 45% during the 20th century *(Section 3.1.3).* The reduction in river flows is a probable cause of the very unfavorable conservation status of the biodiversity dependent on rivers: 40% of the fish species found in Mediterranean wetlands are endangered (Mediterranean Wetlands Observatory 2018; *Fig. 4.13*).

Groundwater depletion

The close connection between streams and aquifers is responsible for base flow during periods of scarce recharge, controlling stream discharge as

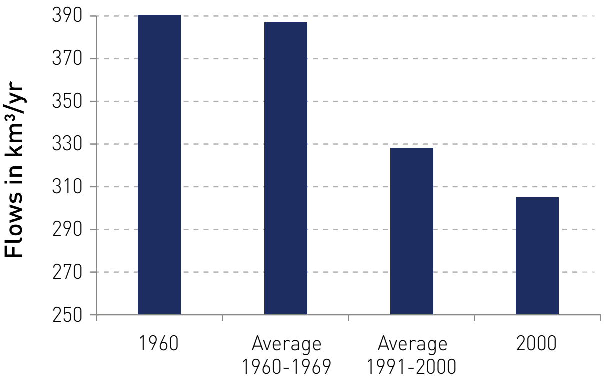

Figure 4.13 | Reduction in freshwater discharge flows into the Mediterranean for all rivers (Mediterranean Wetlands Observatory, 2018).

well as other hydromorphological characteristics (Winter 1999; Woessner 2000; Menció and Mas-Pla 2010). Human activities, such as groundwater withdrawal or major changes in land cover primarily for agriculture, can result in a reduction of subsurface inflow to streams, changes in groundwater dynamics, and thus, loss of biological quality (Benejam et al. 2008; Menció and Mas-Pla 2010). The needs for water abstraction have risen and it has become difficult to meet water needs (Qadir et al. 2007; Collet et al. 2013; Mediterranean Wetlands Observatory 2018), which is also disrupting the functioning of surface irrigation (EEA 2018; Mack et al. 2019). This is particularly true for Mediterranean islands that are largely dependent on groundwater resources (MED-EUWI 2007; Koutroulis et al. 2013). Exploitation of water resources causes changes in the water balance which leads to low or zero flows, especially during the summer, but also decreases surface water quality (Baldock et al. 2000; Moustadraf et al. 2008; Menció and Mas-Pla 2010).

Hydrologic regimes

Rivers and streams in Mediterranean areas are subject to naturally occurring high variability in their flow, with predictable seasonal disturbances such as floods and droughts (Menció and Mas-Pla 2010; Zaimes et al. 2010) *(Section 3.1.3)*. They can experience wet winters and consequent floods to severe droughts in the summer, when intermittency in otherwise perennial systems can occur (Cid et al. 2017) *(Section 2.2.5.3)*. In addition, Mediterranean regions are often rugged, marked by a notable altitudinal gradient between the headwaters and the outlet (Emmanouloudis et al. 2011). Mediterranean streams, located in high elevated areas experience annual rainfall exceeding 1,000 mm, and are characterized by low temperatures in winter with the chance of snow accumulation. This creates a typically bimodal pattern in the flow regime, with the highest discharge following the onset of rain and following snowmelt in spring (Sabater et al. 1992), but maintaining a permanent flow throughout the year. In contrast, rivers located in semi-arid areas (low land areas), with mean annual precipitation ranging from 200 to 500 mm, show a less permanent flow regime (many are intermittent and ephemeral) (Lobera et al. 2016).

Human competition for water enhances the natural deficit in water resources of the region, due to mean annual precipitation lower than the mean potential evapotranspiration (Gasith and Resh 1999). Additionally, water diversion, damming, flow regulation, increased salinity, pollution and introduced species have also severely impacted Mediterranean freshwater ecosystems over time (Moyle 1995; Gasith and Resh 1999; Aguiar and Ferreira 2005; Hooke 2006). Overall, the discharge has decreased almost by half in many Mediterranean catchments in the second half of the 20th century (García-Ruiz et al. 2011; Mediterranean Wetlands Observatory 2018). Mediterranean river ecosystems also have a highly endangered biodiversity, with 40% of the fish species being endangered (Mediterranean Wetlands Observatory 2018), which cannot be dissociated from the long history of human disturbances (Zeder 2008; Feio et al. 2014).

Finally, while we are seeing decreases in water availability and runoff, urbanization and infrastructure have encroached river floodplains leading to higher exposure of both people and capital risk to flood damage (Geijzendorffer et al. 2019b). With climate change leading to more unpredictable flash floods, especially in intermittent and ephemeral torrents, the risk and potential damage of river floods has significantly increased in the Mediterranean Basin *(Section 3.1.3.3)*.

Land-use changes, reduction of wetlands and riparian areas

In recent decades, coastal Mediterranean wetlands have suffered considerable pressures from land use change, intensification of urban growth, increasing tourism infrastructure and intensification of agricultural practices (Sanchez et al. 2015). The recent Ramsar Global Wetland Outlook (Ramsar Convention on Wetlands 2018) highlights that the Mediterranean region, where water shortages coincide with demography, had total wetland losses of 48% between 1970 and 2013 (significantly higher than other regions). In addition, 36% of assessed wetland-dependent animals in the Mediterranean are threatened with global extinction (Mediterranean Wetlands Observatory 2018). Special attention should be given to temporary aquatic habitats that are characteristics of the Mediterranean region that provide flood control, groundwater recharge, toxin removal and recycling of nutrients (Balzan et al. 2019). Some temporary wetlands in the Mediterranean region are a priority habitat under the Natura 2000 Network (Natura code 3170, 92 / 43 / CEE, 21 May 1992) (Waterkeyn et al. 2010). Land use intensification in/and adjacent to rivers and streams has eliminated or simplified riparian the structural diversity of ecosystems (Robinson et al. 2002; Corbacho et al. 2003; Kingsford and Thomas 2004). These ecosystems have substantial fragmentation in the lowlands of Mediterranean areas primarily due to agriculture, compared to the mountainous areas that can have detrimental effects on their functionality (Zaimes et al. 2011). The maintenance and re-establishment of riparian ecosystems is a difficult but also an important task in southern Europe where most riparian ecosystems have experienced an extensive history of intensive land-use changes and other human disturbances (Corbacho et al. 2003; Zaimes et al. 2010).

The most important parameters for riparian vegetation were the distance from dams, the sea and rivers (Zaimes et al. 2019). Overall, the riparian vegetation of a Mediterranean Basin decreased with increasing drought, flow regulation and agriculture (González et al. 2010; Bruno et al. 2016; Aguiar et al. 2018). Agriculture is the most important stressor for riparian functionality in the Mediterranean. Agricultural land use and hydro-morphological alteration intensification increases in Mediterranean and semi-arid areas (Nilsson and Berggren 2000; Allan 2004; Bruno et al. 2014a) led to a general decrease in both richness and ecological condition. Agricultural land use was the main pressure explaining riparian richness and quality, whereas the responses of aquatic communities were highly related to hydromorphological alteration. These basin-wide variables had a greater effect than variables operating on a local scale (Bruno et al. 2014b).

The riparian sites with the worst quality were near the river mouth and were characterized by an artificial and highly variable flow regime (Zaimes et al. 2011). This artificial flow variability as well as the presence of lateral structures in the river channel and geomorphological characteristics were the main factors driving the hydromorphological and floristic pattern in the regulated river. This flow-biota interaction is remarkable in Mediterranean rivers (Prenda et al. 2006) due to their high biological diversity and extremely variable flow regimes (Blondel and Aronson 1999; Naiman et al. 2008; Zaimes et al. 2010; Garófano Gómez 2013). Many native species of riparian vegetation exhibit life cycles adapted to seasonal peak flows, the loss of which may hinder the regeneration of these riparian communities, reducing their growth rates or favoring the invasion of alien species (Poff et al. 1997). Lateral connectivity is also altered by the reduction of the frequency, magnitude and duration of events that periodically flood banks and floodplains (Charlton 2008), causing loss of native riparian vegetation (Burch et al. 1987; Garofano-Gomez et al. 2011; Zaimes et al. 2019).

In conclusion, the loss of natural wetlands is a major concern, since their loss is nearly irreversible and leads to significant impacts on wetland biodiversity and ecosystem services. Restoration initiatives exist but have a low rate of success when it comes to re-establishing the same richness and stability that can be found in natural wetlands.

Water quality

Based on the Water Framework Directive (WFD; Directive 2000/60/EC), European Union (EU) countries are obligated to assess the ecological status of their freshwater ecosystems using biological indicators, as well as chemical, hydrochemical, and hydro-morphological parameters and to achieve good qualitative and quantitative status of all ground and surface water bodies (Van den Broeck et al. 2015). Additionally, the new Groundwater Directive (GD; Directive 2006/118/EC) considers groundwater as a valuable natural resource that should be protected from deterioration and chemical pollution (Menció and Mas-Pla 2010). However, a concern is that the WFD programs do not incorporate assessment techniques for temporary wetlands (Van den Broeck et al. 2015) whilst the links between water quality and ecosystem functions and services, and the implications of water management on ecosystem services are either implicit or overlooked (Acreman et al. 2017). Outside of the EU, data on water quantity and quality are sparse and often biased. This is a real problem, where countries can affect both water quality and quantity flowing downstream to another country, as is the case for some rivers in the eastern part of the Mediterranean Basin.

The global Sustainable Development of Agenda has included water as an important priority, and SDG6 emphasizes safe access to water and sanitation. Water quality is considered as a major environmental problem across the Mediterranean region *(Table 3.4, Section 3.1.3.5)*, with recent assessment indicating that the WFD has improved water quality in the European countries of the Mediterranean Basin while water quality has degraded further in North Africa and the Middle East (Mediterranean Wetlands Observatory 2018).

Freshwater species

Declines in the Living Planet Index (LPI) of Mediterranean wetlands was continuously observed between 1990 and 2008, after which it increased, but with varying results depending on the group and sub-region. Between 1990 and 2013 waterbird numbers show a positive trend and increased in Western Europe (+101%) and Northern Africa. However, more moderate increases were observed in the eastern Mediterranean (+27%) while declines have been observed in the Middle East since 2008. Contrastingly, declines in amphibians, reptiles, mammals and fish have been observed since 1990 (Mediterranean Wetlands Observatory 2018).

Freshwater communities of the Mediterranean region have adapted to the natural variability in water flows through shorter life spans, mechanisms to resist or avoid desiccation, and higher colonization rates (Lytle and Poff 2004; Bonada et al. 2007; Stromberg et al. 2008; Santos 2010). These Mediterranean communities are, therefore, different from those of temperate rivers, showing interannual fluctuations in richness and composition and in trophic structure (Ferreira et al. 2001, 2002; Bonada et al. 2007; Feio et al. 2010, 2014). During dry seasons (predictable and periodical seasonal droughts), groundwater that flows towards streams is highly significant as it represents a unique input for water discharge, leading to steam/river reaches that are permanent, intermittent or ephemeral (Uys and O´Keeffe 1997; Argyroudi et al. 2009). Seasonal droughts can cause habitat loss, poor water quality and biotic interactions, but in severe droughts (longer, unpredictable, seasonal or supra-seasonal droughts) as expected due to climate change, major ecological effects will be observed, stressing and depleting both fauna and flora (Boulton 2003; Lake 2003; Bond et al. 2008; Menció and Mas-Pla 2010).

Mediterranean rivers present rich and dynamic riparian plant communities, which are highly interconnected with lateral and vertical ecotones and have multi-scaled biotic drivers that act in both space and time (Ferreira et al. 2019; Kontsiotis et al. 2019). Natural and human disturbances are entwined forces that shape riparian plant communities, to the point that undisturbed plant communities are difficult to find or characterize. Though there are few truly aquatic species, Mediterranean riparian plants nonetheless play an important role in stream functions (Zaimes et al. 2010; Magdaleno and Martinez 2014). The protection of these species should be a priority in the region, and many riparian areas are included in the Natura 2000 Network and the Ramsar Convention (Zaimes et al. 2010; Ferreira et al. 2019).

Freshwater ecosystems are under threat from the effects of multiple stressors, including non-indigenous species (Navarro-Ortega et al. 2015). Non-indigenous species are considered in the top five causes of biodiversity loss (Bruno et al. 2019) and result in the accelerated impairment of aquatic and riparian habitats and their ecosystem services worldwide (Saunders et al. 2002; Dudgeon et al. 2006; Van den Broeck et al. 2015; Rouissi et al. 2018; Fraixedas et al. 2019). Their increase and expansion are due to the alteration of their hydrologic regimes, and biological and morphological functionality due to agriculture on the floodplain, channel diversions and dams, and increased pollution (Jiménez-Ruiz and Santín-Montanyá 2016). Non-indigenous species in many cases can tolerate and adapt easier to the new conditions. Exotic species often thrive in Mediterranean rivers altered by human activity, further homogenizing river communities worldwide (Cooper et al. 2013). Alteration of the vegetative structure, competitive displacement of native riparian vegetation, reduction of arthropod and avian diversities and abundances are some of the major impacts of non-indigenous species (Saunders et al. 2002; Herrera and Dudley 2003; Dudgeon et al. 2006; Bruno et al. 2019). Examples of non-indigenous species that are serious threats and problems in Mediterranean riparian areas are the *Robinia pseudoacacia, Ailanthus altissima* and *Arundo donax* (Constán-Nava et al. 2015; Bruno et al. 2019; Nadal-Sala et al. 2019). Examples of non-indigenous species that are serious threats and problems in Mediterranean wetlands include *Myriophyllum aquaticum, Carpobrotus edulis* and *Cortaderia selloana* (Lastrucci et al. 2018; Chefaoui and Chozas 2019; Company et al. 2019).

Protected areas (Natura 2000 network and Ramsar Convention)

In the European Union, the importance of conserving and protecting freshwater ecosystems is recognized through the many that have been designated as Natura 2000 sites (Iakovoglou et al. 2013). Wetland protection is also officially a priority for the 159 nations (as of 2009) that have ratified the Ramsar Convention, although wetlands still continue to be under threat of being drained and reclaimed (Ramsar Convention on Wetlands 2018; Geijzendorffer et al. 2019a). Degradation is closely related to the rapid increase in human population, and the increased input of nutrients, pollutants, and sediments, due to increases in urban development, industry, agricultural activities, and water abstraction. The most obvious effect is the loss of biodiversity as a consequence of a reduction in area and the deterioration in conditions, especially in arid and semiarid regions (Brinson and Malvárez 2002).

4.3.2 Projected vulnerabilities and risks

4.3.2.1 Forests

The interactions between different drivers of climate change (CO_2, warming, reduced rainfall, increase in drought frequency and intensity) are predicted to have multiple, and sometimes antagonistic effects on the future condition of Mediterranean ecosystems (Bussotti et al. 2014) *(Fig. 4.14)*. While increasing atmospheric CO_2 concentrations might directly promote forest productivity and growth (Sabaté and Gracia 2002; Keenan et al. 2011), this effect will likely be strongly modulated by increasing temperatures and drought conditions (Peñuelas et al. 2011; Bussotti et al. 2014; Doblas-Miranda et al. 2017; Lo et al. 2019). For pine and oak-dominated Mediterranean woodlands in Israel, Helman et al. (2017) projected that warming scenarios of 1 and 2°C could lead to 16% and 31% reductions of annual gross ecosystem productivity, respectively, despite the increase in atmospheric CO_2.

Warmer and drier conditions also alter plant phenology (i.e., leaf unfolding, flowering and fruiting), usually lengthening the growing season (Peñuelas et al. 2004), with direct consequences on forest productivity and growth (Kramer et al. 2000). Al-

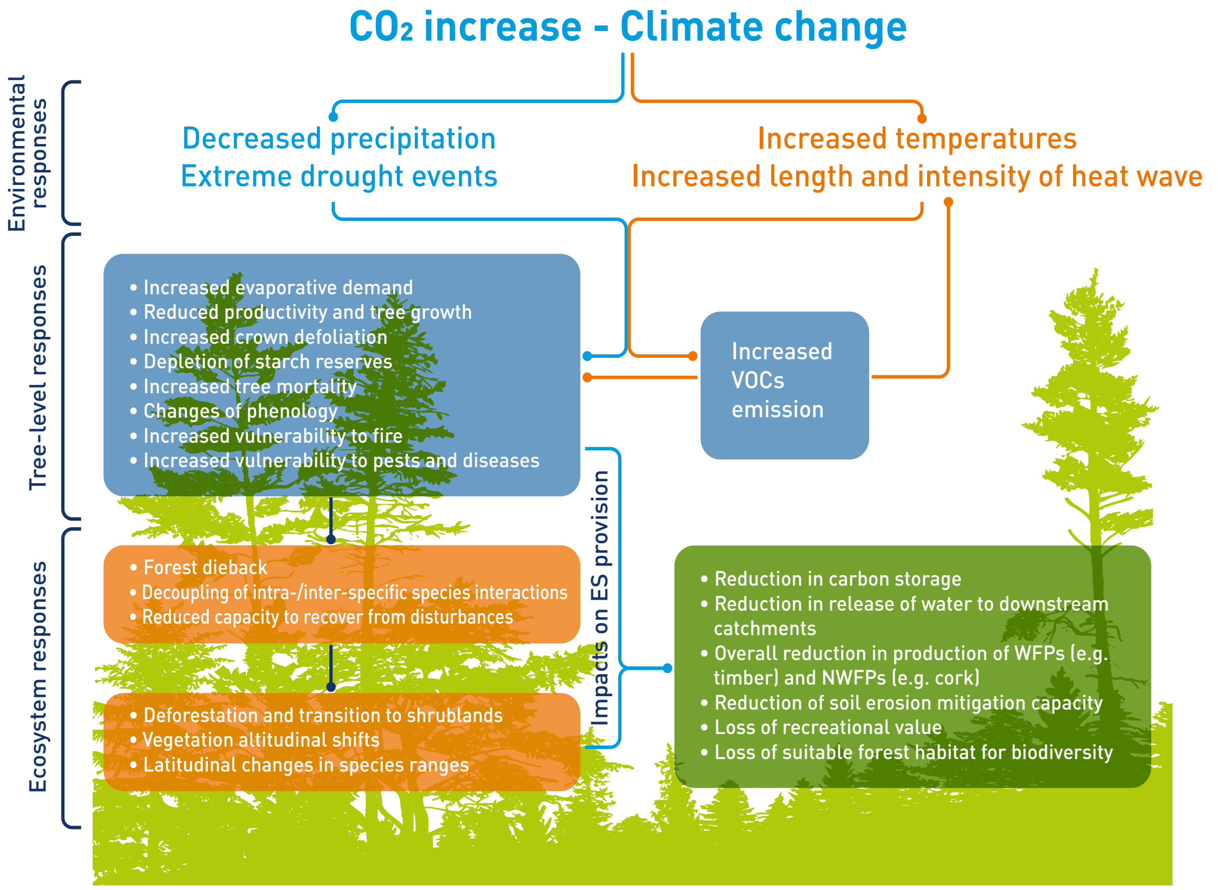

Figure 4.14 | Tree- and ecosystem-level responses in Mediterranean forests to environmental changes associated with climate change and their impacts on ecosystem service (ES) provision. Adapted from Figure 1 in Bussotti et al. (2014) and based on the reviews by Doblas-Miranda et al. (2017) and Peñuelas et al. (2017, 2018).

though a longer growing period may be positive for forest growth, advanced spring phenology may also cause higher risk of frost damage (Mutke et al. 2005), as well as increased transpiration. Moreover, global warming also changes bird migrations and dates of insect outbreaks, leading to a decoupling of species interactions (e.g., decoupling of predator-insect interactions reduces the effectiveness of pine processionary moth control by birds; (Barbaro and Battisti 2011). All factors considered, we can expect a general reduction of site productivity in the mid- and long-term, particularly for species or populations growing in water-limited environments, which constitute the majority of Mediterranean forests (Sabaté and Gracia 2002; Bravo-Oviedo et al. 2010).

Changes in forest ecosystem health and ecosystem services provision

There is evidence that Mediterranean forests and woodlands now experience climate-driven declines in growth and die-back episodes from drought and heat stress (Allen et al. 2010; Lindner et al. 2010; Anderegg et al. 2013; Gentilesca et al. 2017; Klein et al. 2019), similar to shrublands (Lloret et al. 2016; Sapes et al. 2017). Increasing crown defoliation and soil respiration may reduce net primary production and ultimately limit growth in Mediterranean forests, associated with higher mortality and dieback, especially if warming is combined with drought (Peñuelas et al. 2018). The combination of reduced water availability and increased respiration rates of tissues due to rising temperatures can result in hydraulic failure, the exhaustion of reserve carbohydrates and a general weakening of the trees, also making them more vulnerable to pests and pathogens (Rennenberg et al. 2006). Drought has been linked to the general dieback of *Quercus ilex* and *Q. suber* in southwestern Spain, where, known as "seca", the weakened trees are more susceptible to the attack of the fungus *Phytophthora* (Sánchez-Salguero et al. 2013). Although even drought-adapted ecosystems are influenced by growth reductions, these phenomena are expected to become particularly frequent in the trailing-edge of species distribution (Jump et al. 2006; Sarris et al. 2011), or for species found in the Mediterranean Basin, the southern limit of their European distribution (Linares et al. 2010; Dorman et al. 2013), which are particularly vulnerable (e.g., *Pinus pinaster, P. nigra, P. halepensis, P. sylvestris, Quercus ilex, Q. suber, Fagus sylvatica, Abies alba, A. pinsapo, Juniperus phoenicea, Cedrus atlantica*), and especially in dense, unmanaged forests (Lindner and Calama 2013) or in sites with shallow soils (Lloret et al. 2004).

This additional climate stress may lead to important changes in biotic interactions, affecting forest composition and species distribution (see next section). For example, in southern Spain, in a mixed *Abies pinsapo–Pinus halepensis* forest, *A. pinsapo* showed sudden growth reductions under drier conditions, while pine trees were able to maintain almost constant growth values and lower water costs under increasing long-term water stress (Linares et al. 2011). Similarly, Sarris et al. (2011) reported that where mixed *Abies cephalonica–Pinus halepensis* forests exist in southern Greece, *Pinus* did not experience any mortality at this altitude (800 a.s.l.) after drought events, unlike *Abies.* Prolonged droughts and hot spells will aggravate the risk of forest fires, which can further induce problems of soil erosion and fertility. In fact, fire-drought interactions can be complex and trigger vegetation transitions, disrupting ecosystem resilience and even leading to non-forest states (Batllori et al. 2019). In the driest areas, desertification can advance and become a major problem (Karavani et al. 2018a).

Climate change is also expected to affect host plant-pest interactions, favoring the establishment of new ones (Lindner and Calama 2013). Warming already causes changes in the distribution areas of pests, mostly upward and northward. An example is the pine processionary moth *(Thaumetopoea pityocampa),* which is expanding upwards in several mountain ranges due to milder winter temperatures, affecting tree populations that had previously never been exposed to this insect (Hódar and Zamora 2004; Battisti et al. 2005; Roques et al. 2015). The succession of several years of mild winters has favored unprecedented outbreaks in northeastern Spain (Roques et al. 2015). Opportunistic fungi and insects such as *Armillaria* or *Ips* spp. are also being favored by warmer temperatures, which induces better conditions for survival, allowing them to complete more than one generation in one year (Lindner and Calama 2013). The greatest impacts are expected to arise from the establishment of alien pests and diseases, i.e., those that are exogenous to a given environment. The number of alien pests is expected to increase under warmer and drier conditions, as has been the case with the pine nematode *(Bursaphelenchus xylophilus),* native from North America, and with the potential to spread across Europe (de la Fuente et al. 2018) and cause massive wilt and mortality in pine species (Vicente et al. 2012).

All these changes may ultimately lead to profound changes in ecosystem function and associated ecosystem services (Seidl et al. 2014; Peñuelas et al. 2017). Changes in carbon storage and water availability are especially important for their implications in all forest services, because they are the basis of the primary production that supports the services (e.g., timber production) and because of the effects they have on climate change (Peñuelas et al. 2017; Ruiz-Peinado et al. 2017). Increased plant evapotranspiration will decrease the movement of water from forest to downstream ecosystems (Peñuelas et al. 2018), compromising supporting services (e.g., water cycle), provision of habitat for aquatic species and water availability for consumptive uses. Severe summer droughts can reduce the yields of economically relevant NWFP such as cork (Oliveira et al. 2016) and pine nuts (Mutke et al. 2005).

The response of some forest ecosystem services to climate change drivers is still under debate. For example, despite the fact that some studies have highlighted that mushroom productivity in Mediterranean ecosystems may be experiencing a sharp drought-induced decrease (Boddy et al. 2014; Ágreda et al. 2015) due to delayed phenology in the autumn season under warmer and drier conditions (Kauserud et al. 2012; Büntgen et al. 2015), simulations by Karavani et al. (2018b) rather point towards an increase in production of edible and marketable species under climate change scenarios as a consequence of the longer mushroom season. The leisure use of Mediterranean pine forests (for walking, mountain biking hunting, etc.) will probably be negatively affected by the increasing incidence of pest outbreaks of the pine processionary moth (Morán-Ordóñez et al. 2019), as this species is responsible of strong allergic reactions in humans (Battisti et al. 2017). However, simulation studies in Mediterranean forests (Mina et al. 2017) suggest that forest management (i.e., silvicultural interventions) might have a prevailing role over climate in determining the future condition of forests and the provision of their associated ecosystem services. This has also been reported in other forest systems across the globe (Albrich et al. 2018; Schwaiger et al. 2019).

Besides the direct impacts of climate change drivers on the condition of tree species and ecosystem services provision, climate change drivers might push Mediterranean forests past critical thresholds (e.g., changes in community composition, loss of ecosystem functions), which could hamper their capacity to recover from disturbances in the future (Anderson-Teixeira et al. 2013). For example, Mediterranean water-stressed forests are likely to become more vulnerable to pests and pathogens (Lindner and Calama 2013; Gauquelin et al. 2018), as well as to other disturbances such as fire. Post-fire regeneration might be limited under water-limited conditions, ultimately leading to deforestation or transition from oak and pine forest to shrublands (Karavani et al. 2018a), thereby decreasing the overall capacity of the region to sequester atmospheric CO_2 and potentially losing the recreational value of affected areas (Peñuelas et al. 2017).

Changes in species range, abundance and extinction

Climate change is predicted to induce changes in the geographic ranges for many terrestrial species across the Mediterranean Basin (expansion, shrinkage, geographic shifts), with studies showing contrasting predictions depending on the modelling approach, the drivers and the scenarios considered, even when predictions are made for the same species and the same region. For example, on the basis of a process-based model, Keenan et al. (2011), predicted that around 40% of the current suitable stand locations of *Quercus ilex* in Spain will become unsuitable for the species during 2050-2080 under a non-Paris agreement compliance warming scenario (3.1°C) whereas Lloret et al. (2013), predicted an increase in climatic suitability for the same species, region, scenario and time horizon on the basis of a correlative model.

The EU Mediterranean biome was predicted to be the most vulnerable region to plant species loss and turnover in a study by Thuiller et al. (2005), who simulated climatically determined geographic range loss of 1,350 European plant species under seven climate change scenarios (IPCC AR4 SRES scenarios predicting temperature increases ranging from 1.8 to 3.6°C), with climate-related range contractions already reported in Mediterranean mountains (Pauli et al. 2012). Consistent patterns have been forecasted for other taxonomic groups. For example, using bioclimatic envelope models and ensemble forecasting of SRES scenarios, Levinsky et al. (2007) and Barbet-Massin et al. (2012), predicted losses up to 100% and 30% of current potential species richness of mammals and bird species in EU Mediterranean, respectively, for the end of the century. In general terms, species at the rear edge of their distribution in the Mediterranean (e.g., deciduous temperate species like *Quercus petraea*) and mountain species (e.g., *Pinus sylvestris, Abies alba*) will be the species most threatened by climate change (with ranges potentially shrinking), whereas the most xeric Mediterranean species, which are better adapted to drought, are those expected to encounter fewer problems for survival and range expansion under future climate change (Ruiz-Labourdette et al. 2012; Lindner and Calama 2013; Bussotti et al. 2014).

Projections of species range losses due to climate change across the Mediterranean cannot be taken as precise forecasts given the uncertainties in climate change scenarios. Only a few forecasting studies have assessed the interactions of climate change with other drivers (Morán-Ordóñez et al. 2019), there is therefore a risk that the vulnerability of species to other important disturbances, such as land use change, fires and their synergistic effects, is underestimated (IPBES 2019). An additional caveat for studies projecting changes to climatic range is that generally these do not incorporate the role of interactions between species or the effects of extreme weather events, the latter of which is of great relevance in the context of Mediterranean forest systems.

Fire activity and burnt areas across the Mediterranean

The Mediterranean Basin can be considered as a hotspot under future climate conditions conducive to extreme wildfire events, with significant potential impacts for human well-being (Bowman et al. 2017). How exactly climate change will influence future fire regimes is still under debate. While a warmer and drier climate will upsurge fire activity by increasing water demand and decreasing fuel moisture, increasing temperatures may also negatively affect ecosystem productivity and lead to an overall reduction of fuel biomass, which can counteract warming effects on fire activity (Batllori et al. 2013). Drought increases terpene emissions from Mediterranean plants, which are compounds that play a key role in the flammability of forests (Peñuelas et al. 2018). Warming conditions also increase emissions of other volatile organic compounds (VOCs) besides terpenes, with multiple physiological and ecological functions (e.g., plant defense, communication with other organisms) that, in a cascade effect, can affect communities of organisms, ecosystems, atmospheric chemistry and even meteorological conditions, even potentially generating feedbacks to warming (Doblas-Miranda et al. 2017; Peñuelas et al. 2017) *(Fig. 4.14)*.

The increase in exposure to large wildfires in recent years (Bowman et al. 2017), along with the effects of climate change, might still overcome current fire prevention efforts. More and different fire management approaches must therefore be considered in order to increase our resilience towards future Mediterranean forest fires (Moritz et al. 2014; Turco et al. 2018a). Projections indicate an increase of burned areas across the Mediterranean in the future, but it is difficult to compare estimates given the variation between scenarios, future periods and models used. For example, Amatulli et al. (2013) estimated increases of up to 66 and 140% in burnt area in EU-Mediterranean countries in 2071–2100 relative to 1985–2004 under the IPCC SRES scenarios B2 and A2, respectively, and Migliavacca et al. (2013) estimated a 34% increase in burnt area in southern Europe, in 2070–2100 relative to 1960–1990 under the A1B scenario. Turco et al. (2018b) projected future summer burned area in Mediterranean Europe under 1.5, 2, and 3°C global warming scenarios, concluding that the higher the warming level, the greater the increase in burned area, ranging from a ~40% (1.5°C scenario) to ~100% (3°C scenario) increase from current levels across the scenarios. Although the future total burnt area could be smaller if a stationary relationship between drought and fires is assumed, in all the cases the burned area is still expected to increase with warming. Significant benefits (regarding burnt area reductions) would be obtained if warming were limited to well below 2°C (Turco et al. 2018b). These benefits extend beyond plant cover protection or human safety. A reduction of burned areas also reduces risks of soil erosion and desertification, especially in very dry areas (Shakesby 2011).

4.3.2.2 Mountains

Many of the key observed and projected climate changes identified for southern Europe by EEA (2017) apply in the case of Mediterranean mountains, including: (i) significant increase in heat extremes, (ii) decrease in precipitation and river flow, (iii) increasing risk of droughts, (iv) increasing risk of biodiversity loss and (v) increasing risk of forest fires. For Mediterranean mountains, projections indicate warming between 1.4°C and 5.1°C for 2055 (1.6°C and 8.3°C for 2085) and a decrease in precipitation, mainly during spring (-17% under A1fi and -4.8% under B1 for 2085) (Nogués-Bravo et al. 2008).

Mediterranean mountain environments seem to be accelerating towards uncertain ecological states because of changes associated with climate and land use changes (Nogués-Bravo et al. 2008). For the 21st century, projected warming and reduced rainfall are likely to affect: (i) snow pack and glaciers, which provide key habitats for alpine specialist species and, (ii) water availability and river discharge and therefore aquatic and wetland habitats and species. Beyond these indirect effects of climate change in biodiversity, climate change would, (iii) reduce habitat availability of alpine and sub-alpine belts, increasing the risk of extinction for endemic species or range-restricted species and may well disrupt the biological networks that ultimately support ecosystem functioning (Nogués-Bravo et al. 2008).

Mediterranean mountains are susceptible to forest fires and are vulnerable to hydro-geological risks (floods, landslides, infrastructure damage). Most of these hazards will be increased by the predicted rise in temperature and changes in precipitation patterns. Mediterranean mountains provide basic water-based ecosystem services. Therefore, water management and quality-assurance policies need to consider the specific features of mountains and predicted climate change trends. In mountain environments, changes in precipitation (amount and pattern) will be influenced by local geomorphology and therefore predictions are subject to high uncertainty and variation at local and regional scales. Local climate change adaptation strategies require careful consideration in order to counteract specific pressures.

The homogenization of Mediterranean mountain landscapes due to the abandonment of agropastoralism has negative impacts on biodiversity, water resources, soils and natural hazards (Vogiatzakis 2012). For many species in Mediterranean high-altitude zones, including cedars in Cyprus and Lebanon, migrating upwards is not an option (Fernández Calzado et al. 2012). For other species, such as junipers, climate change and increased fires have adverse effects on regeneration, which is already limited by the environment (Vogiatzakis 2012). Fire events are likely to increase in number and intensity in Mediterranean mountain forests and will be associated with elevational shifts of dominant tree species (Fyllas and Troumbis 2009; Pausas et al. 2009). Reduced depth and persistence of snow cover will also affect high mountain vegetation (García-Romero et al. 2010).

4.3.2.3 Drylands and shrublands

There is high confidence in observed drought increases in the Mediterranean and West Africa and medium confidence that anthropogenic climate change has contributed to increased drying in the Mediterranean region and that this tendency will continue to increase under higher levels of global warming (Koutroulis 2019). According to global warming levels of 1.5°C, 2°C and 4°C above pre-industrial temperatures, Mediterranean land will shift to drier types by 11.6%, 20.1% and 41.3% respectively *(Fig.4.15b-d)*. With a 2°C global temperature rise, annual warming over the world's drylands is expected to reach 3.2°C–4.0°C, implying about 44% more warming over drylands than elsewhere (Huang et al. 2016), thus potentially aggravating water scarcity issues through increased evaporative demand. The Mediterranean, North Africa and the eastern Mediterranean will be particularly vulnerable to water shortages, and expansion of desert terrain and vegetation is predicted to occur in the Mediterranean biome, an unparalleled change in the last 10,000 years *(medium confidence)* (Guiot and Cramer 2016). At 2.5°C–3.5°C, risks are expected to become very high with migration from some drylands resulting as the only adaptation option *(medium confidence)*. Scarcity of water for irrigation is expected to increase, in particular in Mediterranean regions, with limited possibilities for adaptation (Haddeland et al. 2014; Malek and Verburg 2018).

Mediterranean drylands are relatively resilient systems with a certain capacity to recover from various forms of disturbance that have occurred for millennia, such as fires, overgrazing and drought (García-Romero et al. 2010). Nevertheless, these ecosystems face critical thresholds with potential catastrophic shifts that may trigger biological diversity losses and modifications in ecosystem functioning and services (Daliakopoulos and Tsanis 2014). The resilience of Mediterranean drylands is currently under pressure from various factors, such as high permanent and seasonal population density, abandonment of traditional practices, continued habitat conversion (2.5% of Mediterranean habitat was lost between 1950 and 1990) and loss of the typically high spatial natural heterogeneity (Fahrig 2003). Although vegetation recovery both from shrubs and forest can reduce soil erosion and enhance carbon sinks, it might change the cultural landscapes frequently developed from initial mosaics of different land-use types towards homogenized states with dense shrubs (Stellmes et al. 2013). Increases in woody biomass and the loss of gaps and breaks as well as edges between different fuel types make these landscapes more vulnerable to fires compared to disconnected patches of forest, shrub and cultivated fields or grasslands (Puigdefábregas and Mendizabal 1998; Viedma et al. 2006; Röder et al. 2008), in particular during drought (Viegas 1998; Duguy et al. 2007).

Since 1960, wildfire occurrence in many Mediterranean drylands has increased because of changes in land use. The level of soil degradation due to these fires depends on fire recurrence, topography, the

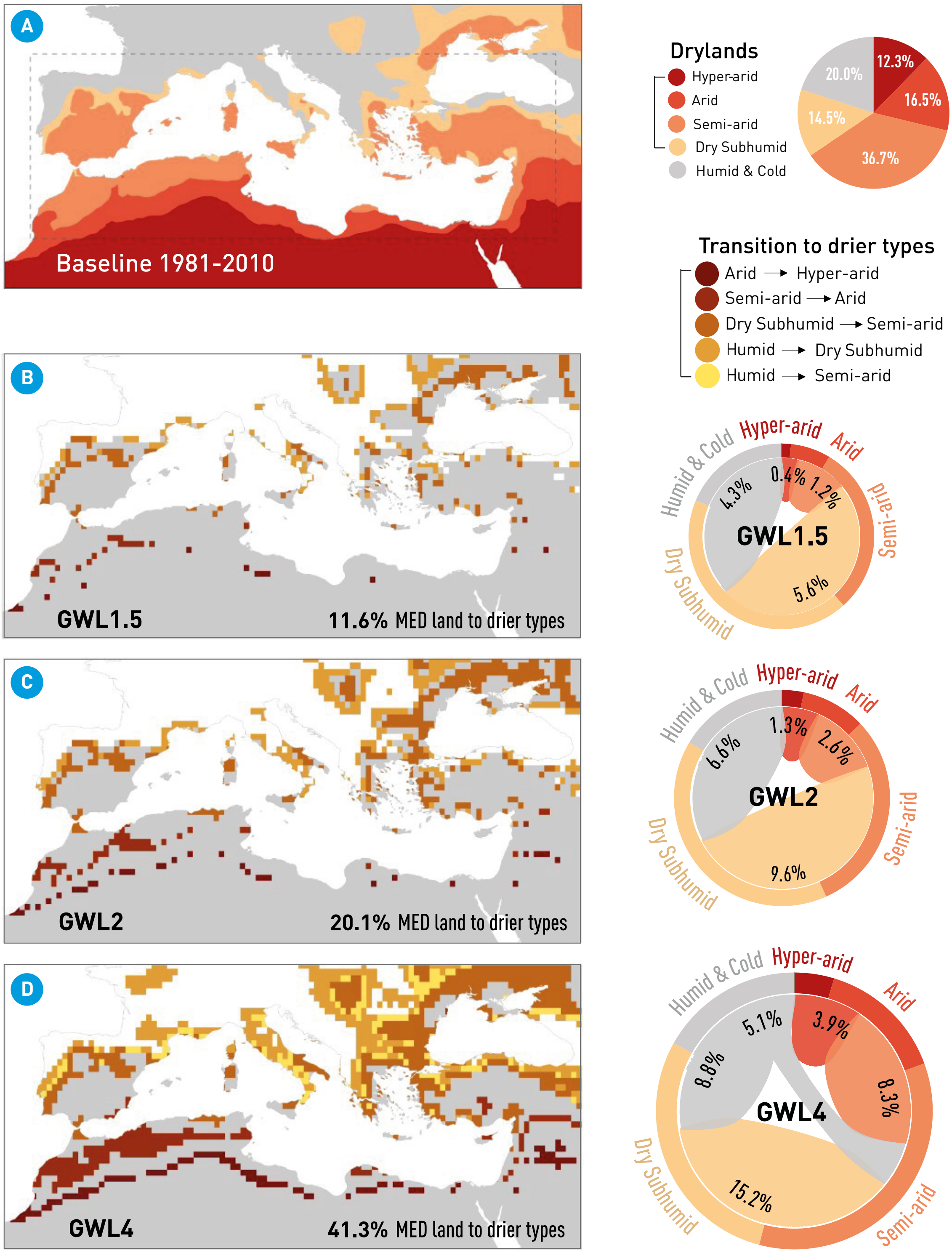

Figure 4.15 | **(A) Distribution of drylands and their subtypes based on observations** (reanalysis combined with station and satellite observations) for the 1981-2010 baseline period. Areal coverage (percentage) of drylands per subtype is presented in the form of pie charts and is calculated within the boundaries of the Mediterranean SREX region (dashed line). **(B, C, D) Distribution of projected dryland transitions according to RCP8.5 for three Global Warming Levels** (GWLs: +1.5°C, +2°C and +4°C from preindustrial levels), relative to the baseline (1981-2010) period, using the high-resolution atmosphere-only version of the HadGEM3A model. Grey shaded areas in (b), (c) and (d) are drylands of the baseline period. Chord diagrams denote the areal extent (fraction of MED SREX land area) of projected transitions in each dryland subtype under the three GWLs. The size of the chord diagrams is proportional to the total areal extent of the MED land changing to drier types. Figure adapted from (Koutroulis 2019).

intensity of soil erosion processes and post-fire plant cover regeneration rate (Caon et al. 2014). To promote the accumulation and retention of nutrients in soil after a fire, it is important to stabilize the burnt site by applying post-fire measures that limit soil erosion, surface runoff and loss of the ash due to wind. Depending on the plant species and the time that elapses between consecutive wildfires, fire is responsible for the transition from forests to shrublands, which are poorer in soil nutrient status. High fire frequency may cause the eradication of keystone species, which has consequences for soil nutrient pool recovery (Caon et al. 2014). In addition to the increased risk of soil erosion, frequent wildfires also induce changes in the water cycle by altering the infiltration capacity of soil and increasing soil hydrophobicity (Vallejo and Alloza 1998; Fernández et al. 2012; Carreiras et al. 2014).

Droughts

Mediterranean shrublands are experiencing important episodes of drought-induced die-back explained by the decrease in climate suitability for plants during the drought event (Lloret et al. 2016; Sapes et al. 2017). In anticipation of a drier climate and to project future changes in dryland dynamics, it is imperative to understand species-specific differences in drought resistance (Väänänen et al. 2020). In the long rainless eastern Mediterranean summer, it was found that the physiological traits of species exhibiting different levels of mortality and co-existing in the same habitat (*Phillyrea latifolia, Pistacia lentiscus* and *Quercus calliprinos*) were more associated with drought resistance strategies rather than actual drought stress experienced by the plants (Väänänen et al. 2020). The intensity of drought effects on shrub performance is thus species-specific, and plant species combination-dependent. High shrub richness levels modulate the negative impacts of aggravated drought conditions. Results point to a probable shift in interspecific relationships in response to water shortage. As drought impacts are not mediated in low-diversity communities, species-specific responses to drier conditions could lead to shifts in plant community composition favoring the most drought-resistant species such as oaks and rosemary. Maintaining high diversity appears critical to mediate drought effects for less resistant species (e.g., *Cistus* and *Ulex*) (Rodriguez-Ramirez et al. 2017).

4.3.2.4 Agriculture and pasturelands

The ongoing changes to agricultural systems in the Mediterranean Basin are the outcomes of a combination of climate and other drivers that influence farmers' perceptions and choices (Fahrig 2003; Nguyen et al. 2016), which in turn trigger changes in agroecosystems and their service provision at different scales. These processes have a strong site-specific component with a common background of multiple pressures including global and climate changes (Kummu et al. 2017).

Mediterranean agriculture is generally vulnerable to shocks in the flow of agricultural commodities, particularly in southern countries, because of the heavy dependence on imports (Capone et al. 2014). This is coupled with expectations of future adverse climate impacts leading to the decrease of water-limited crop yields (Schils et al. 2018), increase in irrigated crop water demand, increasing risks in livestock production and mortality associated with heatwaves, expansion of habitats for southern disease vectors and increases in multiple climate hazards (EEA 2017). These impacts hamper the profitability and the ecosystem service provisioning of agricultural activities, particularly in the most vulnerable situations, such as those of farm enterprises relying on natural and semi-natural resources in marginal land or where farmers have made large investments and are therefore exposed to high capital risks (Dono et al. 2014). The latter is the case, for instance of intensive dairy farming, where lower animal productions caused by an increase in the frequency of heatwaves are not counterbalanced by potential benefits in terms of irrigated forage crop yield that can be expected as a consequence of higher temperatures in winter and/or CO_2 concentration rise (Dono et al. 2016).

Water represents a key factor for risk, vulnerability and the resilience of agriculture at farming system and landscape scales (Iglesias et al. 2007). Extreme drought and flooding are two side effects of the same climate pressure (Iglesias et al. 2007; Quintana-Seguí et al. 2016) and there is evidence that the Mediterranean Basin is highly vulnerable to reductions (up to -49%) in provisioning and regulating ecosystem services associated with agricultural water use and management (Jorda-Capdevila et al. 2018). Dramatic changes in the water balance of Mediterranean watersheds are ongoing, as a consequence of a combination of changes in rainfall regime, temperature rise and the increase in vegetation cover from the abandonment of agricultural and pastoral activities, particularly in northern countries (Serpa et al. 2015; Krause et al. 2016; Zeng et al. 2018), which can also result into increased soil erosion (Bussi et al. 2014).

These dynamics are affecting grassland-based systems (e.g., reduction of water pools for animal drinking) and large catchments based on mountain water resources and hence the availability and stability of groundwater and reservoir stocks to be potentially used for irrigation (Rolo and Moreno 2019). There is also evidence of increased vulnerability of water stocks potentially affecting agricultural systems in southern Europe and northern Africa, more than in eastern countries of the Mediterranean Basin, caused by both ongoing climate and socio-economic dynamics, which in most cases, cannot be totally eliminated by adaptation strategies (Koutroulis et al. 2019).

The expected impacts of climate change on croplands and grasslands are often assessed by modelling under current and future climate scenarios (Moriondo et al. 2010; Koutroulis et al. 2019), sometimes integrated with economic (Dono et al. 2016) and policy change analyses (Cortignani and Dono 2018). Unfortunately, only a few studies consider the combined effects of the other drivers of ongoing changes such as those related to technology development, consumer behavior, energy production etc. (Alexander et al. 2015; Doblas-Miranda et al. 2017). Differences in geographic, political and environmental context characterize agriculture and pastureland ecosystems of each sub-region of the Mediterranean Basin, resulting in diverse spatial distribution of vulnerabilities and risks (Prosperi et al. 2014).

In southern European countries the impacts of climate pressures (e.g., increased drought) are coupled with the ongoing transformation agroecosystems (e.g., abandonment in marginal lands and intensification of coastland agriculture). Forest wildfires, landslides and depopulation of marginal rural areas cause additional change (Nainggolan et al. 2012), just as water and air pollution in intensively cultivated areas. Overall, production (food or forage) is given priority over regulating or cultural services (Aguilera et al. 2013; Maes et al. 2018), except for the urbanization of agricultural fertile soils (Ceccarelli et al. 2014).

In the Middle East and northern African countries, multiple stressors include climate, groundwater overexploitation, seawater intrusion in coastal areas, water pollution, land degradation and desertification (Sowers et al. 2011; Schilling et al. 2012; Fouchy et al. 2019), impacting social and political stability (de Châtel 2014). Future trends in agricultural and pastoral land use are very much context-sensitive, as predictions of future dynamics are the consequence of multiple drivers beyond climate, which are much more uncertain in northern Africa than for southern European countries (Prestele et al. 2016).

Focusing on an agricultural and pastoral district (some 54,000 ha) characterized by a mosaic of many different crops and land uses in southern Europe, located in the mid-west Mediterranean Basin, Dono et al. (2016) have shown that the same climate and socio-economic pressures can generate a mosaic of different impacts on diverse farming systems even within the same production system. Several factors, including economic farm size, the dependence on external inputs and the availability of water, contributed to a range of situations: rice and vegetable farms were the "winners", as long as water is not a constraint in the near future, while "losers" were livestock farmers whose feeding system was based on rain-fed grasslands suffering from the increased frequency of extreme drought, hampering hay stock production (e.g, dairy sheep and beef cattle), or those heavily dependent on external inputs, such as the dairy cattle system. Net impacts were associated mainly with the increased frequency of heat waves with a high temperature-humidity index (Bernabucci et al. 2014).

Cropping systems

The potential higher resilience of irrigated cropping systems to increased drought must be managed in the context of +4 to +18% increased crop water requirements due to climate forcing under different scenarios, involving water resource availability in quantity and quality and water use efficiency, particularly in southern and eastern Mediterranean countries (Fader et al. 2016; Malek and Verburg 2018). At present, the Mediterranean region could save some 35% of irrigation water by implementing more efficient irrigation and water management systems, but southern and eastern sub-regions would need around 35% more water than today in the future, even after the implementation of some degree of modernization of irrigation and conveyance systems, taking into account increased CO_2 fertilization effects (Fader et al. 2016) and the need for supplemental irrigation for winter cereals (Saadi et al. 2015). Mediterranean irrigated croplands include a wide range of vegetable crops, including potato, orchards and grapes, forage crops and, in southern countries, sugar cane and cotton. Most C_3 irrigated crops (e.g., many vegetables and rice) would benefit from increased CO_2 fertilization effects and some C_4 from the increased temperature (e.g., sugar cane and maize) but others might be negatively affected (e.g., olives) (Makowski et al. 2020).

Studies on climate change impact on vegetable production are scarce. Bisbis et al. (2018) have shown that climate change may threaten vegetable crop yield and quality in response to rising CO_2 and O_3 concentrations as well as extreme events. Heat stress reduces fruit set of fruiting vegetables and accelerates the development of some crops, thus reducing assimilation, resulting in lower quality and higher product waste. Vernalization of some crops such as cauliflower can also be threatened by cool season temperature increase. Fruit crops such as apples may suffer significant delays to flowering dates due to temperature rise and the difficult achievement of chill requirement fulfillment in milder Mediterranean climates, which might threaten the cultivation of sensitive varieties in currently vacated areas (Funes et al. 2016). Most of these impact assessments are made without considering the threats related to increased incidence of pest, diseases and weeds (Bindi and Olesen 2011; Pautasso et al. 2012; Hulme 2017) and those related to extreme events such as flooding (Erol and Randhir 2012).

In the Mediterranean area, rain-fed croplands include mainly winter cereals, forage crops and other autumn-spring herbaceous crops, and perennials such as grapes and olives. Schils et al. (2018) showed that water-limited cereal yield gaps are still relevant, particularly in eastern European countries, as they are substantially higher than for irrigated crops. Unlocking the potential for production growth requires a substantial increase of crop N uptake and/or N use efficiency. Filling these gaps requires ecological or sustainable intensification of agricultural systems, and has many implications on innovation of cropping systems, their ecosystem services and impacts on GHG emissions and soil functions (Cassman 1999; Serpa et al. 2015; Hamidov et al. 2018; Serraj and Pingali 2019). Currently, the climate resilience of European wheat crops is declining because of the decline in the response diversity that is emerging both from farmers' fields and plot experiments also in southern European countries (Kahiluoto et al. 2019). This suggests that current breeding programs and cultivar selection practices do not sufficiently prepare for climate uncertainty and variability and calls for more coordinated assessment and communication of response diversity among plant breeders,the recovery of old varieties that had been abandoned by seed producers to be considered and the need for domestication to broaden the germplasm pool (Langridge 2019).

Climate change will impact olive crop evapotranspiration (+8%) and irrigation requirements (+18.5%) and crop phenology, up to reducing the possibility of rain-fed cultivation (Tanasijevic et al. 2014). Furthermore, climate change will also impact the interaction of olive and the obligate olive fruit fly *(Bactrocera oleae)* and alter the economics of olive crop across the basin. Climate warming will affect olive yield and fly infestation levels resulting in economic winners and losers at the local and regional scales, that overall result in threatened biodiversity and soil conservation (Ponti et al. 2014a).

Wine grape production provides a good test case for measuring indirect impacts mediated by changes in agriculture, because viticulture is sensitive to climate and is concentrated in Mediterranean climate regions. At the global scale, the impacts of climate change on viticulture are expected to be substantial, leading to possible conservation conflicts in land use and freshwater ecosystems. The area suitable for viticulture is expected to drop up to 73% in major wine producing regions by 2050 in the worst scenario (RCP8.5), which could be partially compensated by upland or northward cultivation, or by irrigated crops, possibly resulting in land or water degradation (Hannah et al. 2013). The projected increasing temperatures will result in a general acceleration and shortening of the phenological stages compared to the present period. Accordingly, the reduction in time for biomass accumulation negatively affects the final yield. In the cooler subregions of the Mediterranean Basin such as southern France and western Balkans, climate conditions are not limiting and the crop benefited from enhanced atmospheric concentration of carbon dioxide (Schils et al. 2018). Impacts are also expected on grape composition and hence wine quality, in particular with respect to aroma compounds. Furthermore, the frequency of extreme climate events such as hail and flooding is likely to increase vulnerability and risks in some areas (van Leeuwen and Darriet 2016).

In the warmer areas, increasing temperature can have detrimental impacts on grape yield due to increased asynchrony between the larvae-resistant growth stages of the grapevine and the larvae of the grapevine moth. On the other hand, the increase in pest pressure due to the increased number of generations might not be as severe as expected, because of the advance in harvest dates limiting damages from late-season generations. Furthermore, powdery mildew is expected to decrease in disease severity, especially in years with a later onset of the disease symptoms and under the most extreme warming scenarios (Caffarra et al. 2012).

Grasslands and grazing systems

Mediterranean pastoral systems in drylands are expected to be severely impacted from climate change, mainly because of altered rainfall regime and grassland ecosystem water balance. Pastoral mobility, where possible, can mitigate the effects in terms of livelihood but not necessarily in economic terms (Martin et al. 2014). These impacts are expected to be site-specific as they are related mainly to the change in precipitation variability, which appears as the main determinant of degradation in terms of losses in fodder and livestock production in drylands. Perennial forage plants adapted to Mediterranean conditions are a fundamental resource (Lelièvre et al. 2011), providing that sufficient rest is allowed between two subsequent grazing periods. However, projected change is expected to outrange the adaptive capacity of pastoralists. Similar conclusions about the dependence of climate change effects on land use and subregions in grassland systems were achieved by Bütof et al. (2012), who showed how single plant species respond in many different ways to climate pressures because of the complex interactions of climate change with land use practices. More assessments are expected from the use of grassland modelling well-calibrated to Mediterranean-type ecosystems (Pulina et al. 2017; Langridge 2019).

Wooded pastures such as dehesa-type habitats, are a typical high nature value (Bernués et al. 2016) agro-silvopastoral vegetation of many Mediterranean countries, particularly in the western basin (Bagella et al. 2013; Torralba et al. 2016; Seddaiu et al. 2018). These types of ecosystems are already threatened by current management systems under present climate conditions (Rossetti et al. 2015) and by increased drought risks in relation to stocking rates and grazing management, leading to potential higher economic losses with high stocking rates (Iglesias et al. 2016). Tree survival in such ecosystems depends on deep water reserves throughout late spring and summer, which helps to avoid competition for water with herbaceous vegetation (Cubera and Moreno 2007).

Few studies have explored how climate change and grazing interactively affect the biodiversity, primary productivity and ecosystem stability of grassland ecosystems. A recent meta-analysis indicates that the effects of climate change on biodiversity and ecosystem functioning were largely dependent on grazing history within same climate conditions. However, more field studies are needed to test how different climate scenarios affect the biodiversity, functioning, structure and stability of grassland ecosystems, to address sustainable grassland management in different environmental and climate contexts (Kairis et al. 2015; Li et al. 2018).

Vulnerability and risks are mainly associated with the increased frequency of heat stress in summer, leading to heavy impacts on animal health and welfare, i.e., increased incidence of diseases and mortality or lower fertility (Lacetera 2019). Indirect effects of climate pressures increase vulnerability and risks associated with new vector-born infections such as bluetongue (driven by *Culicoides imicola*), or other direct parasites, whose spread can be facilitated by a milder winter climate in northern Mediterranean countries (Bosco et al. 2015). Other indirect effects can be related to the increased incidence of mycotoxins in fodders due to a higher incidence of pests and diseases in forage crops favored by increased temperature (Bernabucci et al. 2011).

4.3.2.5 Freshwater ecosystems

Rivers and streams

In most of the Mediterranean region average river discharge is predicted to decrease while both water temperature and the frequency of large floods are likely to increase (Calbó 2010). The projected decrease in rainfall and increase in temperatures will result in a 10 to 30% decrease in river discharge by the end of the 21st century and a significant reduction in the availability of freshwater (Allen and Ingram 2002; Milly et al. 2005; Lelieveld et al. 2012).

In the eastern Mediterranean, many authors have detected negative trends in runoff. This was the case for rivers located in Greece (Giakoumakis and Baloutsos 1997) and the Balkans (Genev 2003; Rivas and Koleva-Lizama 2005; Frantar and Hrvatin 2006), Lebanon (Shaban 2009) and Turkey (Kahya and Kalayci 2004). In the western basin, the Duero Basin in the Iberian Peninsula is the most obvious example. Since 1960, Duero River discharges have decreased by 20 to 50% (Ceballos-Barbancho et al. 2008; Morán-Tejeda et al. 2010). Most Mediterranean catchment headwaters are in mountainous areas and are snow-fed. In various regions across the Mediterranean, snow-fed high mountainous springs are the only source of runoff during the long dry summer of the Mediterranean climate. Hence, an increase in temperatures cause less snow accumulation and an irregular and rapid snowmelt, which will result in turn in higher winter and lower spring discharges and decreasing summer low flows. These impacts are observed in various part of the Mediterranean such as the Pyrenees (López-Moreno and García-Ruiz

2004; López-Moreno 2005) and in Lebanon (Shaban 2009).

Overall, projections suggest decreased hydrological connectivity, increased concentration of pollutants during droughts, changes in biological communities as a result of harsher environmental conditions, and a decrease in biological processes like nutrient uptake, primary production, or decomposition. Furthermore, the increased pressure on shrinking water resources will compound the impacts on river ecosystems (Navarro-Ortega et al. 2015).

Wetlands

Mediterranean wetland water depths and hydroperiods (meaning the water inundation period) along with the increase in their salinity levels and isolation and fragmentation are affected by multiple human activities (e.g., water extraction) (Ramírez et al. 2018). These activities are altering the water budgets of wetlands and reducing their ecosystem services. Reed beds in the region have expanded by 89.3% and are the predominant aquatic plant of the all wetlands in the region, which is a major change. In contrast, open water areas and wet meadows have decreased by 53.7 and 96.5% respectively (Papastergiadou et al. 2007). The loss of these key wetland features (e.g., open waters and wet meadows) are impacting the structure of waterbird communities. The future conditions of climate change scenarios will further reduce the environmental suitability of Mediterranean wetlands for the guilds of diving birds and vegetation gleaners (Ramírez et al. 2018).

Freshwater biodiversity

The high intensity and large-scale water management alterations on rivers and streams of the region have had a particularly strong impact on these ecosystems, possibly the highest in the world (Grantham et al. 2013). A similar trend in fish biodiversity loss, also associated with water management pressures, has been reported for rivers in the Iberian Peninsula (Aparicio et al. 2000; Benejam et al. 2008; Clavero et al. 2010). The establishment of alien species in these ecosystems, which can alter natural processes and adversely affect native biota, has also been associated with numerous anthropogenic hydrologic infrastructure in the region (Elvira and Almodovar 2001; Clavero et al. 2004; Light and Marchetti 2007; Grantham et al. 2013).

The Mediterranean-climate freshwater ecosystems host fauna that have evolved and are adapted to the stresses of its streams and rivers. With climate change predicting longer or more extreme drying events (Lawrence et al. 2010; Filipe et al. 2013), their populations and communities will be highly stressed during dry years, thus reducing the resilience capacity of Mediterranean rivers and streams and compromising the survival of their biota (Magalhães et al. 2007). Under this situation, these new conditions will lead to irreversible, and undesirable, "regime shifts" in Mediterranean rivers (Cid et al. 2017).

Due to climate induced changes, stream biota tend to move towards higher elevations and upper latitudes, while the communities change and homogenize their composition (Filipe et al. 2013). Some life-history traits provide biota with resilience and resistance to adapt to the new conditions although it appears that in many cases, current and future environmental changes are exceeding the biota survival boundaries. The difficulty of distinguishing disturbances due to natural hydrologic variability from the effects of climate change in the region make adaptation forecasts even more challenging. Long-term studies are needed to improve knowledge regarding stream biota ecological responses due to climate change (Filipe et al. 2013).

The reduction of subsurface inflow to streams and the changes in groundwater dynamics that have degraded of their biological quality have already made these ecosystems highly vulnerable (Benejam et al. 2008). In addition, wastewater inflow (whether treated or not) into streams will further exacerbate the pressures on fluvial ecosystems, even though initially the induced drought impacts can be partially offset by these industrial discharges. The hydrological benefits of these discharges are compromised by declines in water quality and habitat quality. Moreover, the capacity of aquatic ecosystems to cope with droughts has been lost or significantly reduced in many regions (Andersen et al. 2004; Bond et al. 2008; Rault et al. 2019).

4.3.3 Adaptation

Communities continue to be significantly dependent on ecosystem services for their livelihoods and therefore the preservation of the livelihood and culture of communities together with its biodiversity, in these areas is considered as important to promoting sustainable development and adaptation to climate stresses within the region. The integration of humans, and human actions within the landscapes and seascapes of the Mediterranean region also embraces the IUCN Category IV - Protected Landscapes (Dudley 2008), which provides the flexibility to offer protection to entire landscapes, as shaped through the interaction of human actions and nature, as well as specific protection for specially defined purposes (e.g., habitats/species). Appropriate (integrated) landscape management can be used to promote heterogeneity compensating for the loss of habitat diversity:

- the protection of traditional food systems, conservation of species and functional agricultural biodiversity, and improvement in cropping and irrigation systems to adapt to a changing climate,
- sustainable urban development that promotes the uptake of nature-based solutions that are suitable for a Mediterranean climate in urban areas to provide benefits to biodiversity, contribute to ecosystem services and increase resilience to climate change *(Box 4.2)*,
- semi-natural ecosystems: adaptive management includes the implementation of habitat management, restoration and afforestation actions to provide benefits to biodiversity and human well-being, whilst using species adapted to expected future conditions,
- managing changing disturbance regimes: preventive (e.g., pest monitoring) and remedial (e.g., sanitation felling, pest control).

This section provides an overview of the opportunities for adaptation of ecosystems, through incremental (capacity-building) actions and impact-based actions, whilst considering the limitations to the adaptability of Mediterranean social-ecological systems and the impacts of these actions on biodiversity and the ecosystem services and benefits to human well-being. In this analysis, the role of human influences and inputs on ecosystem structure and functions is critical to promoting (or limiting) adaptation of Mediterranean social-ecological systems.

4.3.3.1 Forests

Mediterranean forests will need to adapt to a warmer and drier climate, which entails extended drought periods, long heat waves, increasing fire risk and exposure to increased intensity and frequency of biotic disturbances (e.g., pests). Mediterranean forests, as any other type of ecosystem, have an inherent adaptive capacity as a result of the co-evolution of plants with environmental conditions that have always changed (Valladares et al. 2014a). However, the speed of current environmental change is unprecedented and poses doubts concerning the ability of Mediterranean species to cope with the change to come, and in some cases might make it advisable to adopt planned adaptive measures.

Biological adaptation

The inherent adaptive capacity of forests includes in situ adjustments to new environmental conditions via phenotypic plasticity or natural selection, and migration to more suitable habitats (Matesanz and Valladares 2014). Climate envelopes are shifting polewards and upwards, and the easiest response to climate change may be a geographic shift in distribution into climatically suitable areas (Christmas et al. 2016). There is already evidence of some species responding to increasingly warmer and arid conditions through altitudinal or latitudinal migration. For example, Peñuelas et al. (2007) and Peñuelas and Boada (2003) showed a gradual upward shift of the temperate *Fagus sylvatica* species in northeastern Spain and their gradual replacement by the xeric *Quercus ilex* in the mid- and low- altitudes. Similarly, Sanz-Elorza et al. (2003) reported an encroachment of sub-alpine grasslands by Mediterranean woody species characteristic of lower altitudes during the second half of the 20th century in mountain systems of central Spain. Upward migration of forest species has also been reported in the Italian Apennines (Palombo et al. 2013), the Spanish Pyrenees (Améztegui et al. 2010, 2016) or southeastern France (Bodin et al. 2013). However, although these movements coincide with an increase in temperatures, changes in land use (agricultural abandonment and reduction of anthropic pressure on forests) seem to play a preponderant role in forest expansion (Améztegui et al. 2010). Most of the species altitudinal displacements have occurred via the colonization of open areas after their abandonment. Replacement of a given tree species by their low-altitude neighbors is only possible when there is a retraction in its trailing-edge distribution, such as in the case of the Montseny mountains studied by Peñuelas and Boada (2003). However, altitudinal range retractions have received much less attention than lead-edge expansions, particularly in Mediterranean mountains, although they seem to be occurring in many mountain areas worldwide (Jump et al. 2009).

Phenological observations since the 1950s show a fairly consistent response of Mediterranean vegetation to rising temperatures. Between 80 and 96% of the species studied advanced their leaf unfolding, delayed the leaf fall, or both, which resulted in an average extension of 30 days in the growing season between 1952 and 2000 (Peñuelas et al. 2002). The lengthening of the growing season could trigger increases in growth but can also cause higher frost damage risk and increased water transpiration. There is less consensus about the physiological plasticity of Mediterranean forest species to environmental stressors. The current available information reveals the potential for some Mediterranean plant species for significant plasticity and rapid evolutionary change, and epigenetic responses have also been documented (Madlung and Comai 2004). However, this information is fragmentary and suggests large differences among species, with some of them being quite vulnerable to fast rates of environmental change (Matesanz and Valladares 2014). Some studies reveal contrasting functional responses to disturbances among tree species and forest biomes. For instance, evergreen gymnosperms growing in drought-prone areas showed lower resistance but faster recovery after drought events than plants dominating in temperate or wet regions, which suggests different physiological strategies to cope with drought (Gazol et al. 2018). This may be of great importance in a changing future, as the response of vegetation may be different as droughts become more intense, more frequent, or both. Tree species with wide a distribution range also seem to display contrasting responses across their entire range (Benito-Garzón et al. 2011) that have been related to intraspecific plasticity and genetic differentiation among tree populations as a result of differences in the intensity of the environmental stresses (Benito-Garzón et al. 2013). In a drier environment, interactions between species may also be altered. According to the stress gradient hypothesis (Maestre et al. 2009), facilitative effects may become more frequent. In fact, the role of shrubs as nurse vegetation for pine seedlings has already been documented in semi-arid and arid Mediterranean regions (Castro et al. 2004; Gómez-Aparicio et al. 2008), and this role could become even more important in the future.

The degree to which physiological responses lead to vegetation shifts (i.e., changes in the composition of the vegetation) is fundamentally unresolved. When two or more species coexist and are differently affected by directional changes in climate and/or by disturbance events, demographic responses become fundamental to project the fate of woody plant communities (Martínez-Vilalta and Lloret 2016). Mortality and regeneration thus become the key processes, since a vegetation shift will only occur if the initially affected species is not able to regenerate and dominate again (Martínez-Vilalta and Lloret 2016). In a drier environment, interactions between species may also be altered. According to the stress gradient hypothesis (Maestre et al. 2009), facilitative effects may become more frequent. In fact, the role of shrubs as nurse vegetation for pine seedlings has already been documented in semi-arid and arid Mediterranean regions (Castro et al. 2004; Gómez-Aparicio et al. 2008), and this role could become even more important in the future.

Limits to adaptation

Forests are particularly sensitive to climate change, because the long life-span of trees does not allow for rapid adaptation to environmental changes (Lindner et al. 2010). Moreover, the Mediterranean region is likely to experience more adverse effects of climate change when compared to Europe, while being the least prepared to cope with such drastic changes (Lindner et al. 2010; Lindner and Calama 2013). On the one hand, the strong human impact on Mediterranean forests has led to high levels of fragmentation, which alter population genetics and species ecology, and affect the ability of populations to respond to environmental changes. Furthermore, adaptive capacity is usually the lowest at the rear edge of species ranges, where plants are growing close to their physiological limits, as is the case for many species dwelling in Mediterranean forests. These forests cannot benefit from gene flow from better adapted populations, so only short-term adaptation and plasticity are available to cope with the extinction risk (Lindner and Calama 2013).

Fragmented populations suffer from greater genetic drift, homozygosity and inbreeding within populations, and are less likely to benefit from the positive effects of gene flow (Valladares et al. 2014b; Christmas et al. 2016). Both the adaptive capacity to new environmental conditions and the ability to migrate are hampered by fragmentation. Shifts in species or population ranges to track optimal climate conditions can be limited by fragmentation, which acts as a barrier for the colonization of many species. Indeed, migrations are not as common as could be expected (Harsch et al. 2009; Zhu et al. 2012), potentially putting populations at higher risk of becoming increasingly maladapted over time (Christmas et al. 2016), particularly at the rear end of species distributions, where populations are deprived of gene flow from better adapted populations (Lindner et al. 2010). Under the projected rates of future climate change, migration will rely on the evolution of very long dispersal distances in order to enable species to reach suitable new habitats. Moreover, global warming will also lead to a decoupling of species interactions (pollinators, predator-prey, etc.) that can further complicate the migration of several forest species.

If species fail to migrate, then *in situ* adaptation will be the only strategy for persistence (Christmas et al. 2016). In this regard, fragmented populations also show lower capacity of adapting and responding to changing conditions. Forests with a greater diversity of response traits (i.e., traits that confer the organisms the ability to cope with disturbances), are indeed more resistant and resilient to disturbances, increasing the likelihood that such communities may persist under future conditions (Sánchez-Pinillos et al. 2016). Moreover, the effects of fragmentation on the genetic diversity of organisms can last for centuries, and some populations still hold legacies from the effects of human actions centuries ago, as is the case of *Fagus sylvatica* in northeastern Spain (Jump and Peñuelas 2005). In the absence of migration or evolutionary adaptation, the ability of populations to persist in the new environment will depend exclusively on their phenotypic plasticity, i.e., their ability to alter their phenotype with environmental conditions. Although Mediterranean forests have shown relatively high levels of plasticity, being plastic has an important metabolic cost, and there are universal physicochemical constraints that prevent the ability of a species to simultaneously tolerate several stresses (Laanisto and Niinemets 2015). In this sense, the succession of disturbances can cause an important limitation to the adaptation of the species. For example, the regeneration of *Pinus nigra* after wildfires depends both on the existence of nearby unburned vegetation patches and on climate conditions in the years following the fire (Martín-Alcón and Coll 2016; Sánchez-Pinillos et al. 2018). Distinct sequences of disturbance events can cause vegetation transitions, with non-linear responses and tipping points, even if the recurrence of individual disturbances is moderate (Batllori et al. 2019). Therefore, the succession of fires and droughts could trigger massive failures in regeneration, leading to a change in the ecosystem towards a greater dominance of oaks. In the driest areas, the combined effects of several disturbances is likely to exceed the response capacity of organisms, leading to the extinction of some species and even triggering shifts in ecosystem state (from forest to non-forest) (Batllori et al. 2019), which entails a high risk of soil erosion, degradation, and desertification.

Measures to promote adaptation

Whenever the inherent adaptive capacity of species is not sufficient, or too slow, planned adaptation measures can be implemented to decrease the known risks, increase forest resistance, or promote its recovery capacity (Lindner and Calama 2013). Adaptation measures in the Mediterranean commonly seek to address the two main disturbances in the region: drought and fire, and can be classified into five categories (Vilà-Cabrera et al. 2018).

Reducing tree density through thinning has the triple effect of increasing the growth and value of the remaining trees while also improving their water status and reducing fire risks. In a climate change context, thinning can diminish interception losses and reduce stand transpiration, increasing the amount of available water, which is apportioned among fewer trees (Sohn et al. 2016b). Some studies report a direct reduction of drought-induced mortality of Scots pine for high thinning intensities (Giuggiola et al. 2013), and an increase in the resistance and recovery of growth following drought events (Martín-Benito et al. 2010; Sohn et al. 2013, 2016a), which may be particularly important in dry areas or under sever climate change scenarios (Ameztegui et al. 2017; del Río et al. 2017). However, there is also evidence to suggest that, under extremely dry conditions, tree mortality risk may be density-independent, as all the available soil moisture can be lost to evapotranspiration before it can be harnessed by trees (Dorman et al. 2015).

The reduction of the understory cover has mainly been applied with the aim of reducing the risk of fire propagation by breaking the vertical and horizontal fuel continuity. Reduction of understory cover can be achieved either through mechanical treatments, prescribed burning or by promoting understory grazing in forest areas (Vilà-Cabrera et al. 2018).

The promotion of **mixed-species stands** (at the species or genotype levels) can increase resistance and recovery capacity to extreme droughts (Pretzsch et al. 2013), higher temporal stability (Jucker et al. 2014; Sánchez-Pinillos et al. 2016; del Río et al. 2017), and reduce the risk of biotic and abiotic disturbances (Guyot et al. 2016; Jactel et al. 2017) and the maintenance of ecosystem service provision (Gamfeldt et al. 2013).

The change in species or genetic composition seeks to replace the maladapted species or populations with species or genotypes better adapted to the forecasted climate conditions, and can include (i) assisted population migration (i.e., the active relocation of well-adapted populations of a given species within its current range); (ii) assisted range expansion (relocation of a species to an area adjacent to its current range); and (iii) assisted species migration (i.e., the displacement of a species beyond its current range, where the future climate is expected to be suitable for its development) (Williams and Dumroese 2013). Although the effectiveness of these practices seems apparent, there are still many doubts about their risks and consequences on the host environment, especially in the latter sense. At present, there is no consensus on their suitability, and they generate significant rejection both by a large part of the scientific community and by the general population (Lawler and Olden 2011), and in the Mediterranean they have not yet been applied beyond small-scale scientific experiments (Martín-Alcón et al. 2016).

The promotion of **the spatial heterogeneity of the landscape matrix** has mostly been advocated as a way to reduce the impacts of fire by slowing or preventing its expansion and allowing for greater effectiveness in firefighting (e.g., minimizing total burnt area) (Loepfe et al. 2012; Regos et al. 2016). A heterogeneous landscape also allows for the coexistence of different habitats (forests, open areas, etc.) each with different goals and providing different services. Moreover, greater heterogeneity can also contribute to enhancing gene flow and natural species migration, provided that enough corridors are available (Saura et al. 2018; Vilà-Cabrera et al. 2018). Fire risk management can also be achieved through the promotion of particular land covers/uses that reduce the risk of intense crown fires (e.g., fagaceae vs. conifers: Moriondo et al. 2006).

However, the socio-economic adaptive capacity of the Mediterranean forest sector also has to face several constraints derived from the low economic incomes of many Mediterranean forests, mainly due to low fertility and water limitation, the lack of a developed road network and the limited implementation of technological advances (e.g., harvesting machinery), which results in a large part of Mediterranean forests not being managed at all (Lindner et al. 2010; Lindner and Calama 2013), limiting the capacity of forests to adapt to climate change. Moreover, managing forests to increase adaptive capacity can lead to trade-offs with other ecosystem functions and with biodiversity (Vilà-Cabrera et al. 2018).

4.3.3.2 Mountain ecosystems

Implementation of effective adaptation measures depends on the availability of human resources and expertise. However, the knowledge base about Mediterranean mountains varies significantly.

Enhancing connectivity is a key measure to facilitate expected range shifts (Keeley et al. 2018) which in mountain areas may be achieved by "building" linear and latitudinal corridors and taking advantage of the river network. In addition, due to interconnected risks, wider spatial frameworks are necessary, for instance at the watershed level, since upstream changes influence downstream. There are still pristine areas in many Mediterranean mountains that sustain a diversity of plant and animal species. However, this role is impeded by ongoing human activities and most importantly, climate change has pointed to the need to design a flexible reserve system along with conventional ex situ conservation measures. Such as reserve system may place emphasis on the permeability of the intervening landscape matrix, dispersal corridors and habitat networks (Jongman and Pungetti 2004; Watts and Handley 2010). Mountains have played a refuge role in geological history and to a certain extent they retain this role today, with many of their endemic species surviving in places located in such refugia (Vogiatzakis and Griffiths 2008; Vogiatzakis 2012). This is at the core of climate-wise connectivity as proposed by recent studies (Keeley et al. 2018). Mountain ecosystems may prove more resilient since upward migration of lower zone species will be conditioned by topography and geomorphology i.e., habitat suitability (Kazakis et al. 2007).

4.3.3.3 Drylands and shrublands

Plants exhibit a variety of mechanisms to avoid (e.g., annual life-cycle) or to tolerate drought (e.g., perennial shrubs), and to deal with disturbance pressures, such as fire and herbivory (Noy-Meir 1973; Davies et al. 2012). Dryland biodiversity interacts with abiotic factors to determine ecosystem functioning (e.g., productivity, nutrient fluxes) and resilience (i.e., the ability to return to a previous state after disturbance), both of which are critical to ensuring the provision of ecosystem services (MEA 2005). Climate change predictions point to an overall increase in aridity and in the variability of precipitation distribution in drylands (Dai 2013). Climate change is therefore expected to further reduce productivity over time.

Topography creates contrasting microclimates, especially between northern and southern slopes in drylands, which result in clear differences in tree cover patterns in the landscape. These local-scale differences in tree cover patterns may result from limitations occurring at different plant development stages, such as seed germination, seedling establishment, tree growth rate and survival, all crucial for the maintenance and expansion of plant populations through natural regeneration. Leaf physiological performance was similar under contrasting microclimatic conditions. However, in areas with higher Potential Solar Radiation, tree age and density were significantly reduced. These results suggest that microclimatic differences on southern slopes with high Potential Solar Radiation are limiting for germination and sapling establishment. Thus, forest regeneration, restoration and nature conservation practices aiming at increasing forest resilience in Mediterranean dryland climates should account for the importance of microclimate in defining the niche of seedlings and adult trees (Príncipe et al. 2019).

Shrub encroachment was largely predicted by topo-edaphic factors in Mediterranean dryland ecosystems subject to conventional low-intensity land use composed of savanna-like holm oak woodlands, along with a regional climate gradient (Nunes et al. 2019). Management strategies to reduce encroachment therefore need to take these drivers into account for efficient forecasting and higher cost-effectiveness. Climate had a stronger effect on a set of functional traits involved to a limited extent in shrub encroachment, related to flowering and dispersal strategies. These results suggest that climate change might not greatly impact shrub encroachment in the Mediterranean Basin, but may affect the functional structure and reduce the functional diversity of plant communities, thus affecting ecosystem functioning (Nunes et al. 2019).

Drylands are very susceptible to the effects of climate change due to water stress. One possible climate change adaptation measure is the construction of lakes to increase water availability for drinking and irrigation (food production) and decrease fire risk. These lakes can also increase local biodiversity and human well-being. However, other non-target services such as carbon (C) storage, water purification, and sediment retention might also change.

An evaluation of the trade-offs on non-targeted ecosystem services due to lake construction in drylands was carried out by Santos et al. (2018). This was done using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) modelling tools, comparing a Mediterranean area located in southwestern Europe, with and without artificial lakes. Results showed that the construction of artificial lakes caused an increase of 9.4% in carbon storage. However, the resulting increase in agricultural area decreased water purification and sediment retention services. This could diminish the lifespan of the lakes, changing the initial beneficial cost-benefit analysis on lakes as adaptation measures to climate change. As a global measure for mitigation and adaptation to climate change strategy, we consider lake construction in drylands to be positive since it can store carbon in sediments and reduces the vulnerability to water scarcity. However, as a general recommendation, and when built to support or increase agriculture in semi-arid landscapes, we consider that lakes should be supplemented with additional measures to reduce soil erosion and nutrient leaching, such as (i) locating agricultural areas outside the lake water basin, (ii) afforestation surrounding the lakes, and (iii) adopting the best local agriculture practices to prevent and control soil erosion and nutrient leaching.

4.3.3.4 Agriculture and pasturelands

Transformational adaptation in agriculture has been described as a redistribution of at least a third of the production factors and/or production output in a 25-year timeframe, which mostly involves qualitative changes in inputs and outputs (Vermeulen et al. 2013). Transformational adaptation can result into a radical change to the area of production, to the main crops or production types (e.g., shift from animal to crop productions, abandonment of a specific type of farming, reclaim of abandoned lands, shift from rain-fed to irrigated agriculture, from nomadic to settled grazing systems, from conventional to organic farming systems). Vermeulen et al. (2018) also pointed out that the success factors and drivers of positive transformational adaptation include changes in governance in favor of disadvantaged stakeholders. They also showed that the capacity of producers, processors and consumers to adapt is highly context-sensitive and depends on public policy, market drivers and cultural values.

Farmers' long-term responses and investments in adaptation are constrained by barriers: (i) climate change signals can be biased by the perceptions of farmers (Nguyen et al. 2016), (ii) the projections are uncertain, (iii) climate change communication is difficult and often does not result in behavioral change (Wise et al. 2014), (iv) timescales for farm planning are relatively short and other priorities take precedence, (v) there are expectations of technology being able to cope with the negative effects of climate change, (vi) scientific knowledge and tools developed in agriculture rarely support long-term strategic decisions (Robertson and Murray-Prior 2016). Also, short-sighted state policies can increase the vulnerability of farmers to climate change and constrain their adaptive capacities (Turhan et al. 2015).

Opening new spaces for learning and generating enabling contexts through translating systems thinking into practice are fundamental steps for raising awareness about adaptation actions in a climate change world (Ison 2010). Vermeulen et al. (2018) examined several case studies on transformational adaptation in agriculture and showed how in practice it often emerges from a disorganized combination of responses from multiple actors to external pressures where climate change can only be an indirect driver. However, farmers rely on their experience to plan their practices, which will become obsolete if climate change occurs too quickly. They design their activities on the basis of a perceived probability distribution of their known drivers and performance indicators but, under climate change, probability distributions are shifted in mean, variance or both and are unknown, thus resulting in increased frequency of unexpected events. Dono et al. (2016) showed how these shifts between actual and expected probabilities can result in winners and losers in an affected area, depending on the type of farming system under the same expectations of climate pressures in a Mediterranean context.

Adaptation in agriculture requires customized support to the choices of any specific farm type in a given environmental situation or context, which is a challenge both for science and policy. The variety of environmental and socio-economic contexts and agricultural systems across the sub-regions of the Mediterranean Basin and across farming types within sub-regions, generate a great diversity of needs, adaptation strategies and have site-specific implications on biodiversity and the ecosystem services of agroecosystems.

Adaptation strategies and plans are being adopted at the continental, country or local level under the Cancun Adaptation Framework of the UNFCCC[37]. However, by December 2018, among the nine Mediterranean countries of the EU, only three (Cyprus, France and Spain) had already adopted a national adaptation plan, while eight had adopted a national strategy. Such plans should create the enabling environment for "last-mile" adaptation to occur, but moving from planning to implementation is a challenge because of the difficulties found in addressing capacity constraints, securing adequate financing and measuring the success of actions (Mullan et al. 2015). The following cases provide some examples of the specific adaptation needs of agriculture and pastureland systems in the Mediterranean context.

At present, cereal production is well below potential in southern Europe. Schils et al. (2018) demonstrated that the yield gap between actual and potential production would require good agronomy for sustainable intensification and thus increase the self-sufficiency food production of the entire Mediterranean area (Vermeulen et al. 2013). The self-sufficiency ratio in northern Africa is lower today than it was in the past as a consequence of demographic expansion, and is also resulting in low stability, not only in low GDP countries (Luan et al. 2013). Under pronounced drying trends documented by recent assessments, particularly in northwest Africa, a strategic objective is to move from maximized to stabilized production (Schilling et al. 2012). This can also be achieved through improved climate-proof agronomic practices such as the incorporation of crop residues combined with supplementary irrigation, where available (Benlhabib et al. 2014; Jacobsen 2014).

Adapting dryland agriculture to climate change in the Mediterranean requires substantial investments in plant breeding for heat and water stress tolerance and to increase yield and quality under conditions of high CO_2 concentration (Asseng and Pannell 2013). The same authors suggest investments in new species and cultivars of perennial plants. Such investments should be coupled with improved seasonal forecasting, which would enable farmers to make timely decisions about agronomic practices, thus improving resource use and crop yield. However, climate resilience is currently not receiving the necessary attention from breeders, seed and wheat traders, and farmers, while there are clear signals of declining resilience, at least for durum wheat, also in Mediterranean countries, including Spain (Kahiluoto et al. 2019). This latter assessment revealed that current breeding programs and cultivar selection practices do not sufficiently prepare for climate uncertainty and variability by applying a variety of responses to the same climate pressures by different wheat cultivars. In the case of barley, a pivotal crop in the Mediterranean area, Cammaron et al. (2019) demonstrated that, besides plant breeding, shifting sowing dates and improving soil organic carbon are viable adaptation strategies to mitigate the expected negative impacts of a future drier and

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[37] https://unfccc.int/topics/adaptation-and-resilience/workstreams/national-adaptation-plans

warmer Mediterranean climate on barley grain yield.

Wheat protein yield gains are expected to be lower and more variable in most rain-fed low-input cropping regions, where nitrogen availability limits growth stimulus from elevated CO_2 (Asseng et al. 2019). This is particularly true for North African countries, where food demand is increasing due to population increase (Schils et al. 2018). Introducing wheat genotypes adapted to warmer climate may not result in increased protein production. Therefore climate adaptations leading to stabilized grain yield could not always be positive in terms of grain quality (Asseng et al. 2019). Adaptive pathways for cereal productions also have impacts on integrated governance aiming to yield stability, such as the implementation of national action plans and policies to regulate and provide incentives for increasing diversity in crop responses to climate uncertainties (Kahiluoto et al. 2019).

Legumes represent a strategic resource for sustainable intensification of agricultural systems and climate change adaptation in the Mediterranean Basin. In addition to serving as a fundamental source of high quality food and feed, legumes contribute to net nitrogen inputs in cropping systems at low N_2O emissions and contribute to net soil carbon sequestration (Volpi et al. 2016; Stagnari et al. 2017). The environmental services provided by legume cultivation are still undervalued, while new opportunities for yield improvement are arising from the ongoing development of cost-efficient genome-enabled selection procedures, enhanced adaptation to specific cropping conditions and more thorough exploitation of global genetic resources (Annicchiarico 2017).

The cropping systems for the production of bioenergy and biomaterials are assumed to occupy part of the residual agricultural land abandoned in the past 50 years, but this will not be sufficient to meet the increased bioenergy demand associated with climate change energy policies in European countries (Cosentino et al. 2012). These crops may also find a strategic position in Mediterranean cropping systems to reclaim polluted arable land from industrial or mining wastelands (Fagnano and Fiorentino 2018).

Increased irrigation water efficiency and the design of climate-friendly agro-ecosystems are key adaptation strategies for Mediterranean agriculture, in particular for countries such as Algeria, Libya, Israel, Jordan, Lebanon, Syria, Serbia, Morocco, Tunisia and Spain, which are at high risk of not being able to meet future irrigation needs (Fader et al. 2016). A range of adaptation strategies are being studied or put in place either to store more water in hot and arid environments (e.g., with managed aquifer recharge) (Salameh et al. 2019), use and recycle non-conventional water sources (Ait-Mouheb et al. 2018; Elkiran et al. 2019), desalinate seawater (Stanhill et al. 2015) or improve irrigation efficiency (Tarjuelo et al. 2015; El Jaouhari et al. 2018). All these strategies have some potential side effects in terms of energy requirements (Rodríguez-Díaz et al. 2011), GHG emissions, high capital investments and social acceptance (Daccache et al. 2014; Chartzoulakis and Bertaki 2015). However, in arid zones, these are often the only alternatives to achieve sustainable agricultural intensification. Some solutions, like desalination, should be considered only where there is evidence that the natural recharge available in surface and underground storage might become limiting considering the economic and environmental dimensions of sustainability (Stanhill et al. 2015).

Supplementary irrigation of rain-fed crops is also crucial for increasing the productivity of traditional Mediterranean rain-fed cropping systems, including winter cereals or perennial crops such as olive and vineyards (Fraga et al. 2012; Tanasijevic et al. 2014). However, the introduction of new technologies for irrigation on traditional rain-fed or irrigated cropping systems has many systemic implications in the environmental, socio-cultural, institutional and economic domains (Ortega-Reig et al. 2017).

Increased water and soil salinity is also a threat for future Mediterranean cropping systems, particularly in coastal areas (Maggio et al. 2011; Pittalis et al. 2016). Adaptation strategies include the introduction of salt tolerant crop species for which there is increasing consumer demand. For example, there is increasing interest in quinoa germplasm and production in the Mediterranean Basin, in relation to its tolerance to salinity and water stress, high water use efficiency and the increasing demand of gluten-free food (Hirich et al. 2014; Lavini et al. 2014; Mahmoud 2017; Noulas et al. 2017).

Combined agro-ecological approaches to climate change adaptation in organic horticulture is suggested by Diacono et al. (2016), following long-term field experiments that showed that such cropping systems can sustain the yield of cash crops in rotation, in spite of changes in temperature and rainfall.

Pasturelands and rangelands will face multiple threats from expected drier and warmer climate in Mediterranean countries. These farming systems rely heavily on natural resources on marginal land, often characterized by shallow and oligotrophic soils, with low water holding capacity. Highland pastures and their biodiversity is being threatened by loss in biodiversity due to climate change (Dibari et al. 2015). Dono et al. (2016) showed that near future climate change will result in losses for rain-fed grazing systems, mainly because of the shift in the probability distribution of rain-fed pasture and hay crop production due to drier springs caused by reduced rainfall and higher evapotranspiration, resulting in higher costs for purchasing external feeds or renting more land. Adaptation strategies range from incremental to transformational strategies in this case. Silanikove and Koluman (2015) project an overall negative impact, but a positive role of dairy goats in adaptation to global warming when compared to dairy cows, given their higher tolerance to heat stress.

The savanna-type pastoral vegetation of the dehesa in Spain, montado in Portugal or pastures with scattered cork-oak trees in Sardinia and elsewhere in northern African countries are considered a multifunctional resource that can support adaptive responses to climate change and the provisioning of multiple ecosystem services (den Herder et al. 2017; Castro and Castro 2019). Mediterranean agro-silvopastoral systems generate unique habitats for plant and microbial diversity, resulting in a wide range of services such as forage, wood and non-wood products, soil organic carbon sequestration and landscape cultural values (Bagella et al. 2013; Seddaiu et al. 2013, 2018; Rossetti et al. 2015; Tardy et al. 2015; Torralba et al. 2016; Garrido et al. 2017). Adaptation strategies in pastoral systems based on wooded pastures include actions that can prevent the threats of degradation due to abandonment (e.g., wildfires, loss of cultural landscape and heritage, increased drought stress) or intensification (e.g., lack of tree regeneration) (Garrido et al. 2017; Rolo and Moreno 2019). Given the complexity of the factors driving the sustainability of agro-silvopastoral systems, adaptation strategies should be designed and implemented through systemic and integrated approaches and not by just targeting a specific service or pastoral activity (Hernández-Morcillo et al. 2018). However, more attention should be devoted to these agro-silvopastoral systems, as they are currently overlooked by rural development policies in Europe, while agroforestry systems can effectively contribute to maximizing the productivity of marginal land (Mosquera-Losada et al. 2018).

Agro-silvopastoral systems in the Mediterranean area are under threat because the income of farmers that contribute to their maintenance does not acknowledge the many ecosystem services they provide (Fagerholm et al. 2016; Rodríguez-Ortega et al. 2018).

The adaptive capacity of grazing systems in the Mediterranean depends on local contexts, with contrasting trends in northern and southern countries, rain-fed or irrigated conditions. A general trend towards increased specialization and related environmental risks is occurring almost everywhere, which is in contrast with the need for increased resilience to climate pressures and reduced environmental impacts (Rodríguez-Ortega et al. 2017). Adaptive development strategies include enhancing the spatial dimension of grazing systems through increased animal mobility, increased feeding self-sufficiency and integration of crop-livestock integration at the regional and sub-regional levels (Alary et al. 2019). These livestock farming systems would also respond to the ongoing change in human dietary recommendations, which is one of the drivers of the meat crisis (D'Silva and Webster 2017). However, this may result in different environmental impacts in terms of greenhouse gas emissions, eutrophication and land use in different regions, depending on the income level (Behrens et al. 2017).

Adaptation strategies are more complex for farmers who have made large long-term investments following market pressures and productivity objectives. Dairy cattle farming systems rely mostly on irrigation water and are threatened by the increasing frequency of heatwaves, to which highly productive cows are very sensitive (Lacetera 2019). These farming systems are facing uncertainties caused by fluctuating world feed prices, climate, market and environmental normative pressures (e.g., nitrate vulnerable zones), which are gradually squeezing their marginal net returns (Dono et al. 2016). Adaptation strategies are constrained by multiple pressures and are often based on crop and animal diversification combined with improved animal feeding and genetics (Rojas-Downing et al. 2017; Henry et al. 2018).

4.3.3.5 Freshwater ecosystems

Successful adaptation measures need to follow a large-scale hydrological approach to determine the origin of variations, which are usually related to human pressures, and to provide further strategies for environmental management (Menció and Mas-Pla 2010). Conservation and restoration efforts traditionally carried out at a local scale need to be accompanied by land use and hydrological planning at a basin-wide scale in order to maintain stream ecosystem integrity and biodiversity (Bruno et al. 2014a, 2014b). In this sense, nature-based solutions can play an important role in maintaining freshwater biodiversity, and because of their multifunctionality, in providing critical ecosystem services (e.g., food provisioning, erosion regulation and cultural ecosystem services) (Balzan et al. 2019). Nature-based solutions (NbS) are defined by IUCN as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits"[38].

The Mediterranean Strategy for Sustainable Development 2016-2025 prioritizes national action to ensure that natural water resources are extracted sustainably. However, reliable methods to assess water demand are needed. Such methods assess the dynamics and determine the main drivers of each type of water demand, and project future water uses (Charlton and Arnell 2011; Collet et al. 2013; Griffin et al. 2013; Reynard et al. 2014), with interdisciplinary approaches that combine physical and human features and incorporate climate change impacts at the local scale (Grouillet et al. 2015). Local water management planning and adaptation strategies need to be improved and updated in order to attain future water security (Koutroulis et al. 2013) (more on human security related to water is highlighted in *Chapter 5.3*). Achieving integrated and sustainable water management will also require enhanced awareness of climate change effects and public demands for water-use efficiency and improved environmental quality (Grantham et al. 2013). Awareness of the practical implications of plausible hydro-climatic and socio-economic future scenarios will shift perceptions and preference towards a more sustainable model (Koutroulis et al. 2010).

The success of mitigation and adaptation policies to restore sustainability depends on implementation efficiency at local level, where awareness and perception often pose barriers (Betzold 2015; La Jeunesse et al. 2015). Communicating relevant and targeted climate change information to stakeholders and decision makers is crucial for gaining commitment in the field. The projected water scarcity in the region highlights the important role for development and deployment of water conservation technologies and practices (Hejazi et al. 2014) and the need for strategic resource planning from global to regional and local scales (Koutroulis et al. 2013). Stakeholders, the beneficiaries of ecosystem services from river bodies and landscapes, play a key role in interpreting the impact of climate change on water resources and usage. A mixed methodology based on a transdisciplinary approach and the involvement of academia, policymakers, and local experts is suggested. Many physical models on the impacts of climate change and on water scarcity exist but approaches that are transdisciplinary with input from local stakeholders and interpretation of intermediary results are limited (Rault et al. 2019). Improving the understanding of ecosystem responses to multiple stressors and defining measures to improve the ecological status of water bodies are needed and sought by the WFD (Menció and Mas-Pla 2010).

Preserving the natural flow variability of rivers and streams is key in sustainable environmental management plans in the Mediterranean (Menció and Mas-Pla 2010) and critical to the long-term conservation of their unique biodiversity (Cid et al. 2017). The high variation in hydrological regimes in the region, however, tends to exacerbate the magnitude of negative responses to anthropogenic and climate impacts. For example, land use changes promote longer dry season flows, concentrating contaminants, allowing the accumulation of waste, algae, and plants, and fostering higher temperatures and lower dissolved oxygen levels, all of which may extirpate sensitive native species. Exotic species often thrive in rivers altered by human activity, further homogenizing river communities worldwide. Future research should rigorously evaluate the effects of management and restoration practices on river ecosystems, determine the cause–effect pathways leading from human disturbances to stream biological communities, and incorporate analyses of the effects of scale, land use heterogeneity, and high temporal hydrological variability on stream communities (Cooper et al. 2013).

The surface water-groundwater relationship is of major interest in the characterization of human pressures on stream hydrological dynamics and the ecological quality of Mediterranean reaches (Menció and Mas-Pla 2010). The ecological status of streams depends on an equilibrium between hydrological processes and biological dynamics. Water discharge is the main requisite for a rich riparian habitat and impacts upon aquifer water storage and

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[38] https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions

on base flow generation have a significant effect on stream biology. Tools for managing these systems, such as those related to biomonitoring, climate change, and conservation, must be tailored to the seasonal and inter-annual variability of these systems.

Much of the ecological surface water monitoring under the WFD focuses on the assessment of biological structure, hydromorphological elements and chemical and physicochemical elements, all of which represent important information about ecosystem condition (Balzan et al., 2019). It is assumed that good ecological and chemical status have a positive impact on the capacity of ecosystems to provide ecosystem services and benefits to human well-being (Grizzetti et al. 2019). The link between waterbody condition, and ecosystem function and services has seldom been explored in detail, with the implication of water management for ecosystem services being either implicit or overlooked (Vlachopoulou et al., 2014). Thus, tools that work at the ecosystem function level, connecting ecosystem condition to services, are required especially in climate change scenarios where ecosystem condition is expected to change with the climate and other interacting drivers *(Chapter 2).* There are a number of studies from the Mediterranean Basin that demonstrate that such links can be made in practice, as demonstrated by the study by Acreman et al. (2017), which shows how the implementation of beach restoration is associated with ecological recovery and recreational ecosystem services.

Wetland management and conservation in semi-arid Mediterranean areas is necessary because they have been highly impacted by agriculture. This can be done with pressure and state indicators at landscape and wetland scales that reflect the status, condition, and trends of wetland ecosystems. Ortega et al. (2004) developed an ecological integrity index with 12 indicators (5 at the catchment scale and 7 at the wetland scale) based on the relationship between pressures from anthropogenic activities and the ecological state of wetlands and their catchments, integrating environmental, biological, economic, and social issues. Overall, a wide riparian zone acts as a buffer for wetlands, diminishing the effects of intensive agriculture. Provisioning services are more relevant in normal and wet years, while regulating service water purification provides higher benefits in dry years, when threats to water quality are increased because of a decreased dilution capacity (Terrado et al. 2014). Protecting water towers in semi-arid regions expected to experience dramatic changes is essential to ensuring water provisioning in dry years. However, the protection of water resources is not sufficient if consumption rates continue or increase in the future. Actions should be planned to enhance the provision of regulating services (Terrado et al. 2014). Overall, in semi-arid basins under continuous human impact, hydrological ecosystem services are very sensitive to climate extremes, and service supply and demand areas are usually spatially and temporally decoupled. Both aspects are relevant and need to be considered in basin management in semi-arid regions (Terrado et al. 2014).

Studies that consider the respective influences of climate, land cover (forest cover dynamics in hydrological processes) and water withdrawals on water availability (e.g., Chauvelon et al. 2003; Varela-Ortega et al. 2011) are required for proper adaptation measures but are still scarce, since the required data are often unavailable or not easily accessible over long periods (Sivapalan et al. 2003). Databases at large spatial and temporal scales are key to understanding the variability of hydrological systems, and in providing water managers with science-based decision-making support information (Hannah et al. 2011). However, such databases are still too scarce in the Mediterranean, despite efforts to maintain and develop data networks at the regional and global levels. At this scale, the physical and human characteristics of catchments, especially in the Mediterranean, are extremely heterogeneous since they encompass extreme contrasts in terms of climatic, topographic and geological characteristics, population distribution and water uses and are therefore difficult to define and grasp (Collet et al. 2014). The climate variability of Mediterranean river basins also makes it difficult to describe general patterns which explain and predict the relationships between runoff, erosion and sediment transport (López-Tarazón et al. 2010; de Vente et al. 2011) and this is even more complicated in rivers affected by regulation. Time-series on sediment transport (Batalla and Vericat 2009) and on lake ecosystems, especially those predating anthropogenic influences, are very scarce (Papastergiadou et al. 2007). Long-term data sets are also important for understanding the interactions among native species and introduced species. These are particularly valuable in understanding the influence of extreme events such as drought and floods (Magalhães et al. 2007; Bêche et al. 2009). Such studies, particularly in regulated systems, help guide flow recommendations to benefit native species but have only begun, although their value is already clear (Kiernan et al. 2012; Resh et al. 2013). Long-term data sets that can reveal trends need to exceed the sub-decade scale for sustainable management of Mediterranean-climate streams and rivers (Cid et al. 2017).

BOX 4.1

Bio-indicators for the assessment of changes in Mediterranean marine ecosystems

Awareness of recent changes in ecological conditions in many seas has fostered a need to assess increasing anthropogenic pressures and their consequences on sediment and water quality, and to suggest measures to reverse this trend. In this context, the European Commission has implemented the Water Framework Directive (WFD, Directive 2008/56/EC) with the aim to obtain (or to maintain) a "good status" for all European waters by 2015. To support this, a large number of monitoring tools have been developed, including several bio-indicators such as phytoplankton, macro-algae, seagrass, angiosperms, fish faunas and soft substrate benthic invertebrate fauna, which are benthic foraminifera.

Phytoplankton and zooplankton are ecologically important groups in most aquatic ecosystems and have been an important component of biological monitoring programs in the Mediterranean (Abboud-Abi Saab et al. 2008, 2012; Tunin-Ley et al. 2009; Gharib et al. 2011; Tunin-Ley and Lemée 2013; Abo-Taleb et al. 2016; Ouba et al. 2016; Abboud-Abi Saab and Hassoun 2017). The genus *Neoceratium* (planktonic dinoflagellates) in the NW Mediterranean is known to be particularly sensitive to water temperature, and is responsive to global warming (Tunin-Ley et al. 2009; Tunin-Ley and Lemée 2013). Moreover, the WFD mandates the use of biological quality element (BQE) phytoplankton to assess the ecological status of coastal and transitional water bodies. Alternatively, Camp et al. (2016) propose a methodology to assess water-quality based on the use of chlorophyll-a (Chl-a), as a proxy of phytoplankton biomass.

For soft-bottom marine habitats, macrofauna is traditionally used as a bio-indicator, and a wide range of different biotic indices have been developed (Borja et al. 2016). The use of meiofauna, occurring in higher densities, is less developed. Among these, benthic foraminifera appear particularly suitable for bio-monitoring in the Mediterranean (Barras et al. 2014; Jorissen et al. 2018). The abundant and diverse benthic foraminifera faunas in the Mediterranean react rapidly to environmental changes such as organic pollution, eutrophication and oxygen depletion. These characteristics led to the development of a standardized biotic index based on foraminifera (Jorissen et al. 2018).

For the coralligenous, several indices of its health status have been suggested. One is the INDEX-COR approach, based on long time series of photographic sampling, standardized and used as a large spatial comparison tool (Sartoretto et al. 2017). This type of index integrates the sensitivity of different coralligenous taxa to organic matter and sediment deposition, the observable taxonomic richness and the structural complexity of the benthic assemblages. With these approaches, the health status of this complex ecosystem can be assessed without invasive or directly impacting methods. When deeper areas are considered in the coralligenous assemblages (e.g., from 30-40 to 200 m depth), Remotely Operated Vehicle (ROV) approaches may be useful (Rossi et al. 2008). The Mesophotic Assemblages Ecological Status (MAES) has been suggested as a tool for conservation and management procedures (Cánovas-Molina et al. 2016). The MAES index is based on community structure, condition of the erect species and visible human impacts (Cánovas-Molina et al. 2016). A combined biomarker index can also be considered as a medium-long term monitoring approach. In selected populations of representative sessile species of the coralligenous, activity (e.g., polyp expansion), growth, reproductive output, stable isotopes, biochemical balance (protein-carbohydrate-lipids), fatty acids and C/N ratio may be used to estimate the nutritional condition and health status of populations or entire communities, considering the biology and ecology of each species (Rossi et al. 2017b).

For large vertebrates, cetaceans and seabirds are widely regarded as reliable indicators of the health of marine ecosystems due to their position near the top of the marine food web, conspicuous nature, and reliance on marine resources (Durant et al. 2009; Bossart 2011; Schwacke et al. 2013; Fossi and Panti 2017; Fossi et al. 2018). Some cetaceans and seabirds are reported as sentinels or indicators for the state of marine ecosystems because they are globally subject to multiple stress factors, such as the bioaccumulation of contaminants, infectious diseases, non-indigenous species, food depletion, and climate change (UNEP/MAP 2012; Poloczanska et al. 2013). The advantage of using cetaceans as sentinels is that they have physiology and/or diets similar to those of humans, so they can indicate earlier potential adverse health effects (Schwacke et al. 2013). For fish, red mullets (*Mullus barbatus* and *M. surmuletus*) have been widely used as quantitative bio-indicators of chemical contamination (Porte et al. 2002; Storelli and Marcotrigiano 2005; Martínez-Gómez et al. 2017). For instance, the recent study by Cresson et al. (2014) confirmed that red mullets are efficient bio-indicators of Mercury (Hg), one of the main chemicals currently altering Mediterranean ecosystems.

BOX 4.2

Urban biodiversity in the Mediterranean Region

Further to being a hotspot of biodiversity, the Mediterranean region is also one of the most densely urbanized areas in the world (FAO and Plan Bleu 2018). The overall population in the region grew by 190 million people between 1970 and 2010, while the urban population increased by 163 million, with more 74% of population growth concentrated in the countries of the southern part of the Mediterranean (UNEP/MAP 2012). Despite substantially lower growth rates of urban populations in European countries of the Mediterranean, surfaces occupied by urban settlements have also increased considerably due to tourism and decentralization of population from high density core cities towards low density residential areas and along the coastlines, as for instance in Barcelona (Domene and Saurí 2007) or Athens (Cecchini et al. 2019).

Also, patterns of land use changes differ between southern and northern parts of the region. In European countries, urbanization has been accompanied by abandonment of agriculture since the post war period and extended mainly onto different types of cultivated areas, and onto shrubland and/or herbaceous areas (García-Nieto et al. 2018), leading to substantial losses of biodiversity and of agricultural area, while shrubland and forest land increased (Domene and Saurí 2007; FAO and Plan Bleu 2018; García-Nieto et al. 2018).

The growth of north African peri-urban areas in that period occurred in parallel with an increase in irrigated arable land, permanent crops, complex cultivation patterns and shrublands and/or herbaceous areas and pastures, at the expense of non-irrigated arable land and forest, both around peri-urban areas, as well as at the national level. In southern Mediterranean countries, environmental change contributed, for example, to a rural exodus in Morocco between 1980 and 1990, and in Algeria and Tunisia in 1999 (García-Nieto et al. 2018).

Consequences for biodiversity and ecosystem services in urban areas

Consequences for biodiversity and ecosystem services available for urban areas differ accordingly. In most cases, urban areas replace former agricultural land, but, while in the southern part of the Mediterranean this coincides with an extension of cultivated areas outside urbanized areas, in most European countries the contemporary abandonment of agricultural areas leads to an increase in shrubland and uncultivated areas and contributes to increasing vulnerability of surfaces, for instance with the threat of wildfires along the wildland-urban interface (San-Miguel-Ayanz et al. 2013; Lafortezza et al. 2015; Xanthopoulos 2015) and desertification (Salvati et al. 2015). Abandonment of agricultural lands also leads to the loss of cultural landscape management practices. For example, traditional Mediterranean agricultural landscapes are in many places characterized by terraces and dry walls which represent small scale practices of erosion prevention (Cecchini et al. 2019). Increasing soil sealing in urban areas and connected infrastructure and abandonment of historic techniques of landscape management lead to increasing risks from flooding and landslides (Salvati et al. 2015; García-Nieto et al. 2018).

The remaining ecosystems are increasingly under threat with particular risks for rare plants depending on small patch ecosystems with highly localized distributions even though they may be protected (Vimal et al. 2012). Peri-urban areas nevertheless provide relevant services for urban populations, for instance the increase in areas of natural or semi-natural

BOX 4.3

Nitrogen deposition and ecosystems

Climate change contributes to an increase in dry deposition of nitrogen and increases the negative impacts of excess atmospheric nitrogen on biodiversity (Oliveira et al. 2020). Reactive nitrogen (Nr) impacts vegetation through direct foliar damage, eutrophication, acidification, and susceptibility to secondary stress depending on the nitrogen form and concentration (Krupa 2003). Grassland, heathland and forest ecosystems are recognized as habitats vulnerable to Nr in Europe (Dise et al. 2011). In Spain, natural grasslands, particularly in the northern alpine area, were found to be the most threatened habitat followed by mountain ecosystems (García-Gómez et al. 2014). At least 14% of the Natura 2000 sites in western Iberia are at risk of eutrophication (Oliveira et al. 2020).

It is not yet clear if different wet-deposited forms of Nr (e.g., nitrate, NO_3 – versus ammonium, NH_4^+) have different effects on biodiversity. However, gaseous ammonia (NH_3) can be particularly harmful to vegetation. The highest relative risk of biodiversity change in Natura 2000 sites due to NH_3 pollution in Portugal was found to be in peats, mires, bogs, and similar acidic and oligotrophic habitats (most located in the northern mountains), whereas in the Atlantic and Mediterranean climate zone (coastal, tidal, and scrubland habitats) they were deemed the least sensitive in Portugal (Pinho et al. 2018).

Exceedance of critical loads for nitrogen is linked to reduced plant species richness in a broad range of European ecosystems (Dise et al. 2011). Experimental evidence shows that species richness and abundance resulted in larger declines with greater amounts of annual N addition including in semi-arid areas (Midolo et al. 2019). Reductions in the abundance of individual species were greater for N-sensitive plant life-form types (legumes and non-vascular plants) (Ochoa-Hueso et al. 2014, 2017; Midolo et al. 2019).

Several conservation plants (e.g., orchids and carnivorous) and cryptogams are naturally adapted to low environment N supply. Thus, increasing Nr alters the natural ecological balance. This results in the loss

BOX 4.2

vegetation such as ecosystem fragments, reserves, nature parks, forests, and river banks, which house varying amounts of native species, potentially provide cultural services. Formal and informal forms of urban agriculture and horticulture (Domene and Saurí 2007; Cecchini et al. 2019) present an opportunity for integration into of diets for urban residents and provide both provisioning and cultural services, as these areas are also used for leisure activities (Domene and Saurí 2007; Cecchini et al. 2019; Palau-Salvador et al. 2019).

The expansion of peri-urban agriculture, for instance, olive cultivation for self-consumption or small-scale economic production, have counteracted land use change in the peri-urban areas of several cities in the Mediterranean Basin (García-Nieto et al. 2018; Cecchini et al. 2019). Olive landscapes have a high tolerance to pests and are characterized by a stable trend of economic production, and abundant insect fauna contributing to biodiversity conservation. They furthermore show a higher resistance to wildfires than other Mediterranean vegetation. The economic stability of olive oil production in small groves, like other small-scale agricultural areas and the status of protected natural areas (e.g., coastal woods in the case of Rome) in the green belt around cities contributes to the ability of these areas to form an efficient barrier against urban dispersion and reduce the impacts of soil sealing on the hydrological cycle and on ecosystem services loss (Salvati et al. 2015; Cecchini et al. 2019).

Urban biodiversity and ecosystem services

Despite the important provisioning and cultural services and their increasing popularity in many cities, urban gardening seems to be not as effective in protecting peri-urban areas from land use changes as in the case of peri-urban agriculture observed in Athens (Domene and Saurí 2007; Heywood 2017; Cecchini et al. 2019). This may be due to less stable legal position of such areas which are often the result of squatting on private or, more often, public land (Domene and Saurí 2007) and their less consolidated economic status. In Rome, managed spaces with cultivated vegetation such as parks and gardens represent a lower level of resilience against transformation despite their importance for cultural and regulating services (e.g., leisure and heat mitigation) for urban residents (Salvati et al. 2015).

In many urban areas of the Mediterranean, street trees provide important regulating services for human well-being by offering shade and reducing heat impacts during summer due to their evaporation rates and the albedo created by foliage (Rana and Ferrara 2019). They also provide important cultural services as characterizing elements of Mediterranean urban landscapes (Heywood 2017).

Furthermore, urban wastelands and shrublands which are mainly colonized by weeds, ruderal plants and non-indigenous species, in many cases house considerable numbers of native plants and are potential places for valuable biodiversity (Heywood 2017). The importance of green spaces in urban areas is increasingly recognized by Mediterranean cities, which are increasingly engaging in urban green infrastructure projects, preserving remnants of biodiversity and natural areas within cities. These are expected to provide important regulating, cultural and provisioning services but there is a general lack of data on urban biodiversity in urban and peri-urban areas of the Mediterranean (Heywood 2017).

BOX 4.3

of the most sensitive species, which are often a priority for protection, and their replacement by non-indigenous or other opportunistic species that prefer high rates of nitrogen supply (Bobbink et al. 2010). Lichens and bryophytes are among the most sensitive organisms to N pollution at the ecosystem level (Cape et al. 2009), having a different response depending on their functional response group (Pinho et al. 2008, 2009, 2011, 2012b, 2012a; Jovan et al. 2012).

There are some clear examples of reductions in faunal diversity that can be linked to Nr deposition, but overall, our knowledge of faunal effects is still limited (Dise et al. 2011). Changes to above-ground faunal communities probably occur primarily through changes in vegetation diversity, composition or structure (Murray et al. 2006). The evidence strongly suggests that ecological communities respond to the accumulated pool of plant-available N in the soil. Thus, the cumulative load of enhanced Nr impacting an ecosystem is probably important (Stevens et al. 2011). Because of this response to cumulative inputs, it is likely that biodiversity has been in decline in Europe for many decades due to enhanced Nr deposition (Bobbink et al. 2010). Equally, full recovery in response to reduced Nr deposition is likely to be slow, especially in highly impacted ecosystems. In some cases, recovery may require management intervention.

BOX 4.4

Mediterranean islands

Islands as laboratories

The high concentration of islands (> 10,000) is one of the features which contributes to the Mediterranean's unique character, placing the region within the richest in the world in terms of islands and archipelagos (Médail 2017). In addition to being biological laboratories, the largest of the islands are also the centers of many of the world's ancient civilizations (Patton 1996). On these islands, the diversity of biogeography, geology and human settlement has produced exceptionally high numbers of biodiversity and endemicity, earning them a place in the global biodiversity hotpots list (Médail and Quézel 1997; Vogiatzakis et al. 2016; Médail 2017). In addition to the role as tertiary and glacial refuges, islands have also contributed to more recent plant diversification (Médail 2017). Biodiversity on islands display an insular syndrome due to abiotic conditions (nature of isolation, particular climate) and their own biogeographical history, and are characterized by unique specific assembly (with several endemics) and biotic interactions (de Montmollin and Strahm 2005; Blondel et al. 2010; Médail 2013, 2017; Schatz 2017).

Recent evidence of change

Despite their relatively small contribution to greenhouse gas emissions, Mediterranean islands are likely to be adversely affected by climate change, in synergy with ongoing land use changes.

- **Land-use change:** The landscapes of Mediterranean islands have evolved as the result of similar pressures to the mainland generated by socio-economic and political factors but amplified on a "matrix" of limited space. Land use changes and associated impacts differ significantly depending on the size of the island and therefore demographics, as well as its popularity as tourist destination (Vogiatzakis et al. 2008). Therefore, to date there is no consensus on the trends of changes since islands seems to respond/behave individualistically (Vogiatzakis et al. 2008; Harris 2012). Recent land uses are associated with temporal and spatial shifts in land-use systems with polarization of land-use intensity, particularly on small/medium size islands (Tzanopoulos and Vogiatzakis 2011; Balzan et al. 2018).
- **Climate evidence:** Observed trends for winter (Nov–Feb) precipitation (mm/50 years) and summer (Jun–Sep) temperature (°C/50 years) for Mediterranean island regions during the second half of the twentieth century do not show a consistent climate pattern (Vogiatzakis et al. 2016).
- **Biological/ecosystems evidence:** Documented evidence on plant and animal phenology changes (Peñuelas et al. 2002; Gordo and Sanz 2010), range shifts (Lenoir et al. 2008) and changes in the function, structure and dynamics of ecosystems e.g., temporal mismatches among mutualistic partners) (Visser et al. 2004), species loss and changes (+/-) in species richness (Kazakis et al. 2007). Plant communities are steadily changing, such as orchids in Corsica (Vogt-Schilb et al. 2016), as well as specialized plant-insect interactions (pollination, seed dispersal) (Traveset and Riera 2005; Blondel et al. 2010; Stefanaki et al. 2015).

Climate change projections and islands

- **Current scenarios:** Projected trends from various climate models agree as far as the direction of change in precipitation and temperature regimes are concerned (*Table 2.1* in *Section 2.2*) (Vogiatzakis et al. 2016).
- **Sea level rise:** For the Aegean archipelagos, Monioudi et al. (2017) assume mean sea-level rise of 0.5 m for RCP4.5 and predict that a storm-induced sea level rise of 0.6 m would result in complete erosion of between 31 and 88% of all beaches, at least temporarily.
- **Island representation and model resolution:** In most modeling studies (niche models or GCMs), islands are simply a subset of the Mediterranean (Araújo et al. 2006; Settele et al. 2008). As a result, neither distribution nor climate data have sufficient resolution to allow climate envelope models for most endemic island taxa (Henle et al. 2010).
- **Synergies with land cover changes:** Changes in land use (Settele et al. 2005) coupled with climate models predict modifications to species climate space (Settele et al. 2008) and islands are no different. Documented land cover changes related to urban/tourism development and increasing linear infrastructure are already having an impact on island biodiversity (Zomeni and Vogiatzakis 2014).

Vulnerability/resilience

The vulnerability of Mediterranean island systems to past and recent extinctions has been well documented (de Montmollin and Strahm 2005; Foufopoulos et al. 2011). A recent assessment of global imminent extinctions includes two Mediterranean Islands (Ricketts et al. 2005). Compared to the rest of the Mediterranean Basin, islands have always been more vulnerable to invasion by exotic species (Hulme 2004). Human activity will be the limiting factor which will determine the future of island flora. Islands are representative examples in the Mediterranean of the co-evolution of social-ecological systems intensified by the element of insularity and which are currently under threat and more susceptible to externalities due to (i) limited resources/space, (ii) administrative/political leverage, (iii) institutional capacities. While many of the islands have experienced demographic losses, concerning their permanent inhabitants, they have become principal tourist destinations (Ioannides et al. 2001) and islands are being faced with a key challenge of balancing economic benefits from ecosystem services delivery (tourism, agriculture) with environmental pressures.

Conservation and adaptation

On islands, opportunities for (human assisted) adaptation are limited. The lack of available space for wildlife to shift presents significant barriers to the natural adaptation of species and habitats. It also leads to more intense land-use conflicts, therefore increasing size of protected areas, and connections might be problematic. In an attempt to promote "climate-wise connectivity" (Keeley et al. 2018), areas not (significantly) affected by climate change could act as refugia to species in the future. Many of the island endemic species of today have survived past climate changes in places in such refugia (Vogiatzakis and Griffiths 2008; Vogiatzakis 2012). In the case of island clusters, the suitable climate space might be a neighboring island, although there are many examples, particularly in the Aegean, where neighboring islands have different floras (Kallimanis et al. 2010). Therefore, biogeography may be more important than climate *per se* in interpreting species distribution patterns (Whittaker and Fernandez-Palacios 2007). Building a coherent ''network'' of protected areas across islands (e.g., in the Aegean) might provide solutions to safeguarding common biotic elements (species or habitats). At the government level, adaptation should include increased institutional capacity for innovation, the increase of monitoring activities, adaptive management, and promotion of inter-island collaboration (Kark et al. 2009). In the case of managing island ecosystems and their services, the key priorities for the future must be to:

- identify ecosystem service capacity hotspots and how they can be affected under climate change scenarios;
- identify ecosystem service demand and flows in hotspots and manage green infrastructure and co-created nature-based solutions to provide synergies for biodiversity conservation and ecosystem services for human well-being;
- manage protected areas for ecosystem service provision given the fact that lack of space is also problematic;
- evaluate tradeoffs and thresholds of ecosystem service provision and assess the impacts from demographics and tourism, as well as land use and climate change projections.

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5

SOCIETY
1-DEVELOPMENT

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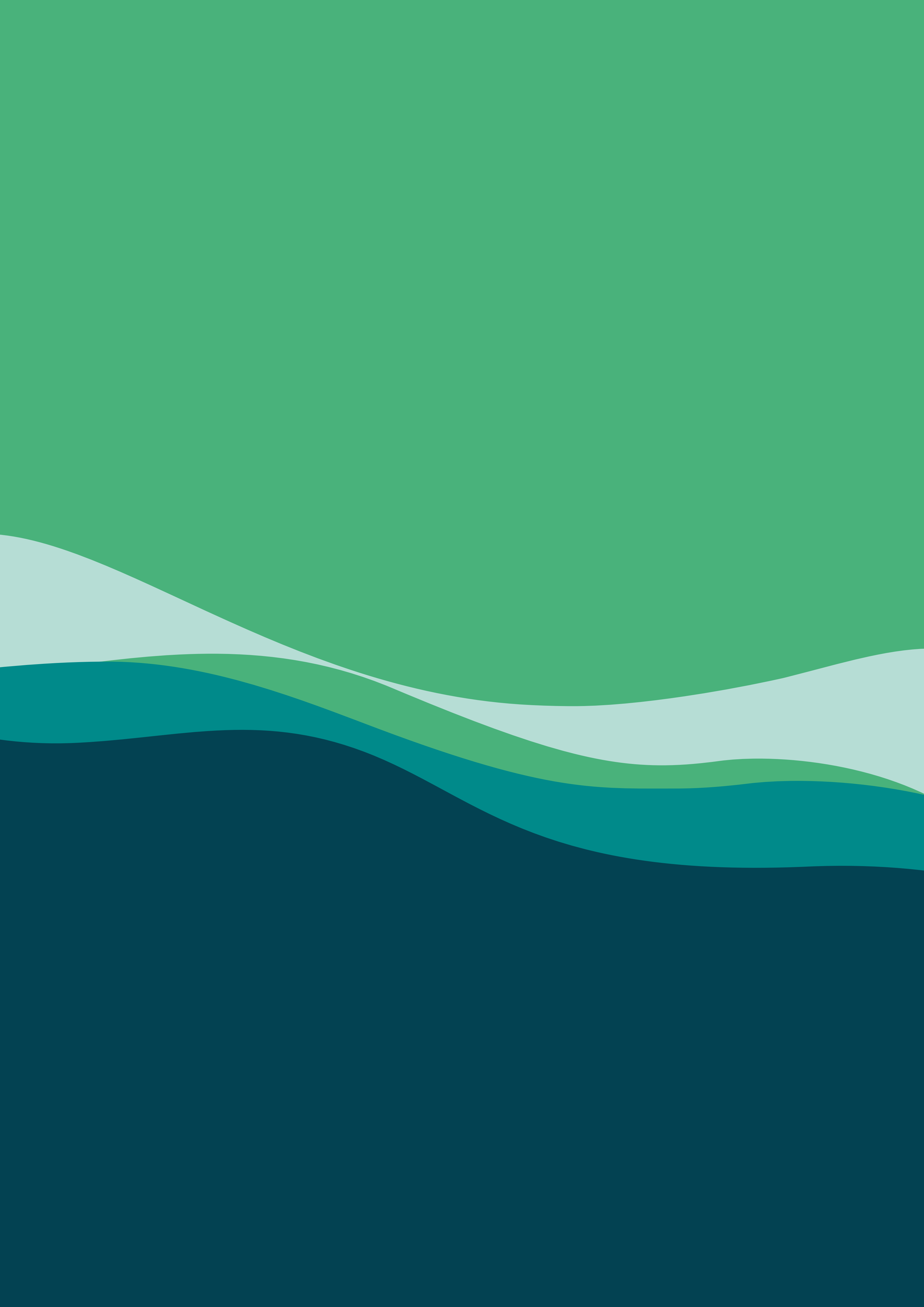
This chapter should be cited as: Dos Santos M, Moncada S, Elia A, Grillakis M, Hilmi N 2020 Development. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 469-492, doi:10.5281/zenodo.7101111.*



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5.1 Development

Executive summary

Sustainable development seeks to address the needs of current and future generations with the objective of increasing well-being by balancing economic, social and environmental dimensions. Current unsustainable development patterns, such as poverty, increasing population pressure, agricultural intensification, land degradation, and air, land, rivers and ocean pollution, will be further exacerbated by climate change impacts.

Environmental and climate change impacts are likely to have an effect on all economic sectors in the Mediterranean Basin, increasing production challenges and costs, affecting low-income cohorts increasingly disproportionally, and generally delaying the achievement of the Sustainable Development Goals (SDGs).

Rising temperatures, with more intense and longer heatwaves, and decreasing rainfall patterns, can exert a further strain on important sectors, such as agriculture and tourism, which represent important cultural, economic and heritage assets for Mediterranean economies and societies.

The existence of poverty, inequalities and gender imbalances relate both directly and indirectly to the challenges faced by Mediterranean countries in achieving the SDGs, with current and predicted environmental and climate change impacts threatening the progress made to date in many areas of the Mediterranean Basin. To address these challenges, a new approach to development must be sought in order to eliminate poverty, sustain economic growth and ensure social protection, while safeguarding environmental standards and integrating mainstream climate change adaptation into policy making.

The growing challenges of environmental and climate change impacts on economies and societies require an enhanced institutional response, at a local, national and international level. Effective preventive and restorative policies, including the promotion of context-specific climate change mitigation and adaptation measures, and economic instruments encouraging behavioral changes, can ensure long-term sustainable development in the Mediterranean Basin.

5.1.1 Past trends and current situation

5.1.1.1 Sustainable development

Sustainable development seeks to address the needs of current and future generations, making it possible to access and use natural resources in an equitable manner both now and in the years to come (Zidanšek 2007; Szopik-Depczyńska et al. 2017; Kilkiș 2018). It sets the framework for securing viable and lasting development and decent livelihoods for all. It aims to promote a dynamic economy with high levels of employment and education, health protection, social and territorial cohesion and environmental protection in a peaceful and secure environment, while respecting cultural diversity (Bontoux and Bengtsson 2015, 2016). Successful societies are known to be built on economic, social and environmental sustainability (Dos Santos 2018; Dos Santos and Mota 2019), ensuring long-term sustainable development.

Traditionally, development has been associated exclusively with increases in income levels, and the conventional manner in which countries, including those located in the Mediterranean Basin, measure progress in development represented by Gross Domestic Product (GDP). While this measurement gives a good indication of the monetary value of the goods and services produced in a specific year, it fails to sufficiently capture other important dimensions of development, especially social and environmental ones. This is mostly due to the fact that GDP, among other things: i) does not capture inequalities in the distribution of income; ii) leaves out some activities (volunteer work) and does not record harmful activities (pollution, climate change); and iii) does not seem to improve well-being beyond certain levels of income (Briguglio 2019). The concept of development, and its measurement, vary. Among these, there is the Human Development Index (HDI), which captures three dimensions: income per capita, health and education (UNDP 2019). Another approach is the OECD better-life index which, along with traditional economic measurements includes other aspects such as quality of health and environmental services (OECD 2017). A further approach is that of measuring happiness. The United Nations Sustainable Development Solutions Network publishes the World Happiness Report annually (Helliwell et al. 2018). The report considers variables for measuring Gross National Happiness (GNH) which are: GDP per capita, social support, healthy life expectancy, freedom to make life choices, generosity, and freedom from corruption. Its ultimate goal is happiness and to ensure a good quality life for the people through people-centric development initiatives. Each variable measured reveals a populated-weighted average score on a scale running from 0 to 10 that is tracked over time and compared against other countries. The ranking of Mediterranean countries for their GNH in 2018 varies significantly, from the highest for Israel (7.190), Malta (6.627) and France (6.488) to the lowest for Tunisia (4.592), Egypt (4.419) and Syria (3.466).

Using sustainability development indicators, it appears that for sustainable development, no sacrifices in happiness are required in the interest of future generations, as it is possible to design strategies that improve happiness and sustainability simultaneously (Zidanšek 2007).

The United Nations defines the sustainable development goals as the blueprint to achieve a better and more sustainable future for all. They address the global challenges we face, including those related to poverty, inequality, climate change, environmental degradation, peace and justice. The 17 Goals are all interconnected, and share the goal "to leave no one behind" (UN 2015).

All the European Union (EU) Member States (MS) in general, and all the countries around the Mediterranean Basin in particular, are facing increasing economic, social, environmental and institutional challenges. The way in which countries are responding to these challenges vary, also according to resource and governance levels. The EU has a considerable set of laws and regulations aimed at addressing environmental and climate change concerns, often making them a priority for all MS (Queralt et al. 2017). The heavily regulated environmental legislation within the EU has often been replicated in bilateral and regional agreements with countries in the Mediterranean Basin, in an attempt to commonly address transboundary concerns. Furthermore, the EU carbon emission reductions targets of 40% by 2030 and 80% by 2050, are increasingly producing spillover effects in other countries in the Mediterranean Basin, prompting the adoption of newer technology and the overall efficient use of energy and an improvement in carbon efficiency (Queralt et al. 2017).

5.1.1.2 The institutional framework

The growing challenges to harmonious development in the Mediterranean Basin have been duly recognized by national and international bodies, prompting an institutional response that eventually led to the creation of the Mediterranean Commission for Sustainable Development (UNEP-MCSD) in 1996. The aim of the MCSD is to provide a bridge between the desire to pursue sustainable development and its effective implementation. It offers a framework in which to define a Mediterranean Strategy for Sustainable Development (MSSD). The MSSD has the objective of pursuing sustainable development goals so as to strengthen peace, stability, and prosperity. The strategy is structured around objectives and interlinked priority fields of action. Specific indicators are also identified to properly monitor and evaluate the strategy. The strategy is regularly reviewed by the parties, and renewed every five years.

5.1.1.3 The economic dimension of sustainable development

Economic development and employment

Two out of three people are already living in the urban areas of Mediterranean countries, which is higher than the global average. The United Nations Human Settlements Programme predicts that by around 2050, the urban population will grow to around 170 million in the countries on the northern shore (140 million in 2005) and to over 300 million to the south and east where they the population was 151 million in 2005 (UNEP/MAP 2016).

Studies demonstrate several projected negative impacts of climate change on economic growth in Mediterranean countries. For instance, based on the severity of the Spanish drought of 1990, it is estimated that economic damages caused by droughts will exceed damages caused by earthquakes or floods (Handmer et al. 2012). Summer crops are particularly vulnerable (Giannakopoulos et al. 2009). As winters become milder while summers become warmer and longer, more cooling by air conditioning is needed in summer, that would increase the demand for electricity generation in most Mediterranean countries *(Section 3.3.3.6)* (Jacob et al. 2014; Kovats et al. 2014). Given that the existing infrastructure was implemented assuming a stable climate around the Mediterranean Basin (Scott et al. 2016a), climate change is making it a challenge for the economic infrastructure to adapt fast enough. This fact points out to the need for investments in adaptive infrastructure in the coming decades. Research and development might reduce the cost of adaptation (Arent et al. 2014).

The main economic sectors driving development in the Mediterranean coastal regions are resource-based activities (i.e., fisheries, aquaculture, forestry, agriculture, and primary industries), secondary industries (e.g., food processing, housing and construction) and services, especially tourism (UNEP/MAP-Plan Bleu 2009). Current and predicted environmental and climate change impacts are expected, especially in the absence of adaptation measures, to increase production costs and reduce productivity (Teotónio et al. 2020) in key sectors, exerting further pressure on economic development trajectories and employment levels in all countries of the Mediterranean Basin.

Tourism

The Mediterranean has a rich history as well as exceptional natural and cultural landscapes. Over 360 million tourists travelled to the Mediterranean region in 2017 – more than double the number recorded in 1995 (Mediterranean Growth Initiative 2017). In the past 20 years the contribution of the tourism sector to GDP has steadily increased by 60% in Mediterranean countries. It should be mentioned that while most Mediterranean countries have experienced significant economic growth in the sector, the vast majority of economic growth corresponds to north-western Mediterranean countries, such as Spain, France and Italy. However, the countries where the tourism sector contributes the highest percentage to the national GDP are Malta, Montenegro, Greece and Morocco (UNEP/MAP 2016). France, Spain and Italy account for 17% of inbound tourism worldwide, corresponding to 234 million people for these three countries alone, as they remain the most attractive of the Mediterranean in terms of numbers of visitors (UNWTO 2019).

In the recent past, Mediterranean coastal regions have been characterized as ideal in terms of climate comfort for outdoor activities, especially during the June to August period (Amelung et al. 2007; Grillakis et al. 2016b). Changes in climate can impact tourism flows, directly by affecting the thermal comfort for outdoor recreational activities (Salata et al. 2018), or indirectly by affecting the natural resources of the destination, such as coastal erosion due to sea level rise (Jiménez et al. 2017), or the reduction of freshwater availability. Given that most Mediterranean tourism is based, and marketed, on the basis of the "sun, sea and sand" model (Koutra and Karyopouli 2013), the socio-economic consequences of a drop in tourist numbers due to climate change impacts can be severe. As sea-level rise leads to coastal retreat, anticipation is needed in order to adapt to, and mitigate the economic impacts of sea-level rise on tourism and populations living in the affected areas (Enríquez et al. 2017).

Environmental degradation caused by climate change and human pressure can have serious impacts on Mediterranean tourism and, eventually decrease the economic benefits arising from this sector (Dogru et al. 2016). Some Mediterranean countries have started to adapt to the changes brought about by these negative impacts, by, for example, developing tourism strategies that try to attract visitors in the "shoulder months", and not focusing entirely on periods (i.e., Summer) where these impacts can affect demand (Niavis 2020). Overall, the vulnerability of tourism is higher in countries with lower adaptive capacity in terms of economic, social and political conditions (Dogru et al. 2016).

Tourism can also directly or indirectly be a driver of environmental and climate change impacts. This is the case, for example, when the lack of energy and water efficiency measures are put into place, exerting further pressure on local ecosystems (Drius et al. 2019) and increasing the cost of infrastructural maintenance. However, tourism could potentially play an important role in both creating jobs and fostering sustainable development in the Mediterranean, assuming that the right set of policies are adopted and well implemented for comprehensive achievement of the SDGs. According to the World Tourism Organization (UNWTO 2018), 64 countries submitted their Voluntary National Reviews (VNRs) in 2016 and 2017 on the SDGs. In these reports, tourism appears to be largely recognized as a high-impact sector with potential to advance all SDGs. 41 VNRs (64%) make one or more direct references to tourism. Tourism is most commonly mentioned in relation to SDG 8 (Decent work and economic growth), SDG 12 (Responsible consumption and production) and SDG 17 (Partnership for the goals) in VNRs on the SDGs among which Mediterranean Cyprus, France, Italy, Monaco, Slovenia, Montenegro and Egypt (UNTWO 2018).

Agriculture, fisheries and food security

International political and economic organizations have become aware that high and volatile food prices and deregulated markets put food security at risk and seriously affect global economic, social and political stability (FAO / IFAD / WFP 2011). The financial crisis in 2007 in the USA affected Mediterranean countries in 2008 and has led to instability in agricultural markets and a rise in the prices of these goods (Dos Santos 2018; Dos Santos and Mota 2019).

Climate change is expected to threaten food security (see *Section 3.2*), especially livestock production and fisheries. Livestock production is an important contributor to the economy. Countries with a higher risk of livestock production being impacted by climate change (e.g., increase in diseases and consequences of higher temperature on animal health) are those which have lower adaptive capacity (Godber and Wall 2016).

Fisheries play an important role in the economy of Mediterranean countries. Total fish landings account for more than €3 billion yearly in the Mediterranean Sea, and including all the ancillaries services, this industry can reach an estimated value of around €10 billion yearly (Sacchi 2011). These values are likely to have been underestimated as significant portion of Mediterranean fish catches are not sold through regulated market outlets (Piante and Ody 2015), not to mention the cultural and tourism value that such an industry adds to local economies.

Economic activities and their impact on inequality, gender and poverty

The presence of poverty and income inequality is interconnected with economic growth (Galor and Zeira 1993; Ncube et al. 2014; Bruckner and Lederman 2015). According to the expectations of the UN SDGs, poverty, in both developed and developing countries, should be abolished by 2030. A priority of governments in this direction is the implementation of policies that enhance economic growth. However, given the tendency of the economic growth process to disproportionally exclude the lower income cohorts from accessing the benefits of new wealth, more equitable approaches to such wealth and social protection systems should be implemented, or enhanced.

These tendencies are confirmed by the data from the UNDP HDI (2019) when adjusted for inequality *(Box 5.1.1; Table 5.1)*, showing that when considering the distribution of income, the HDI ranking for some countries drops and for others improves, which is likely to be associated with policies that try to address the problem of inequality.

The World Bank (2018) has used poverty lines to determine the headcount ratio and poverty gap. Four bases have been considered for poverty lines in order to determine the headcount ratio and poverty gap: 1.90 USD income per day, 3.20 USD income per day, 5.50 USD income per day, in addition to national poverty lines. Since there are many missing poverty data for some national poverty lines, the data are interpreted and countries are compared using standard poverty lines. Firstly, considering 1.90 USD a day as the poverty line, on average about 0.6% of the Mediterranean people are poor. The highest percent of the poor are in Italy, while the highest poverty gap is in Syria. Regarding this poverty line, there are no poor people in countries like France, Malta, Montenegro, Slovenia, Cyprus, and Lebanon. By increasing the poverty line to 3.20 USD, the highest percentage of the poor is in Egypt (16.1%), Syria (15.3%), and Albania (7.7%). In contrast, Slovenia and Cyprus have no such poor people and the percentage of people under this poverty line is low in France and Malta (0.2%). The largest poverty gaps are seen in Syria, Italy, and Albania. When 5.50 USD is used as the poverty line, both poverty percentages and poverty gap increase considerably in the region. Accordingly, the highest percentage of the poor lives in Egypt, Albania, and Morocco. Figures show that more than 60% of Egyptians have income of less than 5.50 USD per day. Also, most poverty gaps belong to the same countries. However, the percentage of people under the poverty line is low in France, Malta, and Slovenia.

Gender inequality indicators for Mediterranean countries, listed in UNDP human development reports, show a varied and complex situation. In the sample countries of the Mediterranean *(Box 5.1.2; Table 5.2)*, Slovenia has the highest Gender Development Index (GDI), at 1.003 in 2017, which ranks it 18th out of 164 international countries in the 2017 index. This means that men and women have relatively the same achievement in three basic dimensions of human development. Croatia, France, and Cyprus are in the next positions in the region and have ranked 31st, 39th and 45th in the world. The last rank in the region belongs to Syria (ranked 159th in the world). The GDI value for Syria demonstrates that there is inequality in human development in favor of men. In fact, the human development index for Syrian men is almost 21% higher than for Syrian women.

For the Gender Inequality Index (GII), the highest value in the region is Slovenia (0.054), ranking it 7th out of 160 countries in the 2017 index. After Slovenia, Spain and France have the least gender inequality in the region and are ranked 15th and 16th in the world. According to the indicator, Syria has again the lowest place in the region and shows the highest gender inequality.

	HDI		INEQUALITY			
Country	HDI Value[a] (2018)	HDI Rank[a] (2018)	IHDI Value[a] (2018)	20:20 Ratio[b] (2010-2017)	Palma Ratio[b] (2011-2017)	Gini Index[b] (2011-2017)
SOUTHERN EUROPE						
Albania	0.791	67	0.705	4.25	1.0	29
Bosnia and Herzegovina	0.769	75	0.656	5.43	1.3	33
Croatia	0.837	46	0.768	5.26	1.1	31.1
France	0.891	26	0.809	5.18	1.3	32.7
Gibraltar	-	-	-	-	-	-
Greece	0.872	32	0.766	7.09	1.5	36
Italy	0.883	29	0.776	7.00	1.4	35.4
Malta	0.885	28	0.815	4.48	1.1	29.4
Monaco	-	-	-	-	-	-
Montenegro	0.816	52	0.746	4.77	1.2	31.9
Portugal	0.850	40	0.742			
Slovenia	0.902	24	0.858	3.66	0.9	25.4
Spain	0.893	25	0.765	7.26	1.5	36.2
Turkey	0.806	59	0.675	8.47	2.1	41.9
LEVANTINE REGION						
Cyprus	0.873	31	0.788	5.33	1.4	34
Israel	0.906	22	0.809	8.50	2.0	38.9
Jordan	0.723	102	0.617			
Lebanon	0.730	93	..	5.06	1.2	31.8
Palestine	0.690	119	0.597	..	1.4	34.4
Syrian Arab Republic	0.549	154	..	..	..	..
NORTHERN AFRICA						
Algeria	0.759	82	0.604	3.96	1.0	27.6
Egypt	0.700	116	0.492	4.56	1.3	31.8
Libya	0.708	110	-	-	-	-
Mauritania	0.527	161	0.358			
Morocco	0.671	121	-	7.02	2.0	39.5
Tunisia	0.739	91	0.585	5.24	1.5	32.8

Table 5.1 | Inequality indicators for Mediterranean countries
[a] Source: UNDP 2019 - [b] Source: World Bank 2019

The existence of poverty, inequalities and gender imbalances relate both directly and indirectly to the achievement of sustainable development goals in Mediterranean countries. Significant theoretical and applied research has shown that the presence of these imbalances, both relative and absolute, are obstacles to the expansion of economic development, de facto blocking parts of society from potentially enjoying the benefits of higher standards of living (Sen 1999; Sachs 2005). Moreover, the traditional way of measuring economic progress by only taking GDP into account, does not capture the problem in the first place, and the extent to which these imbalances permeate societies. The absence of this specific indicator, especially when measuring economic progress, does not bring about reaction or prevention from policy systems, therefore, overlooking the problems related to these distortions of the market economy.

	GDI			GII		
Country	Value[a] (2017)	Rank in Med	Rank in the world	Value[b] (2017)	Rank in Med	Rank in the world
SOUTHERN EUROPE						
Albania	0.970	7	67	0.238	13	52
Bosnia and Herzegovina	0.924	13	117	0.166	10	37
Croatia	0.991	2	31	0.124	8	29
France	0.987	3	39	0.083	3	16
Gibraltar	-	-	-	-	-	-
Greece	0.964	9	80	0.120	7	26
Italy	0.967	8	73	0.087	5	18
Malta	0.960	10	83	0.216	12	45
Monaco	-	-	-	-	-	-
Montenegro	0.956	11	88	0.132	9	32
Slovenia	1.003	1	18	0.054	1	7
Spain	0.979	5	51	0.080	2	15
Turkey	0.922	14	118	0.317	15	69
LEVANTINE REGION						
Cyprus	0.984	4	45	0.085	4	17
Israel	0.975	6	62	0.098	6	21
Lebanon	0.889	16	129	0.0381	16	85
Palestine (Gaza Strip)	0.877	17	132	-	-	-
Syrian Arab Republic	0.788	21	159	0.547	20	136
NORTHERN AFRICA						
Algeria	0.861	19	142	0.442	17	100
Egypt	0.873	18	135	0.449	18	101
Libya	0.929	12	112	0.170	11	38
Mauritania						
Morocco	0.838	20	151	0.482	19	119
Tunisia	0.897	15	125	0.298	14	63

Table 5.2 | Gender indicators for Mediterranean countries (UNDP 2019).
[a] Source: UNDP 2019 - [b] Source: World Bank 2019

5.1.1.4 The social dimension of sustainable development

Education is a fundamental prerequisite for addressing all issues related to Sustainable Development (SD). It creates the necessary enabling environment to enhance skills as well as individual and collective social commitment for the desired transformations, by also allowing for the creation of more sustainable societies (Voegtlin and Scherer 2017). Education can also support the development of better strategies for mitigating and adapting to climate change, thus promoting sustainable development (Anderson 2012).

Education for sustainable development (ESD) is an approach to teaching and learning based on the ideals and principles that underlie sustainability and applicable to all types, levels and settings of education. As such, ESD promotes multi-stakeholder social learning, emphasizes the empowerment of communities and citizens, engages with key issues such as human rights, poverty reduction, sustainable livelihoods, environmental education and gender equality in an integral way and encourages changes in behavior that will create a more sustainable future (Voegtlin and Scherer 2017).

A further important factor in the social dimension of sustainable development is participation. More active participation of the community, especially children and youth, as agents of change, can increase public authorities' understanding of problems, and facilitate the implementation of solutions among communities (Anderson 2012).

The removal of social imbalances, such as gender gaps in education and in salaries, can increase productivity and facilitate economic growth. The main results highlight that the educational gender gap hinders economic growth and development as a whole (Tansel and Güngör 2016; Minasyan et al. 2019). The majority of the results confirm a positive effect of female education on economic growth and development (Forbes 2000; Tansel and Güngör 2016).

5.1.2 Economic vulnerabilities and risks

Expected extreme climate conditions and pollution can enhance economic vulnerabilities and risks in the Mediterranean Basin *(Chapter 2)*. In recent decades, a growing number of publications have identified and assessed how natural hazards occurring in the Mediterranean Region interact with its society and economy. This evidence is being produced on a sectoral level, with assessments of biodiversity, agriculture and cultural heritage systems (Palatnik and Lourenço Dias Nunes 2015; Fatorić and Seekamp 2017), according to the type of hazard (Llasat et al. 2013; Iglesias and Garrote 2014; Oliveira et al. 2018), or with a specific geographical scope (Schilling et al. 2012; Radhouane 2013; Monioudi et al. 2017). An underlying common denominator in the available literature seems to point towards the Mediterranean region experiencing a higher intensity of, and associated risks related to specific natural hazards than other European regions.

This seems to be the case of disastrous flash-floods, which are much more recurrent in some areas of the Mediterranean Basin, when compared to the rest of Europe *(Section 3.1.3.3)* (Llasat et al. 2010). These trends are confirmed by research that looked at flood event mortality in the eastern Mediterranean, which, when accounting for "high" number of causalities is higher, and for "no-deaths" is lower, than central Europe (Doocy et al. 2013). In selected areas of the Mediterranean Basin, the economic sectors more prone to be directly affected by floods are agriculture, followed by commerce and artisan trades, tourism, and industry (Llasat et al. 2013).

Current observations show an increase in drought events, and reduced soil moisture and groundwater availability (*Sections 3.1.3.1* and *3.1.3.4*). These impacts interact negatively, especially with the agricultural sector in the Mediterranean, threatening food security in rainfed yields (Tigkas and Tsakiris 2015) *(Section 3.1.2.2)*, economic performance in terms of reduced wheat exports (Dellai and McCarl 2010) and livestock production (Blauhut et al. 2015). Combined with increasing population in Mediterranean countries, these impacts could intensify the problem of food security.

Changes to precipitation patterns and increased temperature *(Section 2.2.5.3)*, can also affect the quantity and quality of grazing areas, directly impacting farmers' income, with a higher negative impact in non-EU Mediterranean countries, especially at the small-scale level (Abdul Malak et al. 2017).

The increase in sea temperatures and ocean acidification will likely have a negative impact on the fishery industry *(Section 3.2.2.2)*, with these phenomena already linked to mass mortality events in the Mediterranean (Coma et al. 2009), affecting aquaculture by reducing available space to operate businesses (Bird et al. 2016), and potentially increasing mortality rates of the species cultivated, especially due to the increase in heat waves in summer (Rodrigues et al. 2015).

The economic vulnerabilities associated with sea-level rise and coastal erosion have received considerable attention in the Mediterranean region, also given the economic implications of tourism, which for some economies represents more than 30% of the aggregate GDP (Koutroulis et al. 2018a). Summer tourism in Mediterranean countries, which is based on beach holidays, can be threatened by hotter and drier summers, in turn affecting the comfort levels of tourists (Koutroulis et al. 2018b). However, the degree to which Mediterranean countries' tourism sectors might be affected by climate change is often a function of income levels, with the highest levels of vulnerability coming from the lowest income and least resilient countries (Dogru et al. 2019). The effect of sea level rise, together with changes in storm features can seriously affect port operations, slowing down trade operations and productivity levels (Sánchez-Arcilla et al. 2016).

Climate change is expected to cast a shadow of uncertainty over tourism in the Mediterranean. Uncertainties in the assessment of tourism demand under future emission and socio-economic trajectories are subject to factors that affect the visitors' sensitivity to thermal comfort (age, type of tourism, country of origin) (Dubois and Ceron 2006; Dubois et al. 2016). Additional uncertainties stem from the adaptation and mitigation response to climate change (Koutroulis et al. 2018a), as well as the lack of integrated assessment that considers cross sectoral interactions to climate change (Scott et al. 2016b). Mediterranean summertime thermal comfort is expected to generally negatively affect tourism flows in the core summer tourism months of June to August (Amelung et al. 2007; Grillakis et al. 2016a). Improvement in the climate resource is expected for the same regions in the spring and autumn season (Amengual et al. 2014; Grillakis et al. 2016b).

Limited research has quantified the effect of global warming on the net economic impacts on tourism in the Mediterranean. A tourism climate index has been correlated to the total overnight stays in European summer tourism, quantifying the effect of climate change on future overnights stays under 1.5°C and 2°C of global warming above preindustrial levels (Jacob et al. 2018). It was found that 1.5°C of global warming will have an impact on European Mediterranean summer tourism comfort in the July to August period. For the May to October period, marginal positive changes are projected over the majority of the European region, while for the June to August period, a negative effect over southern Spain and Cyprus and for most coastal regions of the Mediterranean is projected. These comfort changes may have a direct impact on the number of overnight stays, with Cyprus and Greece to face a potential decrease of 8% and 2%, respectively. In Spain and Italy, the decrease in comfort over the southern regions of the countries could be compensated by an increase in the north, with a possible northward shift of tourism activity. At 2°C of global warming, this pattern of change is expected to augment further. From an economic perspective, northern Mediterranean regions could exhibit climate induced tourism revenue decreases up to –0.45% of their GDP per year by 2100 (Barrios and Ibañez 2015). A regional temperature increase of 2.2°C in selected regions of Sardinia and Tunisia (Cap Bon) is expected to improve in the shoulder (spring - autumn) season, while increased heat stress may cause a decline in tourism demand in summer (Köberl et al. 2016). The annual net effect is expected to be marginally positive in terms of overnight stays, however the net profit might be less than the present due to the potential increase in the cost of water.

5.1.3 Adaptation

Climate change adaptation can be defined as the process of adjustment to actual or expected climate change and its effects (Smit and Wandel 2006). Climate change adaptation has been identified by the international community as an essential policy response, and its integration into development planning is a key measure for the effective achievement of sustainable development goals. However, the limited resource base of some countries tends to hinder climate change adaptation measures, which are also unlikely to occur automatically in response to observed or expected changes. This kind of response is highly dependent on the specific characteristics of a system, or community, affected by the impacts. The overall long-term adaptive capacity of a population is, in fact, shaped by existing developmental deficits, by exposure to sensitive risks, and by the strategies employed by individuals and communities to cope with these deficits and risks. Existing developmental deficits in some Mediterranean countries, such as endemic poverty, limited infrastructure and technology, ecosystem degradation, conflicts and poor health, among others, challenge the capacity to cope with emerging climate change, in turn affecting the way socio-economic adaptation strategies are applied.

Promoting climate change adaptation is believed to be a win-win strategy. The concept of adaptation has become increasingly associated with what can be considered good development. Such actions to improve climate change adaptation span over a spectrum of initiatives involving investments in, for example, human capital, such as increasing levels of education, skills, and the health status of poor households, or physical capital, such as climate proofing infrastructure projects and investing in self-sustaining renewable energy projects. A lack of human capital, or having poor infrastructure status, can also have a direct impact on labor productivity, and the related capacity to provide secure livelihoods, both in more industrialized Mediterranean countries by slowing down economic development, and in less developed Mediterranean countries by also increasing inequalities. Predicted climate change impacts will only exacerbate such circumstances, especially if nothing is done to account for these impacts (Mavromatidi et al. 2018).

Although applied research is increasing (Cramer et al. 2018), how specific regions or communities in Mediterranean countries may be affected by climate change is still partially unknown. A lack of data and research capacity remains a major problem in some Mediterranean countries. Generally, the most impoverished and vulnerable communities are frequently neglected in impacts and adaptation research (Satterthwaite 2013; Moncada et al. 2018). Additionally, any available data is frequently interpolated over large spatial or temporal scales. While such data can provide some initial insight into potential risks, the data may not be meaningful at the scale at which people live. Failure to identify specific local impacts may lead to adaptation activities that are poorly targeted, inadequate, or even maladaptive (Albizua et al. 2019). Maladaptation refers to actions that might lead to increased risks of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future (adapted from Agard et al. 2014).

The promotion of climate change adaptation can be achieved by either acting on those constraints that impede the attainment of human needs (Sen 1999), or by directly improving the management of specific climate stressors (Pelling 2011). In this regard, a study by McGray et al. (2007) screened more than 100 projects considered to be climate change adaptation initiatives that mostly occurred in low- and middle-income countries. They subsequently found that the beneficial outcomes of the projects had little difference to what can be considered as good development (Klein 2010). McGray et al. (2007) identify a continuum of actions that can be undertaken in order to address climate change impacts. These range from pure development actions, with usually no intentions to tackle climate change adaptation, to purposely designed adaptation efforts. When the first set of actions, aimed at addressing vulnerabilities, can have a positive effect on adaptation, this is known as no-regret, win-win options (Kelly and Adger 2000). On the other hand, the actions targeted to tackle specific climate change impacts might not have any effect on development, unless they are effective at tackling climate change adaptation. In between "lies a broad spectrum of activities with gradations of emphasis on vulnerability and impacts" (Bapna and McGray 2008).

An additional aspect in which climate change adaptation affects development relates to the financial implications for countries to invest in climate change adaptation. External financial and technical assistance is needed in order to cope with the impacts of climate change. Interestingly, the tendency of the majority of the international community has been to finance adaptation mostly through tackling climate change impacts, and largely ignoring the benefit of addressing baseline vulnerabilities/deficits, and effectively enhancing long-term adaptive capacities. Increasing the adaptive capacity of a given system, thus raising the overall level of development, reduces the undesirable impacts of climate change, by allowing a system to better cope with changing conditions, risks or opportunities related to climate change (Smit and Wandel 2006). It has therefore been argued that supporting short-term adaptive capacity, especially in poor communities, is an urgent priority (McGray et al. 2007), as well as being increasingly recognized as an essential element of development (Ayers and Dodman 2010).

This is especially true for investments that address context-specific vulnerabilities, as highlighted in the previous section. Adaptation, therefore, must permeate all policy areas and not only the environment. Investment decisions that do not consider mitigation and adaptation can block regional and national development for many years. Thus, the success of adaptation strategies will also involve adapting actions to specific regional climatic conditions, in sectoral, political and socio-economic contexts by ensuring dialogue between stakeholders, through cooperative structures and knowledge transfer and monitoring progress to support regular reviews of policy objectives and the inclusion of new scientific information when it becomes available (di Gregorio et al. 2017).

Although the links between climate change impacts, climate action and sustainable development are broadly accepted, there has been limited structured investigation in terms of specific SDG Targets, synergies and trade-offs. The Intergovernmental Panel on Climate Change (IPCC) special report on Global Warming of 1.5°C features a chapter that investigates links between certain climate mitigation and adaptation actions and the 17 SDGs (Roy et al. 2018), but it does not assess the specific synergies and trade-offs between climate impacts, climate action and all 169 individual targets of the 2030 Agenda (di Gregorio et al. 2017).

5.1.3.1 National legal and policy framework for adaptation

In accordance with the existing EU framework, EU member States adopted a series of legal measures and a strategic plan of actions to promote adaptation. These measures are related to multiple sectors potentially impacting the environment and aim to reduce and/or mitigate actions affecting climate change. Between them, Spain, Portugal, and Italy, have adopted a few relevant measures. For example, Spain adopted the Royal Decree-Law n. 15/2018, aiming to accelerate the integration of renewable energies into the economy and to promote energy efficiency. Relevant measures adopted by Portugal include the Law-Decree n. 4/2018 introducing incentives for urban electric mobility (similarly to the Spanish Royal Decree of 16th June 2017, n. 617/2017), Decree-Law n. 64/2017 creating a legal framework for the implementation of biomass plants by municipalities, the Portuguese Strategic Framework for Climate Policy was adopted through the Resolution of the Council of Ministers n. 56/2015, including the National Program for Climate Change 2020/2030 (in line with the EU law and strategy) and the National Strategy for Adaptation to Climate Change. The Italian case is more complex, because of the legislative powers divided between the central State and Regions (Art. 117 of the Italian Constitution). Even if the Italian Climate Adaptation Strategy was adopted in 2015 by Decree of the Ministry of Environment, local governments are responsible for its implementation.

Outside the EU, Israel adopted its National Plan for Implementation of the Greenhouse Gas Emissions Reduction Targets and for Energy Efficiency on 10th April 2016, by Government Decision n. 1403/2016. In relation to water resources and the public hydraulic domain, Morocco adopted Law n. 36-15 in 2016, including a total of 163 articles and 12 chapters. Other countries, like Lebanon, adopted two separate national strategies: one related to energy efficiency (with a mid-term scope) and a second broad document related to renewable energy (both in 2016).

The variants of sustainable urban growth (smart cities, green cities, resilient cities, low carbon cities, sustainable cities) have brought renewed opportunities to create pathways for sustainable urban development (Rodriguez et al. 2018). However, the proliferation of all these different concepts, often meaning the same thing, has also created competing agendas and confusion for local decision makers, planners, stakeholders, and business communities. Therefore, progress can be made by focusing on key opportunities that create precedents for transformative and sustainable urban development.

According to the IPCC Fifth Assessment Report (AR5) the majority of cities' adaptation plans and strategies are based on the construction of defensive infrastructure. Although defensive infrastructure is a relevant element of Climate Change Adaptation (CCA) pathways and building resilient cities, making it the center of adaptation plans limits opportunities (Mimura et al. 2014). According to Rodriguez et al. (2018), SDGs can help create recognition for the wider social, cultural, economic, political, institutional and normative elements of adaptation that can lead to the construction of multidimensional operational approaches on the ground.

5.1.3.2 Economic and financial tools to promote environmental management and climate change adaptation in the Mediterranean region

The use of economic instruments to achieve environmental goals and natural resource management (including the management of water quantity-typically extraction charges or taxes), fisheries (taxes, fees and transferable quotas), forestry (charges and subsidies) and wetlands (financial assistance to owners) has increased significantly since the 1970s. The most common market tools in the Mediterranean European countries are charges/taxes (France, Greece, Italy, Spain and Turkey), tradeable permits (France), deposit-refund systems (Italy and Turkey), non-compliance fees (Greece and Turkey) and subsidies (France, Greece and Turkey) (Bartels et al. 2016; Carreño 2019).

Pollution and climate change control instruments can be classified into three categories: 1) institutional approaches to facilitate internalization of externalities; 2) command and control instruments; and 3) economic incentive (market-based) instruments *(Table 5.3)*. Each specific category includes different approaches to achieve the goal of environmental management and climate change adaptation. The institutional approach, where institutions use pollution control instruments to prevent damages to third parties (externalities) or to charge the polluters for the damage that has been produced (internalization of externalities), comprises three specific approaches, as follows:

- Bargaining between generators and victims of pollution could reduce pollution below the critical threshold, but it requires some Institutional intervention, because bargaining often fails to alleviate the targeted pollution. In fact, it is difficult to identify all affected parties, to place importance on future generations with current generations, etc. (Perman et al. 2003).

INSTRUMENT	DESCRIPTION
Institutional approaches to facilitate internalization of externalities	
Facilitation of bargaining	Cost of, or impediments to bargaining are reduced
Specification of liability	Codification of liability for environmental damage
Development of social responsibility	Education and socialization programs promoting citizenship
Command and control instruments	
Input controls over quantity and/or mix of inputs	Requirements to use particular inputs, or prohibitions/restrictions on use of others
Technology controls	Requirements to use particular methods or standards
Output controls: Output quotas or prohibitions	Non-transferable ceilings on product outputs
Emissions licenses	Non-transferable ceilings on emission quantities
Location controls (zoning, planning controls, relocation)	Regulations relating to admissible location of activities
Economic incentive (market-based) instruments	
Emissions charges/taxes	Direct charges based on quantity and/or quality of a pollutant
User charges/fees/natural resource taxes	Payment for cost of collective services (charges), or for use of a natural resource (fees or resource taxes)
Product charges/taxes	Charges/taxes applied to polluting products
Emissions abatement and resource management subsidies	Financial payments designed to reduce damaging emissions or conserve scarce resources
Marketable emissions permits	Two systems: those based on emissions reduction credits (ERCs) or cap-and-trade
Deposit-refund systems	A fully or partially reimbursable payment incurred at purchase of a product
Non-compliance fees	Payments made by polluters or resource users for non-compliance, usually proportional to damage or to profit gains
Performance bonds	A deposit paid, repayable on achieving compliance
Liability payments	Payments as compensation for damage
Loans	Loans available to enterprises to implement pollution control projects
Subsidies	Subsidies paid by the government to firms or consumers for per unit reductions in pollution
Payment for ecosystem services	Payments for environmental services or benefits made by a beneficiary to the provider of the service
Clean development mechanism	Allows a country with an emission-reduction or emission-limitation commitment to implement an emission-reduction project in developing counties
Voluntary emission reduction	Actions that allow the polluter to take advantage of voluntary efforts to reduce greenhouse gas emissions by following certain regulations and standards

Table 5.3 | Classification of finance tools to protect the environment and promote sustainable development (Perman et al. 2003)

- The liability principle, which says that the polluter pays to prevent and remedy environmental damage, and includes the use of direct control tools over polluters, such as mandatory obligations or restrictions on the behavior of firms and individuals. It is the most dominant method for protecting the environment. It is related to property rights and is currently implemented in France (Boivin and Emorine 2019), Italy (Chilosi et al. 2019), Spain (Almenar et al. 2019), Turkey (Perman et al. 2003; Mavioglu et al. 2019), and Slovenia (Justice and Environment 2012).

- Development of social responsibility, which creates incentives for polluters to voluntarily change their behavior. In many - but not all - circumstances, economic incentive-based instruments are more cost-effective than command and control instruments (Perman et al. 2003). This approach includes raising public awareness (UNECE 2013 in Cyprus; UNEP 2015) and environmental education, which is an effective part of the European Union's environment policy (Stokes et al. 2001), and is also implemented in Slovenia (Kraus 1998), Algeria (Environmental Rights Database) and Tunisia (MESD 2018).

The command and control instruments have five key tools, as highlighted in *Table 5.3*. Regulations regarding direct control may apply to:

- outputs of emissions themselves and to the quantity of final production, e.g., fishing quotas in France, when consumption rates exceed 70%, and Spain (OECD 2003),
- the production techniques used, such as regulating industrial emissions within European Union countries, including Spain, under the Industrial Emissions Directive (IED) and Plan AIRE which regulates small installations' emissions in Spain (UNEP 2015),
- the level and/or mix of productive inputs, e.g., input laws in agriculture in Croatia (Grgi et al.); bans on the use of phthalates in toys in France, Greece, and Italy; over 60 PVC-free cities and restrictions on PVC-packing in Spain (Center for Health Environment and Justice (undated)); restrictions on the use of asbestos in 15 Mediterranean countries (Kazan-Allen 2019); restricted financial support by French banks for coal mining and coal powered generation projects (Littlecott 2015); plans to shut all of France's coal-fired power plants by 2021 (White 2018; Climate Transparency 2019), as well as reducing fossil fuel use by 30% by 2030 (Littlecott 2015); and the coal phase-out plan compatible with the limit of global warming below 1.5°C in France and Italy and completing full decarbonization by 2050 (Climate Transparency 2019),
- emission licenses (e.g., in Turkey) (Mavioglu et al. 2019),
- and even to the location of emission sources, e.g., natural regional parks (Salanié and Coisnon 2016) and Zones de Conservation Halieutique (ZCH) in France (OECD 2018); acoustic zoning in Italy (Praščević et al. 2012); and environmental zoning in Bosnia and Herzegovina (Zahumenská et al. 2015).

Economic incentive (market-based) instruments, include many tools, which interface with prices and markets, which can be summarized as follows:

- Emission charges/taxes such as carbon taxes (in France and Slovenia) (CTC (Carbon Tax Center) 2018), as well as SO_2 charges and noise pollution charges (Perman et al. 2003).
- User charges/fees/natural resource taxes such as congestion pricing in France, which does not require a complex system of monitoring, enforcement and compliance, incentivize responsible use of resources and promotes investments (Milewska 2019).
- Product charges/taxes such as costs for plastic bags in Italy (Perman et al. 2003), taxes on energy products in Italy, which earns more than 0.5% of its GDP from taxation of energy products (OECD 2013), taxes on lubricants in France and Italy, and taxes on cadmium batteries in Italy (Barde 1994).
- Marketable emissions permits have been used in some Mediterranean countries like Italy (Recchini 2016). They are allocated by selling them (e.g., by auction) or by giving them away (Devlin and Grafton 1996). Permits are not financially sustainable instruments and had weak performance in the EU (Pettinger 2017).
- Deposit-refund systems are recommended as components of an overall socially optimal set of policies. They can efficiently control pollution in almost the same way as Pigouvian tax (Walls 2011).
- Non-compliance fees are implemented in Greece (Perman et al. 2003), Bosnia and Herzegovina (UNECE 2018), France (Bianco et al. 2015), and Slovenia (OECD 2012b).
- Liability payments are used in different forms in countries like France, Italy (OECD 2013), Spain (Justice and Environment 2017), Bosnia and Herzegovina (UNECE 2018), Slovenia (OECD 2012b, 2012a) and Turkey (OECD 2019). Pursuing liability claims is very costly and the outcome is highly uncertain (Anderson 2002).
- Green loans are used in France (Zakhartchouk 2019), Italy (Lewenhak 2012), Croatia (UNECE 2014), and Lebanon (SwitchMed 2017). Also, Slovenia has plans to reduce water pollutants through loans (GEF 2019).
- Payments for ecosystem services (PES) schemes are implemented in the European Mediterranean countries. While PES are a rapidly proliferating mechanism for natural resource management, their use is sometimes based on an incomplete understanding of their social and economic impacts (DIE 2014). Early PES experiences reveal some positive equity impacts like improved tenure security, community empowerment, organizational and social capital development (Richards and Jenkins 2007). Clean development mechanisms (CDM), e.g., the Concentrated Solar Power plant project in Morocco (ADB and African Development Bank 2011); and CDM or

Joint Implementation projects in several countries including Croatia, France, Greece, Italy, Spain, and Turkey (UNFCCC 2012).

- Voluntary emission reduction is a tool employed by France, Italy, Spain, and Greece, and some for-profit organizations in France, Italy, Spain, and Greece, which reported voluntary carbon offsets (Hamrick and Brotto 2017). Voluntary emission reductions of CO_2, CH_4, and N_2O have also been reported in Croatia (Delija-Ružić 2017).

BOX 5.1.1

Development indicators and terms

Poverty

There is growing consensus among development experts that poverty is multidimensional. In this context, the Multidimensional Poverty Index (MPI) was developed in 2010 by the Oxford Poverty & Human Development Initiative (OPHI) and the United Nations Development Programme (UNDP). The Multidimensional Poverty Index (MPI) provides a sound gauge of poverty. The index measures poverty in three dimensions, i.e., education, health and standard of living. This index is computed for Less Developed Countries (LDCs) and developing countries (UNDP 2018e). According to the MPI, there were 66 million poor in Arab countries in 2018 or around 15% of the total Arab population. Intricately related to poverty is income inequality, which is measured by Inequality-adjusted Human Development Index (IHDI).

The poverty headcount ratio is an index which measures the percentage of poor people whose income is less than the absolute or relative poverty line (World Bank 2018). The poverty gap is a ratio showing the average shortfall of the total population from the poverty line. In other words, it reflects the intensity of poverty in a nation (World Bank 2019). The poverty line is the minimum level of income required to secure the basic necessities for survival.

Inequality

The loss to human development due to inequality over the past few years (2010 to 2017) is consistently more significant in southern Mediterranean countries than northern Mediterranean countries (UNDP 2018d). There are many indicators for measuring income inequalities. Considering a combination of indices would help to better understand the income distribution, because each index is not complete and each of them has strengths as well as weaknesses: 20:20 ratio, Palma ratio, the Gini index, Human Development Index (HDI) and Inequality-adjusted Human Development Index (IHDI).

An inequality measure is often a function that ascribes a value to a specific distribution of income in a way that allows direct and objective comparisons across different distributions. The "20:20 ratio" compares the ratio of the average income of the richest 20 percent of the population to the average income of the poorest 20 percent of the population. In UN reports, it is called "income quintile ratio" (UNDP 2019). The Palma ratio is defined as the ratio of the richest 10% of the population's share of gross national income divided by the poorest 40%'s share (Cobham and Sumner 2013). The Gini index measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution. The Gini index measures the area between the Lorenz curve, indicating the inequality in income spread, and the hypothetical line of absolute equality, expressed as a percentage of the maximum area under the line. A Gini index of zero represents perfect equality and 100 perfect inequality (OECD 2006; UNDP 2018d).

The Human Development Index (HDI) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions. The health dimension is assessed by life expectancy at birth, the education dimension is measured by mean of years of schooling for adults aged 25 years and more and expected years of schooling for children of school entering age. The standard of living dimension is measured by gross national income per capita. The HDI uses the logarithm of income, to reflect the diminishing importance of income with increasing Gross National Income (GNI). The scores for the three HDI dimension indices are then aggregated into a composite index using geometric mean (UNDP 2018c).

The Inequality-adjusted Human Development Index (IHDI) is a viable measure of inequality produced by the UNDP (2018c). The IHDI combines a country's average achievements in health, education and income with how those achievements are distributed among a country's population by "discounting" each dimension's average value according to its level of inequality. Thus, the IHDI is a distribution-sensitive average level of HD. Two countries with different distributions of achievements can have the same average HDI value.

Under perfect equality, the IHDI is equal to the HDI, but falls below the traditional Human Development Index (HDI) when inequality rises (UNDP 2018c). The difference between the IHDI and HDI is the human development cost of inequality, also termed – the loss to human development due to inequality. The IHDI allows a direct link to inequalities in dimensions, it can inform policy makers on how to reduce inequality, and leads to a better understanding of inequalities across populations and their contribution to the overall human development cost.

BOX 5.1.2

Gender-related development indicators and term

Gender

The Gender Development Index (GDI) measures gender gaps in human development achievements by accounting for disparities between women and men in three basic dimensions of human development—health, knowledge and living standards - using the same component indicators as in the HDI. The GDI is the ratio of the HDIs calculated separately for females and males using the same methodology as in the HDI. It is a direct measure of gender gap showing the female HDI as a percentage of the male HDI (UNDP 2018a).

The Gender Inequality Index (GII) measures the importance of gender in inequality. Gender inequality remains a major barrier to human development. Girls and women have made major strides since 1990, but they have not yet gained gender equity. The disadvantages facing women and girls are a major source of inequality. All too often, women and girls are discriminated against in health, education, political representation or the labor market—with negative consequences for the development of their capabilities and their freedom of choice. The GII measures gender inequalities in three important aspects of human development: i) reproductive health, measured by maternal mortality ratio and adolescent birth rates; ii) empowerment, measured by proportion of parliamentary seats occupied by females and proportion of adult females and males aged 25 years and older with at least some secondary education; and iii) economic status, expressed as labor market participation and measured by the labor force participation rate of female and male populations aged 15 years and older. It measures the human development costs of gender inequality. Thus, the higher the GII value the more disparities between females and males and the more loss to human development (UNDP 2018b).

BOX 5.1.3

Vulnerability

The term vulnerability relates to the negative consequences of natural hazards, and is used in economics, hazard and disaster management in different ways (Karagiorgos et al. 2016). Economic vulnerability, at country level, may be defined as inherent proneness to exogenous shocks over which the country can exert little or no control (Briguglio et al. 2009). A widely used measurement of economic vulnerability has been proposed by Briguglio (2010), through an index which attempts to quantify the factors that lead to exposure to economic shocks, which include, among other variables, proneness to disasters, or natural hazards. There are few comprehensive studies on natural hazards for the entire Mediterranean Region (Lionello 2012; Lionello et al. 2014), and the fragmentation of available data does not always allow comparative studies that can extend applications to the whole Basin (González Tánago et al. 2016).

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5

SOCIETY
2-HEALTH

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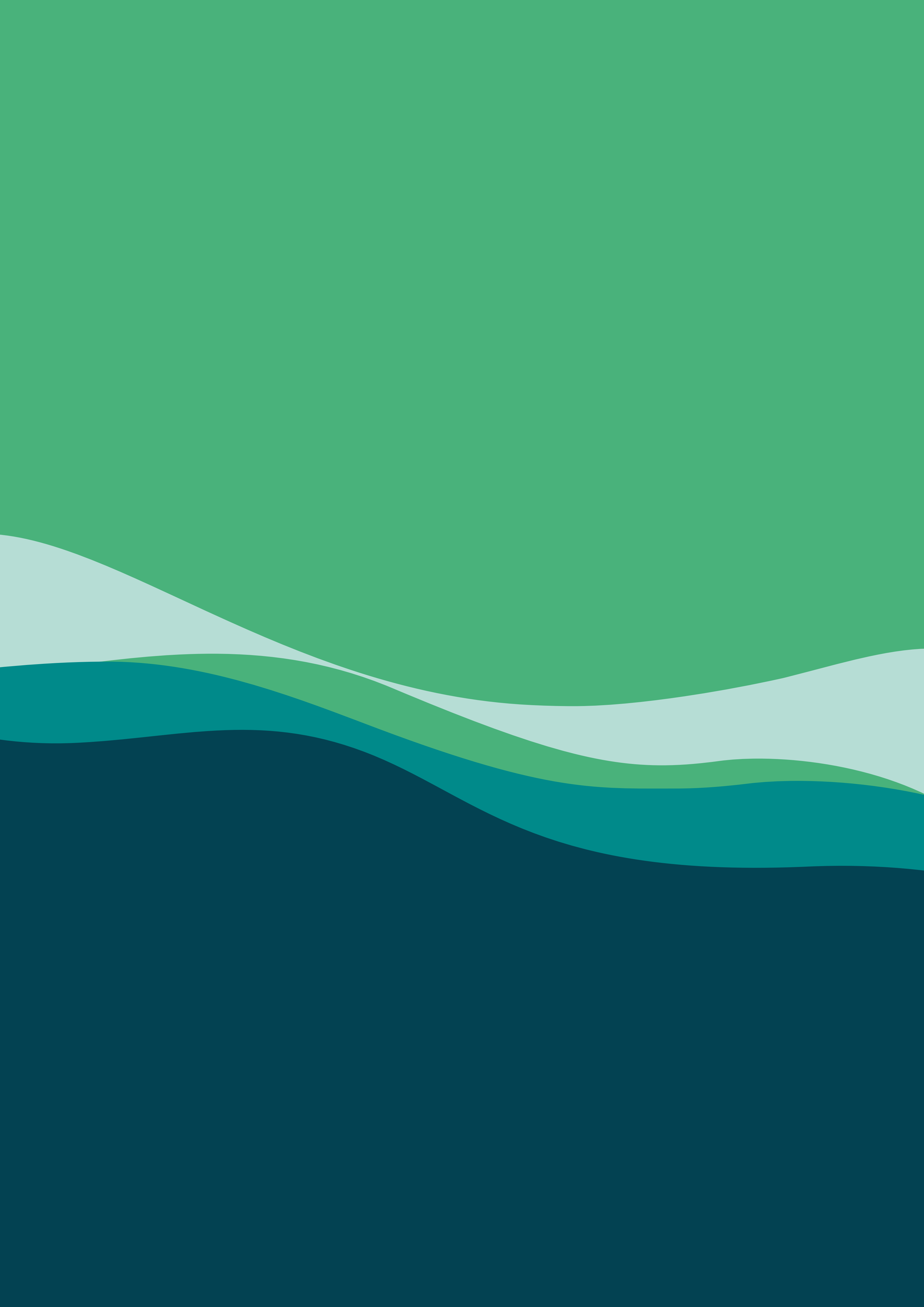
This chapter should be cited as: Linares C, Paz S, Díaz J, Negev M, Sánchez Martínez G 2020 Health. In: Climate and Environmental Change in the Mediterranean Basin - Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 493-514, doi:*10.5281/zenodo.7101115.



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5.2 Health[39]

Executive summary

Climate and environmental change cause a wide range of impacts on human health in Mediterranean countries. The vulnerability of people to the impacts of climate and environmental change is strongly influenced by population density, level of economic development, food availability, income level and distribution, local environmental conditions, pre-existing health status, and the quality and availability of public health care. Poorer countries, particularly in North Africa and the Levant, are at highest risk.

Heat waves have the potential to cause very high rates of premature deaths, especially in large cities and among older people. Heat-related morbidity and mortality have been reduced in the region over recent years thanks to Heat-Health Acton Plans (HHAPs). Despite the rise in mean temperature, cold waves are not expected to disappear with increased future climate variability.

Recent climate and landscape changes in the Mediterranean Basin may create suitable environments for mosquitoes, ticks, and other climate-sensitive vectors, and may exacerbate vector-borne diseases.

Every year, around one million fatalities are attributed to outdoor and indoor air pollution in the European and Eastern Mediterranean regions. There are synergistic effects between ozone levels, particulate matter concentrations and climate variables, especially during heat wave days, with high temporal and spatial variability. An increase in mortality of 1.66-2.1% is observed for each 1°C temperature increase.

Climate change and extreme events have a negative impact on mental health for people who experience loss of homes, destruction of settlements and damage to community infrastructure.

Future changes in the vulnerability of the Mediterranean Basin to vector-borne diseases transmission vary geographically, modifying significantly the extent and transmission patterns of these diseases. For example, by 2050, West Nile virus high-risk areas are expected to expand further, and transmission seasons will extend significantly.

It is important for prevention plans to be implemented. Most adaptation measures offer "win-win solutions" from a public health perspective, including the reduction of air pollution or providing shade. Additionally, Mediterranean countries have the potential to enhance cross-border collaboration for adaptation to many health risks.

5.2.1 Introduction

5.2.1.1 Effects of climate and environmental change on human health

Climate change is a complex phenomenon that threatens all aspects of human society, including increasing risks to human life and health (WHO 2018). Most climate-related health impacts are mediated by complex ecological, environmental and social processes, while impacts vary in magnitude, scale and timing as a function of local environmental conditions and the vulnerability of the human population (Shuman 2010; Smith et al. 2014; Crowley 2016). Climate change impacts human health directly, through exposure to extreme heat and cold events, droughts or storms, or indirectly by changes in air quality, water availability, food availability and quality, and other stressors. The main health effects are related to extreme weather events (including floods and extreme temperatures), changes in the distribution of climate-sensitive diseases (such as vector-, water- and food-borne diseases), and changes in environmental and social conditions (EU Climate Policy).

5.2.1.2 Multi-factorial changes in health attributed to environmental change

The Mediterranean Basin has been undergoing a warming trend with longer and warmer summers, an increase in the frequency, duration and severity of heat waves, and a reduction in rainfall. With significant gradients in socio-economic levels among Mediterranean countries, particularly between the North and the South, together with population growth and migration (World Bank 2017) *(Section 5.3.2.3)*, increased water demand *(Section 3.1.2)*, decreased water availability *(Section 3.1.1)* and quality *(Section 3.1.3.5)* (Bucak et al. 2017), ecosys-

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[39] Parts of this chapter have been published by Linares et al. (2020).

tem degradation *(Section 4.3)* (e.g., Coll et al. 2010) and increased risk of forest fires *(Section 4.3.2.1)* (e.g., Turco et al. 2014), the vulnerability of the Mediterranean population to human health risks is increasing significantly.

5.2.2 Vulnerability and health risk – main causes

Population vulnerability to the impacts of environmental and climate change is strongly influenced by population density, level of economic development, food availability, income level and distribution, local environmental conditions, pre-existing health status, and the quality and availability of public health care (Woodward et al. 2000). Although socio-economic and demographic factors may vary geographically, there are some commonalities across populations in terms of risk factors (UNEP 2018). Characteristics that differentiate populations with particular health risks from environmental change include age, gender, geographic location, socio-economic status, acclimation, occupation, health infrastructure and the (often urban) housing situation (Smith et al. 2014).

5.2.2.1 Aging

Older populations are at particular risk of adverse climate change impacts due to decreased mobility and changes in physiology, as well as limited access to resources. These conditions may limit adaptive capacity among older and more vulnerable people (EASAC 2019). More specifically, with heat-related impacts, such as heat waves, elderly population groups are at particular risk due to dysfunctional thermoregulatory mechanisms, chronic dehydration and medications. People with pre-existing medical conditions, especially cardiovascular or pulmonary illnesses (Mayrhuber et al. 2018) and those with chronic diseases like diabetes are more vulnerable (Yardley et al. 2013), as are those who are obese and have cognitive impairment (Bouchama et al. 2007; Linares et al. 2016).

5.2.2.2 Gender

In addition to differences of a collective nature (such as body size, physical condition and state of acclimatization to heat), there are social factors such as differences in social isolation, that tend to be greater among men than women, and may prove a risk factor e.g., during heat waves (Canouï-Poitrine et al. 2006). There are factors of a physiological nature, such as women's tendency to sweat less than men (Gagnon et al. 2013), a natural thermoregulation mechanism that might explain the greater impact of heat on women. Also single-parent women (De'Donato et al. 2018) are cited as more vulnerable. Moreover, for pregnant women and babies in gestation, extreme heat is a risk factor for adverse birth outcomes, such as low birth weight and premature birth (Arroyo et al. 2016).

5.2.2.3 Geographic location

Most studies show that there is important variability in the effects of climate change on morbidity and mortality related to geographic location and the sensitivity of populations to extreme values such as extreme heat or cold, urbanization level, and distance to health system infrastructures (Allen and Sheridan 2018). For example, rural populations will be at a high risk of vector-borne diseases related to climate warming.

5.2.2.4 Socio-economic status

Population vulnerability to high temperatures will be affected not only by climate change but also by socio-economic factors (Semenza et al. 2008). In socially disadvantaged groups, the effects are particularly pronounced among the poor, socially isolated, substance abusers and homeless (Nicolay et al. 2016). Migrants, refugees and internally displaced people may have pre-existing and post-displacement vulnerabilities such as malnutrition, untreated chronic medical conditions from limited access to health care, and lack of shelters that provide adequate protection, predisposing them to decompensation caused by heat or other extreme events (McMichael et al. 2012).

5.2.2.5 Level of acclimation

Climate change will affect an increasingly aging population, a larger percentage of whom have chronic diseases, and are therefore more susceptible to the effects of increasingly extreme temperatures (changes in the population susceptibility framework). Population effects are quantified through the increased number of people over 65, which is the target population for heat impacts, as well as those in energy poverty or living in older building structures. On the other hand, there are factors that should result in a decrease in the impact of heat in the future. These include, for example, the existence of an active adaptation process within the population (both autonomously by individuals and families, and by the authorities and institutions), due to multiple factors from the so called "culture of heat" (Bobb et al. 2014), to the implementation of prevention plans (Schifano et al. 2012), improvements in health services (van

Loenhout et al. 2016), and improvements in socio-economic circumstances and infrastructure of homes, as well as an increase in the number of air conditioning units (Díaz et al. 2018b), among others.

5.2.2.6 Occupational health

Extreme heat and cold waves have been linked to an increased risk of occupational injuries. Studies report significant losses in work capacity and productivity linked to climate warming. Several mechanisms are thought to be behind the link between ambient temperatures and risk of injury in the workplace (Martínez-Solanas et al. 2018). Exposure to high temperatures can lead to physiological and psychological changes associated with heat strain, which in turn can decrease workers' performance and lead to impaired concentration, increased distractibility and fatigue (Zander et al. 2015). Sectors with a high percentage of outdoor workers, such as agriculture and construction or police and security, have the highest risk of seeing heat stroke or even heat stress develop (Martínez-Solanas et al. 2018). Additionally, despite the rise in mean temperatures, cold waves are not going to disappear. Therefore, factors related to working in cold environments, such as thermal discomfort, hypothermia, or reduced mobility while wearing protective clothing are associated with decreased dexterity and performance among workers and can also trigger occupational injuries (Mäkinen et al. 2009).

5.2.2.7 National public health infrastructures, warning systems

Better surveillance and improved warning systems are needed for vulnerable population groups. Increased urbanization increases the level of population exposure and can put pressure on water management and energy infrastructure, social care and health systems, so as to make them inefficient or unable to adopt necessary measures and prevention plans (Environmental Audit Committee 2018). Prevention plans and early warning systems began in the European region after the heat wave of 2003 and their efficiency is under evaluation. In France, the implementation of the prevention plan and alert system after the heat wave of 2003 is considered to have contributed to a reduction of around 4,400 fatalities during the heat wave of 2006, especially benefitting people over 75 years of age (Fouillet et al. 2008). In recent years, Heat-Health Action Plans (HHAPs) led to a decline in mortality during heat waves (Martinez et al. 2019). Currently, early warning systems for heat and cold waves are active in Mediterranean countries, such as the Egyptian Meteorological Authority (EMA).

5.2.2.8 Influence of urban landscape

Urban Heat Islands (UHI) are considered to be one of the greatest twentieth century problems facing humanity, and they are the result of urbanization and industrialization (Rizwan et al. 2008). Temperature differences between cities and rural areas due to the UHI effect can reach up to 10°C in large cities. The effect of heat in urban areas increases with population density, extensive economic activities and city expansion (Burkart et al. 2016; Milojevic et al. 2016). Factors that amplify the UHI effect include household characteristics such as the age of buildings, residence in the highest floor of a building, the presence of a bedroom immediately beneath the roof (due to the concentration of heat that accumulates during the day), and lack of good thermal isolation (Vandentorren et al. 2006; López-Bueno et al. 2019).

5.2.3 Health impacts: recent and current situation

5.2.3.1 Heat-related impacts

Heat waves have very high mortality rates in Europe causing tens of thousands of premature deaths, especially during the 2003 heat wave. Mediterranean cities like Athens, Barcelona and Rome have all experienced strong impacts of extremely high temperatures (De'Donato et al. 2015). Despite the aging European population and continuously increasing temperatures, Mediterranean cities (and also other areas with commonly high temperatures) have recently shown a reduction in heat-related morbidity and mortality (Díaz et al. 2018a). This reduction is attributable to several factors, such as the existence of Heat-Health Action Plans (HHAPs) and the implementation of prevention plans (Morabito et al. 2012), improvements in health services, infrastructure and housing, changes in patterns of susceptibility of the population and increased awareness of the effects of severe heat (Ragettli et al. 2017), which in turn may be a result of improved communication and media coverage (De'Donato et al. 2015).

An important decrease in heat-related mortality has been observed among children and elderly people, although at a lower rate for the elderly (Schifano et al. 2012; Díaz et al. 2015). The reduction in heat-related mortality does not show consistent differences by age group (De'Donato et al.

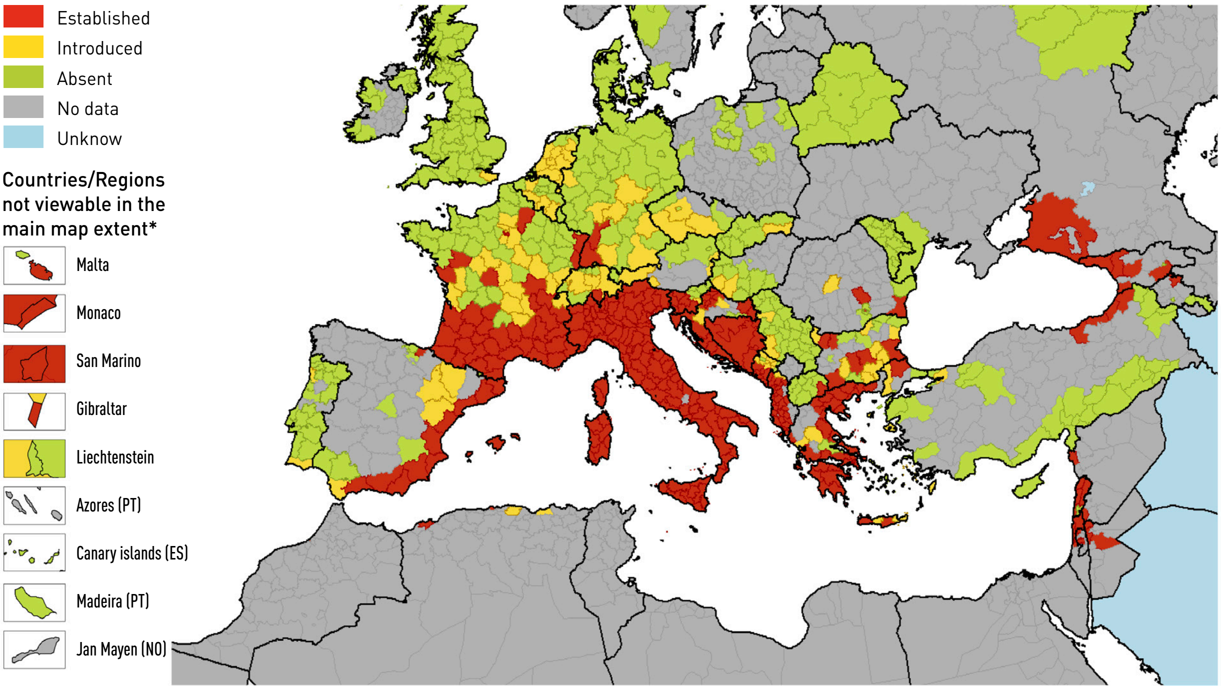
2015) or gender (Allen and Sheridan 2018) and is spatially variable (Toloo et al. 2013; Linares et al. 2015b). Plans and alert systems have helped raise awareness among the population about the risk, but they have probably not been enough to provoke changes in population behavior so as to lead people to take measures to protect themselves (Wolf et al. 2010). Health promotion and behavior studies suggest that people who are most likely to adopt these measures are also those who have a high risk perception, but the opposite is true for the most vulnerable groups.

The cost of investing in protection measures against heat is one of the barriers that prevent vulnerable populations from taking action. The negative environmental impact of air conditioning must also be considered *(Chapter 3.3)*. Educational programs are required to inform the population, especially the most vulnerable and their caregivers, about the risks of exposure to high temperatures. In the European part of the Mediterranean Basin, the increase in temperatures will affect both warmer and temperate countries, and it is therefore important that prevention plans are implemented in those countries that currently have no prevention plans in place, and that they are improved where they already exist. Ultimately, the effectiveness of prevention plans depends on the capacity (of the health sector, the local community, etc.) to adapt to the changes, the plan's ability to incorporate climate change into research frameworks on adaptation and implementation, and the knowledge generated in the field (Hess and Ebi 2016).

There is insufficient research on public awareness regarding climate change and health in the Mediterranean. People who perceive climate change as a risk to public health are more supportive of mitigation policies and show more willingness to take individual measures to mitigate climate change (Debono et al. 2012).

5.2.3.2 Cold-related impacts

Winter mortality is associated with low temperatures, extremely low temperatures or cold waves (The Eurowinter Group 1997). This phenomenon has attracted less attention than the analysis of heat waves, though its impact on mortality is higher and up to an order of magnitude greater than those related to heat (Vardoulakis et al. 2014). By the end of the 21st century, southern European regions are expected to experience a clear decline in cold-relat-



ECDC and EFSA, map produced on 16 Jan 2019. Data presented in this map are collected by the VectorNet project. Maps are validated by external experts prior to publication. Please note that the depicted data do not reflect the official views of the countries. Administrative boubaries © EuroGeographics, UNFAO, TurkStat.
* Countries/Regions are displayed at different scales to facilitate their visualisation.

Figure 5.1 | Distribution of the tiger mosquito, *Aedes albopictus,* in 2019 - a known vector of chikungunya and dengue viruses (from ECDC 2019).

ed mortality opposite to the increase in heat-related mortality (Gasparrini et al. 2017). These conclusions are based on the dual assumption that there will be no population acclimatization processes to such extreme temperatures and no changes in mortality rate. Other studies indicate populations may adapt to heat (Oudin Åström et al. 2018). Despite the rise in mean temperatures *(Section 2.2.4.2),* cold waves are not expected to disappear. Added to the fact that the impact of cold-related mortality is greater than that of heat-related mortality (Carmona et al. 2016), from a public health standpoint it is essential that the climate impact on mortality risk is analyzed by considering the impacts of both heat and cold waves together.

5.2.3.3 Vector-borne diseases

One of the main impacts of environmental and climate changes on human health is the influence of warmer climates and changing rainfall patterns on vector-borne disease (VBD) transmission which, together with anthropogenic changes in landscapes may create hospitable environments for mosquitoes, ticks, and other climate-sensitive vectors (Crowley 2016) *(Fig. 5.1).*

Long-term anthropogenic climate change interacts with natural variability, influencing the transmission of VBDs from shorter (seasonal, annual) to longer (decadal) time scales, with variable effects and complex interactions at different times and locations (Campbell-Lendrum et al. 2015). These impacts are complex and may involve nonlinear feedback inherent in the dynamics of many infections (Metcalf et al. 2017), including impacts of other environmental drivers such as biodiversity loss or changes in land use (Reisen et al. 2006; Marcantonio et al. 2015; Paz 2015) *(Chapter 2).* It is therefore expected that VBD outbreaks will be exacerbated in the region.

Most cities in the Mediterranean Basin are compact and densely populated. Air conditioning is used in regions with sufficient resources, but windows often remain open even during the hottest months. Many activities, particularly social gatherings, occur in outdoor locations such as shaded balconies, courtyards, and outdoor restaurants - all ideal places for contact with the vector. While warmer summers extend the potential season of the disease throughout the basin, poorer countries, particularly in North Africa and the Levant, are at highest risk (Negev et al. 2015).

Currently, the main vector-borne diseases in the Mediterranean basin, transmitted by insects and potentially influenced by the changing climate are West Nile virus, Chikungunya and Leishmaniasis.

West Nile virus

West Nile virus (WNV) is a vector-borne pathogen of global importance since it is the most widely distributed virus of the encephalitic *Flavivirus* spp. Mosquito species from the genus *Culex* (family *Culicidae*) are the primary amplification vectors and also act as bridge vectors. The enzootic cycle is driven by continuous virus transmission to susceptible bird species through adult mosquito blood meal feeding, which results in virus amplification (Paz and Semenza 2013; Petersen et al. 2013).

The establishment of WNV in new regions is facilitated by warmer conditions. Ambient warming increases the growth rates of mosquito populations, decreases the interval between blood meals and shortens the incubation time in mosquitoes (Paz 2015; Moirano et al. 2018). Clear associations have been found between warm conditions and WNV outbreaks in Mediterranean countries (Paz et al. 2013; Tran et al. 2014; Marcantonio et al. 2015; Moirano et al. 2018).

Since the unprecedented WNV outbreak in 2010 in southern and eastern Europe, which was accelerated by extreme temperatures (Paz et al. 2013), outbreaks occur every summer (2011-2019) and there is evidence of ongoing transmission in Euro-Mediterranean countries (Semenza and Suk 2018). During the last decade, WNV outbreaks in humans erupted in many Mediterranean countries including France, Italy, Croatia, Slovenia, Greece, Turkey, Israel and the Mediterranean islands. During the 2018 transmission season, a higher number of cases was reported compared with previous years (ECDC 2018).

The impact of changes in rainfall patterns on disease incidence is influenced by precipitation levels (increased and extreme precipitation, e.g., Moirano et al. 2018, floods or droughts), depending on local conditions, the landscape (e.g. wetlands, Tran et al. 2014) and the differences in the ecology and sensitivity of mosquito species (Paz 2015). In the Mediterranean area, increased rainfall and humidity together with high temperatures probably favored the multiplication of *Culex* species, which led to numerous cases of WNV human infections in northern Greece in summer 2010 (Papa et al. 2010). Climate parameters were found as key predictors of WNV outbreaks including high precipitation in late winter/

early spring and summer drought (Marcantonio et al. 2015).

Chikungunya

Chikungunya is a viral disease transmitted by *Aedes* mosquitoes to humans. The most common symptoms are fever and severe joint pain. In 2007, an outbreak of chikungunya virus infections took place for the first time in Italy, indicating the possibility of mosquito-borne outbreaks by *Aedes albopictus* in the Euro-Mediterranean area. In 2010 and 2014, autochthonous cases were reported in France. The risk of chikungunya spreading in the EU and the Mediterranean is high due to importation through infected travelers, presence of competent vectors in many countries (particularly around the Mediterranean coast) and population susceptibility (ECDC). In August-September 2017, local transmission of chikungunya was confirmed in southeastern France (WHO 2017a) and in Italy, six transmissions were reported in Rome and eight in the coastal area of Anzio in the Lazio Region (WHO 2017b).

Rift Valley fever

Rift Valley fever is a mosquito-borne zoonotic climate-sensitive disease closely associated with high-rainfall conditions (e.g., after prolonged excessive rainfall in sub-Saharan Africa). However, large outbreaks have also occurred in the dry and low-rainfall climate of Egypt (Linthicum et al. 2016).

Leishmaniasis

Leishmaniasis is a vector-borne disease with three main clinical forms: Visceral (Kala-azar), Cutaneous Leishmaniasis (CL), and Visceral Leishmaniasis (VL) caused by infection of Leishmania parasites and transmitted by the bite of infected females of *Phlebotomine* spp. sandflies. Leishmania genus includes about 20 species, widely distributed in more than 85 endemic countries, with 0.7-1.2 million new cases of CL every year, of which about a third occur in the Mediterranean region (Alvar et al. 2012). In the eastern Mediterranean Basin, two CL species, which manifest as skin sores, are common: *Leishmania major* and *Leishmania tropica. Leishmania tropica,* transmitted by the *Phlebotomus sergenti* sandfly, was first discovered in Israel in the early 1990s. Since the late 1990s, rapid unexpected outbreaks occurred in new urban and rural foci in Israel, Jordan and the Palestinian Authority (Al-Jawabreh et al. 2017; Waitz et al. 2018).

5.2.3.4 Food- and water-borne diseases

Climate change increases the risks of food- and water-borne diseases (Ebi et al. 2018). For example, the survival and multiplication of salmonellosis in the environment and in food is influenced by high temperatures (Miraglia et al. 2009; Milazzo et al. 2016). It was shown for ten European countries that temperature influences infection transmission in about 35% of all cases of salmonellosis, while the greatest effect was apparent for temperature one week before the onset of illness (Kovats et al. 2004).

Campylobacter species have emerged as leading bacterial causes of gastroenteritis and food-borne infections in high-income countries (EFSA and ECDC 2015). The incidence of campylobacteriosis varies seasonally and geographically, and tends to be highest during the summer months (Bassal et al. 2016). While the temperature may directly affect the rate of replication of pathogens and their survival in the environment, increased ambient temperatures may increase bacterial contamination at various points along the food chain and also influence people's behavior which, in turn, may be translated into more risky patterns of food consumption (Lake et al. 2009). A recent retrospective study in Israel found that higher temperatures across seasons, prior to or around the time of food purchasing, played a role in human infection (Rosenberg et al. 2018).

Leptospirosis, caused by *Leptospira interrogans,* is a highly infectious emerging water-borne zoonosis of global significance. A study in Croatia showed strong influence of climate conditions on incidence of human leptospirosis at annual level. In the years 2010 and 2014 that were characterized as warm/extremely warm and wet/extremely wet, a significant temporal increase in incidence was observed. Increased risk for human infections is related to season, gender and age with peaks in incidence occurring cyclically and associated with extreme weather conditions. The influence of weather should not be considered without taking into account the wider impact of climate change on domestic, peridomestic and wild animals (Habus et al. 2017). In Israel, human leptospirosis is uncommon, but in summer 2018, a large outbreak of human leptospirosis was linked to contaminated water bodies in northern Israel after years of severe drought conditions which had resulted in particularly low water levels in the region (Dadon et al. 2018).

5.2.4 Indirect impacts: recent and current situation

5.2.4.1 Air quality

Climate and environmental change, anthropogenic activities, urbanization, industrialization, etc. affect air quality and impact human health, through several pathways, such as changes in atmospheric circulation, ventilation and dilution of air pollutants, removal processes, stratosphere–troposphere O_3 (ozone) exchange (e.g., Akritidis et al. 2016) and increase in the frequency of wildfires (Fiore et al. 2015) (see *Section 2.3.2*). Every year, around one million fatalities are attributed to outdoor and indoor air pollution in the European and eastern Mediterranean regions (WHO Regional Office for Europe and OECD 2015). In Lebanon, the prevalence of cardiovascular disease has been linked to exposure to pollution (Salameh et al. 2019). In Europe the cardiovascular diseases burden from ambient air pollution is substantially higher than previously assumed, though subject to some uncertainty (Lelieveld et al. 2019).

In Europe, 90% of citizens are exposed to levels of fine particulate matter (PM) that exceed World Health Organization (WHO) air quality guidelines. There are synergistic effects between ozone levels, PM concentrations and climate variables (Analitis et al. 2018), especially on heat wave days (Katsouyanni et al. 2009), together with a large variability on both temporal and geographical scales, likely connected to local climate characteristics, activity patterns and physical adaptation (de Sario et al. 2013). An increase in mortality of 1.66% was observed for each 1°C temperature increase on low ozone level days, and an increase of up to 2.1% on high ozone level days (Analitis et al. 2018). There is a positive relationship between cardiovascular mortality and the concentrations of nitrogen dioxide (NO_2), the main precursor of tropospheric ozone (Nuvolone et al. 2013). Out of 524,000 pollution-related premature deaths, 432,000 are estimated to be attributable to PM2.5, 17,000 to O_3 and 75,000 to NO_2. Reducing exposure to PM improves the life expectancy of Europeans by about 8 months (WHO Regional Office for Europe and OECD 2015). As the main emission source of these pollutants is vehicle traffic, largest impacts are concentrated in large cities due to microcirculation.

Atmospheric pollutants that are linked to climate change are considered major contributors to the large rise in the number of people affected during the allergy season. Airborne allergens chemically modified by the presence of NO_2 and O_3, seem to increase their potency. Airborne allergies are thus becoming more common in combination with global climate change. Together with global warming, increased pollen production and earlier spring phenology, this leads to earlier, more frequent and more widespread pollen allergies (American Chemical Society 2015).

5.2.4.2 Mineral dust and forest fires

The main health impacts associated with PM occur in densely populated urban areas where the principal component is from anthropogenic emissions (Karanasiou et al. 2012). In southern European urban areas, these account for approx. 80% of PM and aerosol emissions, while the remaining 20% are of natural origin, mainly from advections of desert dust (Viana et al. 2014), sea spray (O'Dowd and de Leeuw 2007), volcanic emissions (von Glasow et al. 2009), and aerosols from wildfires, with Saharan dust intrusions and PM advection from wildfires being the primary sources.

Impacts of PM due to wildfires on human health are mainly respiratory problems (Mirabelli et al. 2009) or exacerbations of previous respiratory diseases (Martin et al. 2013), while exposure to forest fire smoke has also been linked to cardiac diseases (Weichenthal et al. 2017). Medium-size fires are found to increase daily mortality in Athens (Analitis et al. 2012), while the accumulative impact of PM10 (PM with diameter less than 10 μm) during forest fires smoke advection exacerbates mortality for different age groups and causes (Faustini et al. 2015; Linares et al. 2015a).

Long-distance transport generates a change in the respective atmospheric concentration of the different sized particles and in the chemical composition of the particles present in the air (Pérez et al. 2012), while there is evidence that desert dust itself transports biological allergens or irritants (Garrison et al. 2006; Griffin 2007; Polymenakou et al. 2008). Non-biological compounds in dust may cause adverse health effects, or local conditions may modify the toxicological properties of the dust. The two circumstances of change, i.e., in PM concentration and chemical composition, are related to clearly differentiated morbidity-mortality patterns, which are observable on days with desert dust intrusions (Jiménez et al. 2010).

The human health effects of dust storms range from respiratory disorders (including asthma, tracheitis, pneumonia, allergic rhinitis and silicosis), to cardiovascular disorders (including stroke), conjunctivitis, skin irritations, valley fever, diseases associated with toxic algal blooms, and mortality and injuries related to transport accidents (Goudie 2014). Spatial and temporal variability of the PM effects on human health due to Sahara dust intrusions in Euro-Mediterranean countries stems from co-existing PM concentrations due to traffic sources and their higher toxicity (Samoli et al. 2011; Stafoggia et al. 2016), the varying impacts on the different age groups (Zauli-Sajani et al. 2011), the specific causes of health impacts and PM groups (Neophytou et al. 2013).

5.2.4.3 Mental health

Climate change and extreme events have a negative impact on mental health in several ways. Floods, droughts and sea level rise have long-lasting impacts on societies who have experienced loss of homes, destruction of settlements and damage to community infrastructure. These impacts on mental health include anxiety, depression and post-traumatic stress disorders (Watts et al. 2015). However, there is insufficient research on the mental health impacts of climate change, both internationally (Watts et al. 2018) and also regionally in Mediterranean countries. The few studies that have been conducted in the Mediterranean found negative impacts of high temperature on mental health. For example, in Thessaloniki, Greece, high temperatures may be associated with increased male suicide rates. In the context of the recent economic crisis in Greece, a multilinear regression showed that high temperatures explain 51% of the variance in male suicides, while unemployment was insignificant (Fountoulakis et al. 2016). Another study in Northern Italy found a strong positive association between the number of daily emergency psychiatric visits and mean daily air temperature (Cervellin et al. 2014). More research is needed regarding the impact of different extreme climate events on diverse mental health outcomes.

There is some evidence that climate change may intensify violence in the Mediterranean, across all levels. Climate change-induced water shortage and food insecurity may intensify conflicts in the eastern Mediterranean (Brown and Crawford 2009), especially in counties that lack adaptive capacity (Feitelson and Tubi 2017). At the domestic level, a study in Madrid found an association between heat waves and increase in domestic violence, including an increase in police reports and helpline calls three days after the heat wave (Sanz-Barbero et al. 2018).

5.2.4.4 Migration

Displacement related to environmental change and climate disasters is not a new phenomenon in the Mediterranean *(Chapter 5.3)* (Charef and Doraï 2016). Migration potential has increased over recent decades due to the increasing impacts of climate change, frequent and more intense extreme events, especially in areas with high population density and areas at risk, with direct and indirect impacts on the well-being, livelihood and security of populations *(Chapter 5.3)*. Displacement may lead to adverse health outcomes, especially for vulnerable population groups as well as those suffering from chronic diseases (Schütte et al. 2018). In lower-income countries hosting refugees in particular, it may undermine national health systems and diminish access to health care for domestic, as well as migrant, populations (Gostin and Roberts 2015). In Egypt, re-emerging diseases such as tuberculosis have been reported as an indirect effect of climate change linked to the crowdedness of slum areas due to irregular internal migration of farmers who have lost their land (Girardi et al. 2017).

5.2.5 Projections for global warming of 1.5°C, 2°C and more

5.2.5.1 Vulnerabilities and risks under different warming scenarios

The IPCC special report on 1.5°C global warming (IPCC 2018) shows that global warming of 2°C poses substantially greater risks to human health than 1.5°C, with actual risk levels varying regionally (Hoegh-Guldberg et al. 2018). The risks may be particularly high for heat-related morbidity and mortality, heat stress, ground-level O_3, and malnutrition. For vector-borne diseases, the risks are more variable because warmer temperatures may result in some regions becoming too hot and/or too dry for a vector (Ebi et al. 2018).

5.2.5.2 Heat-related impacts

Many projections around heat-related mortality are made without considering the socio-economic conditions of the population. In order to show the contribution of changes in socio-economic and climate conditions to mortality due to heat in the European population, a study was developed that combined socio-economic scenarios with greenhouse gas emissions (RCP) (Mayrhuber et al. 2018). The percentage of the European population at risk of thermic stress is expected to increase constantly over coming years, and could increase from the

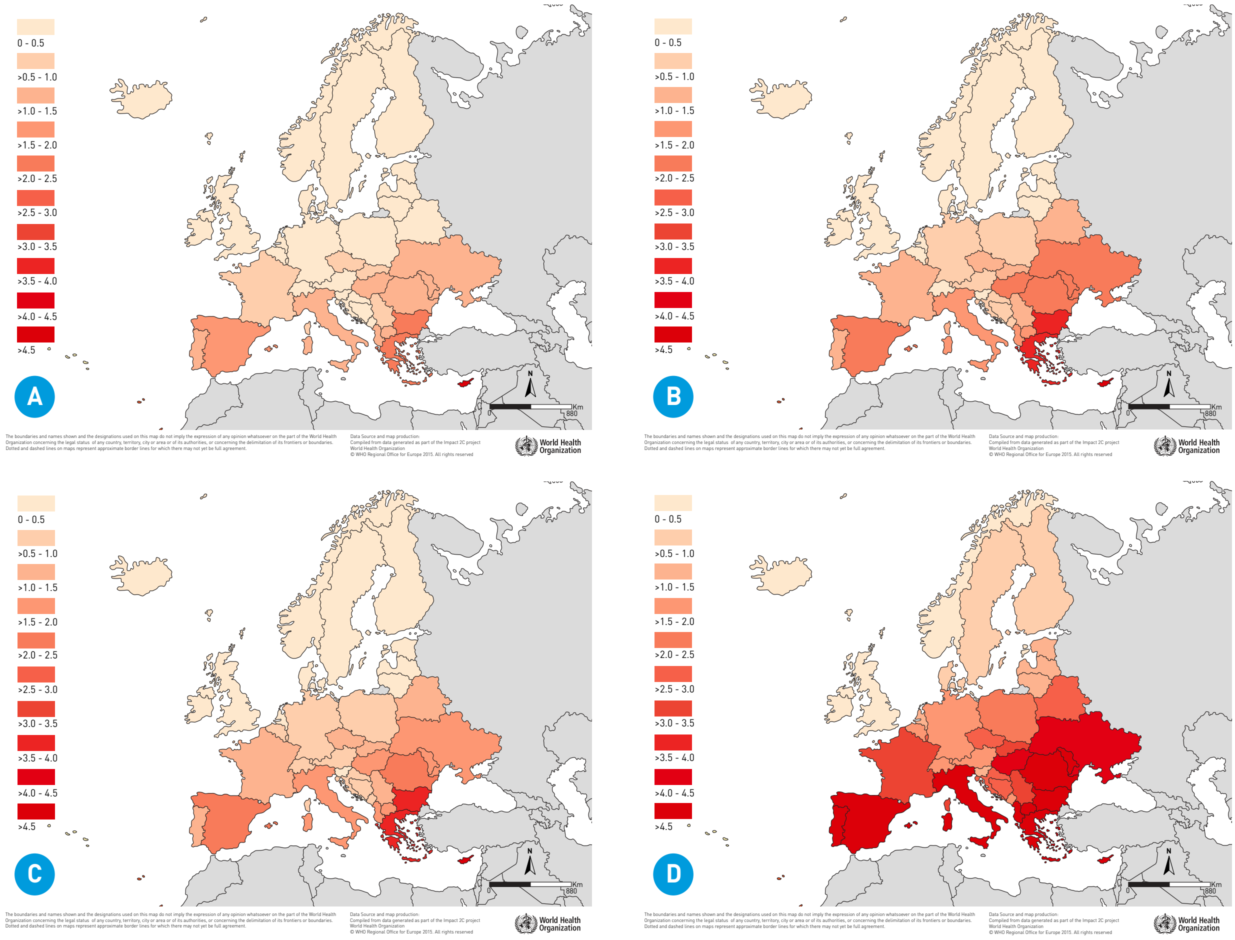


Figure 5.2 | Attributable fraction of heat-related deaths during summer by country in European sub-region, A) RCP4.5 in 2050; B) RCP8.5 in 2050, C) RCP4.5 in 2085 and d) RCP8.5 in 2085 (from Kendrovski et al. 2017).

current 0.4% to 20.3%, 32.6% or even 48.4% in 2050 depending on the scenario combination – unless substantial political changes occur rapidly and steadily shift the current socio-economic development pathway towards sustainability (Rohat et al. 2019). However, the impact of heat on mortality will be influenced more by socio-economic factors that enhance vulnerability than by exposure to high temperatures. Effects of heat-related mortality in Europe will vary considerably, with the Mediterranean region being the most affected (Mayrhuber et al. 2018).

Heat wave changes under the RCP4.5 and RCP8.5 scenarios will mainly affect the countries of Mediterranean Europe and eastern Europe (Kendrovski et al. 2017). More specifically, for the middle of the 21st century, 2035-2064, annual attributable mortality will increase by a factor 1.8 and 2.6 for RCP4.5 and RCP8.5, respectively, compared to the period 1971-2000. Heat wave attributable mortality at the end of the century will increase by around 3 and 7 times under RCP4.5 and RCP8.5 (Kendrovski et al. 2017). *Fig. 5.2* presents the mean warm season attributable fraction (the fraction of deaths attributable to mean apparent temperature above the threshold) based on the SMHI RCA4/HadGEM2 ES r1 (MOHC) climate model.

By the end of the 21st century (2090–2099), southern European countries are expected to experience a temperature increase of 1.9°C (1.3-2.2°C) and 4.5°C (3.0-5.1°C) respectively for RCP4.5 and RCP8.5, compared to the mean of 2010–2019 in a GCM-ensemble assuming no population changes (Gasparrini et al. 2017) *(Section 2.2)*. The greatest changes in heat-related excess mortality are projected for southern Europe, with a 10.5% increase (IC95%: 5.6-17.3). For mortality related to heat waves, although the largest temperature increases are expected in southern Europe (for the period 2031–2080, changes in the 95th percentile: Italy 1.7°C and 3.2°C and Spain 1.4°C and 3.0°C, under RCP4.5 and RCP8.5, respectively), the area will not experience the greatest excess mortality linked to heat waves, as a result of population adaptation and prevention plans (Guo et al. 2018).

5.2.5.3 Cold-related impacts

As global warming progresses, a decreasing trend in cold extremes is expected. However, highly variable future climates may retain cold wave hazards as a locally important threat. Cold-related mortality is also expected to increase with expected demographic changes in European cities (Smid et al. 2019), but the effect of cold waves on aging populations is not as pronounced as the heat, since its relationship with respiratory diseases affects younger age groups. At European level, cold-related mortality is projected to decrease by the 2080s as much as heat-related mortality is expected to increase for the same period (EEA 2017). Better social, economic and housing conditions in many European countries may encourage the estimated decreasing risk, despite the expected higher variability.

5.2.5.4 Vector- food- and water-borne diseases

The rise in temperature may lead to a geographic expansion of Euro-Mediterranean areas that are currently climatically suitable for WNV, and also to an extension of the transmission season, with the extent and pattern of changes varying depending on the location and degree of warming (Semenza et al. 2016). The transmission risk for WNV in Euro-Mediterranean areas varies spatially as well as temporally (Conte et al. 2015). Early summer months will provide suitable climatic conditions in Tunisia, Libya and Egypt, while in the European continent suitable conditions prevail only from July. From August to October, significantly increased transmission risk will characterize Italy, France, Spain, the Balkan countries, Morocco, northern Tunisia, and all along the Mediterranean coast of Africa and the Middle East. In November, with the exception of limited European coastal areas of the Mediterranean, the risk will be very low, while in North African and Middle Eastern coastal areas the same is valid from December. Projections for Europe indicate a continuous extension of regions with an increased risk of WNV infections, mainly on the fringes of the regions of transmission (Conte et al. 2015). Predictions for 2025 show an elevated risk in northeastern Greece, eastern Croatia and northwestern Turkey, while in 2050 high-risk areas expand further (Semenza et al. 2016; Semenza and Suk 2018).

Southernmost parts of Europe do not generally provide climatically suitable areas for Chikungunya transmission in the 21st century, except for restricted areas in France and North Italy at the end of the century (Fischer et al. 2013). A significant reduction of habitat suitability for Aedes albopictus is projected for the middle of the 21st century in southern Europe and the Mediterranean, related to significant increase of summer temperatures (Caminade et al. 2012; Proestos et al. 2015). Similar results are found for the end of the century (Tjaden et al. 2017) *(Section 2.2.4.2)*.

Since populations are exposed to variability in weather patterns and increasingly warm temperatures, there is high confidence for increased risks of food- and water-borne diseases, such as diarrheal diseases and *Salmonella* spp. (Smith et al. 2014). With rising average temperatures and an increase in the frequency and length of heat waves, a rising number of cases of food-borne illness are expected in a business-as-usual scenario unless education, epidemiological surveillance and enforcement (related to food safety) are intensified. This will be compounded in the event of power outage due to peak energy demand (e.g., during heat waves) that may lead to malfunction of food preservation practices (refrigeration) (The Malta Resources Authority 2017).

5.2.5.5 Air quality

Climate change alters the dispersion of primary pollutants, particularly particulate matter, and intensifies the formation of secondary pollutants. According to global estimates, the number of days with ozone concentrations exceeding the thresholds for protection of human health are expected to increase. In polluted areas with high levels of nitrogen oxides (NO_x), high surface temperature and humidity *(Section 2.2.4.2)* may generate an increase of surface O_3 concentrations, especially in southern Europe (Doherty et al. 2017). By the middle of the 21st century in southern Europe, climate change is expected to lead to an increased summer mean O_3 (0–3 ppb) and increased summer daily maximum O_3 (3–6 ppb) (Langner et al. 2012; Doherty et al. 2013, 2017; Colette et al. 2015). For RCP8.5, the Mediterranean Basin may experience an annual average difference in stratospheric origin ozone concentration at sea level of above 5 ppb by the end of the 21st century (Meul et al. 2018).

Regional projections indicate an increase of 10 to 14% in ozone-related morbidity and mortality from 2021 to 2050 in several countries, including France, Spain and Portugal. For 2050 a 8 to 11% increase in non-accidental mortality is expected, and for 2080 a 15 to 16% increase, compared to the year 2000 (O_3 and PM2.5 combined) in Europe (Orru et al. 2017). Changes in PMs under climate change still require further study, and important uncertainties remain with regard to the impact of temperature change on PM components, together with still uncertain precipitation patterns (Doherty et al. 2017). The relationships between climate change, air pollution and air pollution-related health impacts depend highly on the climate change scenario used, and on projections of future air pollution emissions, with relatively high uncertainty. Further studies focusing on effects on morbidity are needed (Orru et al. 2017).

5.2.6 Resilience, preparedness and adaptation

5.2.6.1 Health preparedness and adaptation measures

Health preparedness and adaptation to climate change includes adaptation of health systems to access morbidity due to extreme events, and adaptation of the built environment in order to reduce the burden of extreme climate. The quality of health systems and accessibility to healthcare is different across countries in the Mediterranean, largely along the North/South division. Health systems in the Mediterranean face climate change in the context of an increasingly elderly population, which is particularly vulnerable to heat waves, an increase in vector-borne diseases, and an increase in climate migration to Mediterranean countries. For health systems in the southern Mediterranean, another challenge is the declining resources for this sector (Sanderson et al. 2018). While investment in climate-related adaptation health systems appears to be cost-effective (Jeuken et al. 2016), health adaptation in the region is lacking, with only one out of 22 countries in the eastern Mediterranean having a Heat-Health Action Plan (UNEP 2018). Increasing preparedness of health systems in the Mediterranean Basin may be supported by the following measures:

- Implementation of heat early warning systems,
- Preparedness of emergency medicine professionals for treating morbidity related to extreme climate events, such as heat waves, cold spells and floods,
- Monitoring climate-related morbidity and mortality and designing interventions,
- Monitoring and surveillance of vector-borne diseases, including across borders with neighboring countries,
- Prevention of water-borne and food-borne diseases,
- Provision of access to healthcare, including mental health, to climate migrants,
- Training health professionals, including physicians, nurses and administrative staff regarding the health impacts of climate change, preparedness and adaptation in the health system,
- Increase public awareness of climate change-related health risks, and recommended prevention and mitigation of negative health outcomes, including behavior during heat waves, elimination of habitats for vectors, etc.,
- Expand urban green infrastructure including protecting inside areas and settlements.

5.2.6.2 Regional coordination and collaboration

The Mediterranean Basin, particularly its eastern and southern regions, is an area troubled by internal and cross-border conflicts, limited cross-border collaborations and limited links to the international frameworks for the whole Mediterranean. There are EU-funded regional frameworks such as Climate ADAPT Mediterranean area, that covers the southern part of Portugal, Mediterranean areas of Spain and France, almost all of Italy and the whole extension of Slovenia, Croatia, Greece, Malta and Cyprus, Albania, Bosnia-Herzegovina and Montenegro (https://climate-adapt.eea.europa.eu/). ClimaSouth covers Algeria, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Palestine and Tunisia (http://www.climasouth.eu/en). While both frameworks emphasize on increasing resilience, human health is not at the center of these programs. Other frameworks focus on infectious diseases, e.g., the Middle East Consortium on Infectious Disease Surveillance (MECIDS) that coordinates between Israel, Jordan and the Palestinian Authority (http://www.mecidsnetwork.org/). Climate change is expected to affect the Mediterranean, with heat and drought impacts on morbidity and migration, and vector-borne diseases spreading across borders. It is a challenge for countries that lack diplomatic relations to collaborate, but health agencies prove that it is possible (e.g., in the case of MECIDS), and regional collaboration at the Mediterranean level should be a priority for health agencies in the region.

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5

SOCIETY
3-HUMAN SECURITY

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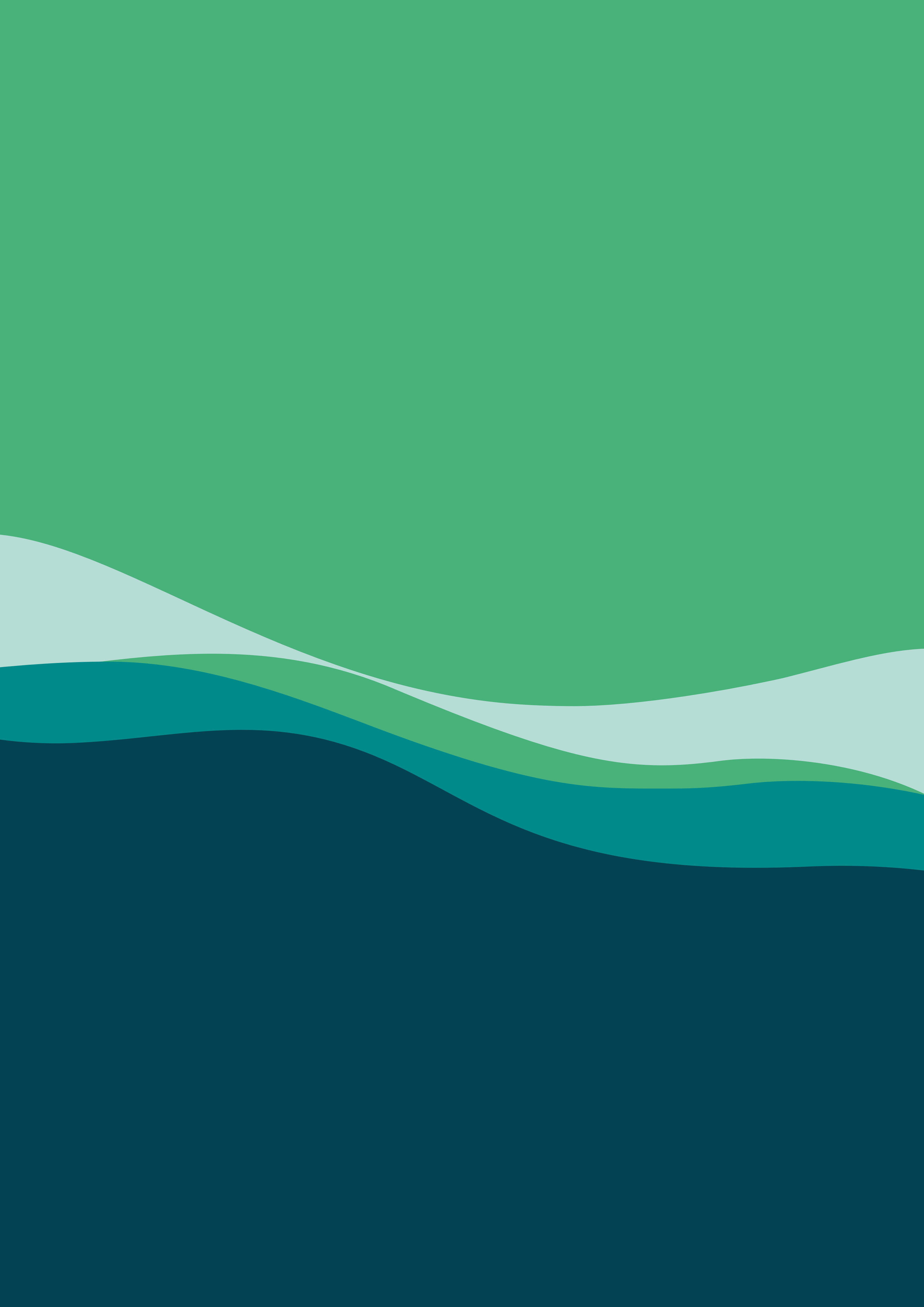
Koubi V, Behnassi M, Elia A, Grillakis M, Turhan E 2020 Human security. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 515-538, doi:10.5281/zenodo.7216161.*



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5.3 Human security

Executive summary

Climate change is a risk to human security *(medium confidence)*. Climate change threatens human security by a) undermining livelihood, culture, and human rights *(Sections 5.3.2.1; 5.3.2.2)*; b) increasing migration *(Section 5.3.2.3)*; and c) indirectly influencing violent conflict *(Section 5.3.2.4)*.

The impact of climate change on human security depends not only on climate events but also on country's contextual factors, such as geographical, social, cultural, economic, and political conditions, resulting in a substantial heterogeneous effect among Mediterranean countries *(Section 5.3.1.1)*.

Climate and environmental changes interfere with the realization and enjoyment of fundamental, internationally recognized human rights such as life, self-determination, health, and education *(Section 5.3.3.2)*.

Climate change and extreme events influence migration behavior and patterns *(medium confidence)*. The majority of migration associated with climate change impacts is internal (mostly within southern and eastern countries of the Mediterranean Basin), but also international migration (primarily between the South and North). While fast-onset environmental and climatic events such as floods and storms lead to more sudden, involuntary, and short-term and short-distance movements, slow-onset events such as drought, desertification and salinity by allowing for adaptation, usually tend to result in immobility or in migration that is generally perceived as being voluntary and often predominantly economically motivated. Migrants themselves may be vulnerable to climate change impacts in destination areas, particularly in urban centers *(Section 5.3.2.3)*.

Climate change could lead to conflict *(low confidence)*. Climatic changes have likely played a role in the decline or collapse of ancient civilizations around the Mediterranean Basin. The evidence on the effect of climate change and variability on violent conflict is contested. Although there is little agreement about a direct relationship, there is evidence that climate change increases the risk of violent conflict indirectly through declining human well-being, especially in countries which are poor and are characterized by pre-existing tensions and conflict. Higher food prices caused by climate changes have led to urban social unrest in MENA countries. The relationship between climate, migration, and conflict is highly complex as it depends on the social, political, cultural, and economic conditions of a specific country *(Section 5.3.2.4)*.

Climate change poses a severe threat to many UNESCO World Heritage sites *(high confidence)*. A large number of cultural sites are located in low-lying coastal areas of the Mediterranean, which are predicted to experience severe floods and coastal erosion in the future, indicating an urgent need for protective measures *(Section 5.3.3.1)*.

Climate change is likely to act as a threat multiplier in the MENA region *(low confidence)*. Establishing a strong link between future climate change and intrastate conflicts in MENA countries is challenging due to the lack of research for this region, which makes future research essential. Climate change is likely to affect inter-state relations concerning shared water resources, if existing water institutions are not able to accommodate change *(Section 5.3.3.2)*.

Culture is a key factor for successful adaptation policies to environmental change in the highly diverse multicultural setting of the Mediterranean Basin. Climate adaptation policies have the potential to infringe on human rights in the Mediterranean region if they are disconnected from justice, equity, poverty alleviation, social inclusion, and redistribution. To successfully implement adaptation policies, many lower-income and climate-vulnerable Mediterranean countries need sufficient financial resources and science and technology transfers *(Section 5.3.4.1)*.

5.3.1 Concepts and evidence

5.3.1.1 Definition and scope of human security in this report

This chapter assesses what is known about the risks climate change poses to individuals and communities, including risks to livelihoods, culture, human rights, migration and political stability in the Mediterranean region. For this assessment, human security is considered a condition that exists when the vital core of human lives is protected, and where people have the freedom and capacity to live with dignity (IPCC 2014, AR5 Chapter 12:759). Human security encompasses universal (e.g., health and food), and culturally-specific (e.g., religion), material (e.g., clean water), and non-material (e.g., social recognition) elements necessary for survival, sustainable livelihoods, and dignity. Human rights, politically and legally legitimized by the international community, are a specific means of defining limits, benchmarks and social processes that provide human security.

Much research on human security focuses on various short-term threats to the vital core of people's lives, including economic crises, epidemics, extreme events, and violent conflict. There are also social and environmental threats that are more incremental in nature, for example slow economic development or land degradation. In addition, a part of existing research is biased because it disregards threats to human security, which are more pertinent to other social contexts, or tries to advance generalizable findings, which are context-specific (i.e., relevant research done either in northern or southern Mediterranean States).

This chapter specifically assesses research that investigates the ways in which climate change may exacerbate threats such as water security *(Chapter 3.1)*, food security *(Chapter 3.2)*, health *(Chapter 5.2)* and others. There are underlying processes that reduce the freedom and capacity of individuals and groups to adequately respond to these threats, including poor health, poverty, and restricted access to economic, social, political, and natural resources. The chapter also assesses research on the interaction between state security and human security that suggests that the increased human insecurity that arises from an inability to adapt to climate change may in turn create risks to national security through large-scale migration and an increased risk of violent conflicts. It also assesses countries' role in protecting human security in the presence of climate change.

Human security is an analytical lens that focuses attention on the ways in which cultural, demographic, economic, and political forces interact with climate change in ways that affect individuals and communities to different degrees. The focus is at the local level, but the analysis concerns drivers of change across multiple scales and sectors, including climate, culture, economic and political institutions, and population. Consequently, understanding the effects of climate change on human security requires evidence about social and environmental processes across multiple scales and sectors. This process-based evidence is collected through a wide array of methods (e.g., ethnographic techniques and large datasets) used in a wide range of academic disciplines including environmental sciences, economics, political science, and law.

This chapter includes assessment of empirical studies from the social sciences using both qualitative and quantitative research designs. Most of these studies examine the interactions between environmental changes and social processes to explain social outcomes. While very few studies are explicitly about climate change and human security (since they mostly focus on climate variability and extreme weather events), all provide insights that could be used to make inferences about the effects of climate change on human security (Koubi 2019). Given the complexity of the processes that link environmental change to human security, uncertainties about the biophysical dimensions of change and the nature of the social science evidence thus far, high-confidence statements about the general effects of environmental change on all aspects of human security are not possible (Scheffran et al. 2012). Yet, there is strong evidence about some aspects of the links between environmental change and human security. While the impacts of environmental change on human security will be experienced the most in developing countries (including many MENA countries), human security is at risk for vulnerable populations throughout the Mediterranean region (IPCC 2014, 2018a).

5.3.2 Past trends and current situation

5.3.2.1 Livelihood, culture, human rights

Although anthropogenic climate change may be new, significant local and regional variations in climate have occurred throughout history. Prehistoric modern humans had experienced repeated periods of abrupt and severe climate change, albeit at a slower pace than presently, which was often global in nature, and they responded and adapted to this change with varying degrees of success and a variety of different outcomes (Heyd and Brooks 2009). Many studies have shown that climate change threatens cultural dimensions of lives and livelihoods including the material and psychological aspects of culture, identity, community cohesion and sense of place (e.g., Hess et al. 2008; Brace and Geoghegan 2011; Adger et al. 2012). Since culture, differing widely between countries around the Mediterranean, is embedded in the dominant modes of production, consumption, lifestyles and social organization that give rise to emissions of greenhouse gases, the impacts of these emissions are often given meaning through cultural interpretations of science and risk (Douglas and Wildavsky 1982; Shove 2003; Hulme 2008). Culture plays an important role in mediating human responses to environmental change and these responses depend heavily on the extent to which societies see themselves as separate from, or as part of the wider physical or "natural" environment (Heyd and Brooks 2009). The cultural dimensions of climate change risks and responses play a role in framing environmental change as a phenomenon of concern to society and they are not less important because they might inform adaptation planning (Adger et al. 2012). Countries require a diversity of adaptation measures very much depending on individual circumstances (UNFCCC 2007). In this perspective, Heyd and Brooks (2009) analyzed the influence of culture on conceptions of, and behavior towards natural systems and processes in a non-western context, and compare this example with the mainstream of western societies (this comparison may be relevant to the Mediterranean context, especially regarding its southern and northern shores). They conclude that culture may serve as a resource in two ways, in relation to the "management" of the non-human sphere and in relation to the development of governance processes, and that a deeper understanding of the cultural mediation of responses to environmental dynamism may be of significant value in the development of resilience to accelerating climate change.

For Richardson et al. (2009), no environmental policy will receive the support it needs, either formally in the political arena or at the pragmatic day-to-day level, unless cultures, values and world perspectives are considered from the outset – this also applies to the Mediterranean context. There are two reasons for this. First, individuals/societies do not perceive sophisticated science-based information and risk assessments in the same way, as those who produce them. Secondly, in order to be effective, policies need to consider the socio-culturally shaped setting that pre-dates the attempt to implement the policies. The following points underscore the significance of this main finding: information about climate change and local interpretations of risk assessments are culturally mediated through particular emotional ways of reasoning, typical meaning-making processes, specific conceptions of landscape and climate variability and change, and idiosyncratic notions of mitigation of risk. Local religious and spiritual beliefs, knowledge systems, understanding of nature-society relationships, and values and ethics influence how individuals and communities perceive and respond to climate change; and the implementation of adaptation strategies can raise issues that cut across power relations in existing situations of inequality, which may have unforeseen long- term effects for individuals and communities. Therefore, research on the role of culture, values, and worldviews in both the generation of and responses to climate change should become a top priority (Richardson et al. 2009).

Most regions in the Mediterranean Basin (and the rest the world) have undergone environmental change since their first occupation by humans, and understanding how people who settled in these places chose to cope and/or adapt (or failed to adapt) may play a vital role in sustainable planning of our modern societies (Latorre et al. 2016). By affecting the availability of food and water to people, environmental and climate drivers are key factors for understanding this process. It is, however, an oversimplification to state that these drivers are directly responsible for livelihood and cultural changes. Although there are many examples in the literature of large civilizations that suffered some degree of collapse, to attribute these social changes solely on shifting climatic conditions disregards other complex processes associated with how human societies make decisions regarding resource constraints. Lattore et al. (2016) assert that the effects of climate change on past societies cannot be understated and there are often multiple feedbacks. Case by case comparative studies can bring out commonalities across livelihoods and cultures, varying geographies and global climate shifts.

5.3.2.2 Human rights

Climate change affects the rights of individuals and communities. The IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels (IPCC 2018a) recently assessed that climate change constitutes a massive threat to the enjoyment of economic, social and cultural rights. Following the release of this report, the Committee on Economic, Social and Cultural Rights adopted a statement on "Climate change and the International Covenant on Economic, Social and Cultural Rights" in which it welcomed the voluntary national commitments made under the climate change regime, and also emphasized that States have human rights obligations that should guide them in the design and implementation of measures to address climate change (CESCR 2018).

The current scientific and policy debate on links between environment and human rights increas-

CLIMATE CHANGE	IMPACT ON PEOPLE	RIGHTS IMPLICATED
SEA LEVEL RISE • Flooding • Sea surges • Erosion • Salinization of land and water	• Loss of land • Drowning, injury • Lack of clean water, disease • Damage to coastal infrastructure, homes, and property • Loss of agricultural lands • Threat to tourism, beach loss • Quality of agricultural food products • Fishing and marine life that may affect the quality and quantities of sea foods	• Self-determination (ICCPR; ICESCR, 1) • Life (ICCPR, 6) • Health (ICESCR, 12) • Water (CEDAW, 14; ICRC, 24) • Means of subsistence (ICESCR, 1) • Adequate standard of living (ICESCR, 12) • Adequate housing (ICESCR, 12) • Culture (ICCPR, 27) • Property (UDHR, 17)
TEMPERATURE INCREASE • Change in the pattern of diseases • Coral bleaching • Impacts on fisheries	• Spread of disease • Changes in traditional fishing livelihoods and commercial fishing • Threat to tourism, lost coral and fish diversity	• Life (ICCPR, 6) • Health (ICESCR, 12) • Means of subsistence (ICESCR, 1) • Adequate standard of living (ICESCR, 12)
EXTREME WEATHER EVENTS • High intensity • Storms • Sea surges	• Displacement of populations • Contamination of water supply • Damage to infrastructure: delays in medical treatment, food crisis • Psychological distress • Increased transmission of disease • Damage to agricultural lands • Disruption in educational services • Damage to tourism sector • Massive property damage	• Life (ICCPR, 6) • Health (ICESCR, 12) • Water (CEDAW, 14; ICRC, 24) • Means of subsistence (ICESCR, 1) • Adequate standard of living (ICESCR, 12) • Adequate and secure housing (ICESCR, 12) • Education (ICESCR, 14) • Property (UDHR, 17)
PRECIPITATION CHANGES • Change in disease vectors • Erosion • Change in water safety	• Outbreak of disease • Depletion of agricultural soils	• Life (ICCPR, 6) • Health (ICESCR, 12) • Means of subsistence (ICESCR, 1)

Table 5.4 | Climate change impacts on selected human rights (source: submission by the Maldives to the Office of the High Commissioner for Human Rights (OHCHR) in September 2008, as part of OHCHR's consultative study on the relationship between climate change and human rights, reproduced in CIEL (2013)).

ingly perceives climate change as a "risk multiplier" and a key cross-cutting issue. Climate and environmental change thereby are seen as one of the greatest challenges to the promotion of and effective implementation of fundamental rights since its human implications are already serious and alarming. Climate change is thus rapidly becoming an issue of justice and inequality for millions of people around the world and for future generations, which will suffer severe loss and damage as well. The international community's past failure – and insufficient current actions – to mitigate and adapt to climate change according to available scientific evidence further threaten human rights (CIEL and CARE 2015). More specifically, the rights of vulnerable peoples, who are already experiencing the adverse effects of climate change, are more threatened than ever (CIEL 2013).

Recent studies and assessments have demonstrated that climate change is putting development and human security at risk (IPCC 2007, 2013, 2014) and the United Nations Human Rights Council has acknowledged in many statements (i.e., UNHRC 2008) that the environmental changes brought about by global warming can interfere with the realization and enjoyment of fundamental, internationally recognized human rights – including those protected by the International Covenants on Civil and Political Rights (ICCPR) and Economic, Social, and Cultural Rights (ICESCR).

Many Human Rights Judicial bodies, both at the universal and regional level, have underlined the link between environment and human rights effectiveness, and State-related obligations in different cases brought before them. For example, the European Court of Human Rights (the ECtHR) has developed its jurisprudence related to human rights and environment in recent years. The ECtHR emphasized on several occasions the impact of a "severe degradation of environment" on the breach of the right to life. Environmental degradation is thus increasingly recognized to threaten the human rights of individuals and minority groups. Therefore, states have the duty to respect, promote, protect, and fulfill human rights, and to secure a healthy environment by adopting positive actions to prevent environmental degradation, in order to guarantee a sustainable environment.

The "right to the highest attainable standard of health" is considered indispensable for the enjoyment of other human rights, and it is widely protected in international and regional instruments, and under national constitutions as well (Elia 2016). Climate change is a serious challenge that undermines and places the fundamental determinants of good health (such as clean air, fresh water, food security, and freedom from disease) at risk (health, *Chapter 5.2*). In the Mediterranean Basin, health impacts on populations vary significantly in terms of the risks individual countries are exposed to, available health services and socio-economic status. The most severe problems are likely to be faced by those countries that already have the biggest problems today – notably those in North Africa and the near East. Climate change could further increase the divide between northern and southern Mediterranean countries. Addressing environmental change is, therefore, perceived as a huge health opportunity that includes reducing the over 6.5 million annual deaths (WHO 2016) from air pollution (most victims are poor, elderly, women and children including rural households and people living in burgeoning low-income cities) (*Sections 2.3* and *5.2.4.1*).

Direct climate impacts, such as extreme weather events (e.g., floods) and rising sea levels, threaten millions of people in coastal and low-lying areas of the Mediterranean Basin and elsewhere. Seawater intrusion contaminates groundwater in coastal communities, negatively affecting agricultural production and potable water availability. Ocean acidification and changes in weather patterns alter ecosystems and their capacity to provide services to human communities. Increasing weather extremes constrain food security and access to nutritious forms of food while changing the prices of commodities in global markets, making food more expensive and harder to access for the poorest people *(Table 5.4)*. The links between environmental change and human rights are being increasingly documented *(Table 5.4)*, and therefore becoming less controversial and seem beyond dispute (Behnassi et al. 2019).

5.3.2.3 Environmental change and migration

Migration has been a defining feature of human populations in the Mediterranean for millennia, well before the emergence of nation states. Environmental changes, both in their rapid and slow-onset versions, have likely been influential to some extent in these migration flows. The question of a direct link between migration and environmental factors has therefore been debated intensely (de Haas 2011; Boas et al. 2019). Nevertheless, the empirical evidence from a large body of recent research, which employs macro-level and micro-level data as well as a diverse range of approaches, shows that, one the one hand, sudden-onset climatic events such as floods and storms lead to more sudden, involuntary, and short-term and short-distance movements (McLeman and Gemenne 2018). Empirical knowledge regarding the effects of slow-onset events such as droughts, on the other hand, remains varied (Adger et al. 2015; Hunter et al. 2015; IPCC 2018a). That is, there is no conclusive evidence on the direction and magnitude of the influence of gradual events on migration and their effects are multidimensional and heterogeneous. Still, it seems that slow-onset events usually tend to result either in migration that is generally perceived as voluntary and often predominantly economically-motivated or in immobility (Hunter et al. 2015; Koubi et al. 2016; Cattaneo et al. 2019).

On a century time-scale, the reduced dependence of Mediterranean people on subsistence agriculture during the 20th century has likely reduced possible direct causalities between environmental change and migration. This shift has been uneven both geographically along North-South and East-West axes of the Mediterranean and has been experienced at different times. Thus in a region whose migration patterns are marked with high uncertainty, environmental factors may "play a certain but rather indirect role" together with demographic, economic and political factors (de Haas 2011). While the effects of environmental and climate change are only "beginning to shape a new and more urgent need for the human security paradigm" (Behnassi and McGlade 2017), evidence about the relationship between climate change and migration in the Mediterranean is often disputed. The region is often referred to as being among the regions whose human security is most threatened by climate change (Brauch 2012).

The bulk of migration in Northern Africa (White 2011) and the eastern Mediterranean (Weinthal et al. 2015) happens locally and regionally. The effect of climatic factors on migration is, however, contentious. For instance, while some authors argue that the 2006 to 2010 drought in northeastern Syria led a large number of individuals to migrate (Kelley et al. 2015; Ash and Obradovich 2020), others take issue with both the number of migrants and the extent to which climate factors affected migration (Selby et al. 2017). Thus, "whether the drought was a relevant cause of rural livelihood loss and whether this livelihood loss facilitated a significant migration to urban areas remains contested, although the majority of studies support these claims" (Ide 2018a). Other studies on the case of Sahelian migration to Italy between 1995 and 2009, offer explanations for variance by climate factors and yields in migration data, where average annual temperatures are suggested to be the dominant factor in explaining migrations (Pasini and Amendola 2019). A recent global study suggests that climate change will not likely impact asylum seeking patterns everywhere, but probably only in countries undergoing political transformation when faced with immediate impacts of climate change due to inefficient policy response to the latter (Abel et al. 2019). Some authors also suggest that migration in the Mediterranean may be towards higher environmental risk rather than away from it due to pressing challenges of rapid urbanization, depopulation of rural areas, and the decline of traditional livelihoods (Geddes 2015). The challenge, therefore, is to better prepare and adapt infrastructure to sustain and protect migrants in their destinations.

A part of this framing can likely be credited to the work of NGOs and think tanks (Felli 2013). The eastern and southern shores of the Mediterranean Basin (MENA) in particular are frequently "cast as hotspots of mixing social, political and ecological problems, populated by racialized, helpless and passive victims, exposed to erratic and dangerous climate change" (Methmann and Rothe 2014). Rothe (2017) details how the Mediterranean came to be seen as the hotspot of climate migration with "interventions coming mainly from either international organizations or scientists and think tanks in northern industrialized countries."

5.3.2.4 Conflict and collapse of civilizations

There is a recent increase in research examining the effects of climate change and violent conflict, reflecting policy discourses that climate change impacts and resource scarcity could lead to conflict. While changes in climate could bring groups of people into conflict over scarce resources (Homer-Dixon 1999), there is also evidence that in specific circumstances resource scarcity may drive adaptation and innovation (Butzer 2012). While, on a decadal time-scale, violent conflict appears to have become less common and less intense after the end of the Cold War, since 2013, there have been upsurges in both the number of armed conflicts in the Mediterranean region, and also in the number of battle deaths - mainly as a result of the civil wars in Syria and Iraq (Dupuy et al. 2017). During the same period, there has been an increase in the occurrence and severity of drought events *(Chapter 2),* which by affecting agricultural production and crop yields *(Chapter 3)* (Durigon and de Jong van Lier 2013; Siebert et al. 2014; Schauberger et al. 2017), raise the question whether these factors could contribute to social unrest and conflict (discussed in *Box 5.3.1*).

A few studies explore the relationship between longer-term climate variations and the collapse of past civilizations and empires around the Mediterranean Basin using statistical analysis and data derived from archeological and other historical records (Holmgren et al. 2016; Kaniewski et al. 2018). Major changes in weather patterns, in particular drought conditions, have coincided with the collapse of several previously powerful civilizations in the Aegean and Eastern Mediterranean (Kaniewski et al. 2015), as well as of empires such as the Akkadian (Weiss et al. 1993; Carolin et al. 2019), and the Ottoman empires (Kaniewski et al. 2012). Regarding the Akkadian Empire, which ruled Mesopotamia from the headwaters of the Tigris-Euphrates Rivers to the Persian Gulf (all in what is now Iraq, Syria and parts of southern Turkey) during the late third millennium BC, archeological evidence has shown that this highly developed civilization collapsed abruptly around 4,200 years ago, possibly due to a shift to more arid conditions (Weiss et al. 1993). A recent study using speleothem geochemical records from northern Iran identified two major drought periods, which started 4,510 and 4,260 years ago, and lasted 110 and 290 years respectively. The latter event occurred precisely at the time of the Akkadian Empire's collapse (Carolin et al. 2019). Similarly, a study coupling climate proxies with archaeological-historical data and a pollen-based record of agriculture shows that an abrupt shift to drier conditions at ca. AD 1,400 could have contributed to the Ottoman Empire's decline (Kaniewski et al. 2018).

Several studies also provide evidence for a climate-conflict relationship via reduced agricultural production across many centuries. The Little Ice Age appears to have been associated with more cases of political upheaval and warfare in the Ottoman (White 2011; Haldon et al. 2014) and Byzantine (Xoplaki et al. 2016) empires. In particular, the Gelali rebellions between the years 1,550 and 1,603 were reactions to social and economic crisis stemming in part from climatic hardship associated with the Little Ice Age. This evidence from historic antecedents, however, cannot be taken to mean that future changes in climate would lead to large-scale political collapse mainly due to globalization in the contemporary world (Butzer 2012).

Most of the recent research on the connections between climate change and conflict focuses on the effects of climate variability, mainly temperature, precipitation, and, to a lesser extent, natural disasters as proxies for the kinds of longer-term changes that might occur due to climate change on interstate conflict, e.g., civil conflict/war, communal violence as well as low intensity conflict such as demonstrations, protests, and riots. There is very limited research on the climate-conflict nexus in the Mediterranean region. Studies using global datasets have failed to uncover a robust direct relationship between climate variability or natural disasters and civil conflict. On the one hand, some studies report a positive effect of temperature on conflict onset or incidence at the global level (e.g., Landis 2014; Bollfrass and Shaver 2015). In particular, in countries with climates that have strong seasonality such as in most countries in the Mediterranean basin, civil conflict is more likely to occur when warm weather is prolonged (Landis 2014). Deviations in temperature, whether they are positive or negative, as well as changes in mean precipitation show no statistical association with the onset of civil war. On the other hand, others find that precipitation, in particular more rainfall, rather than temperature anomalies are associated with increases in organized political violence—especially in less developed countries (Salehyan and Hendrix 2014). Yet, other studies do not find any effect.

For the Mediterranean region, Böhmelt et al. (2014) report that climate variability measured as a deviation of the current level of precipitation and temperature, respectively, from their past long-run levels, did not affect the onset of armed conflict during the 1997-2009 period. In addition, the authors show that population pressure, agricultural productivity, and economic development are likely to have a stronger impact on water conflict risk than climate variability (Bernauer et al. 2012; Theisen et al. 2013; Buhaug et al. 2014). They conclude that violent water conflicts are extremely rare, and that factors conducive to restraint, such as stable political conditions, may stimulate cooperation. Higher temperature, though, seems to increase the likelihood of low-level conflicts such as political instability in the form of irregular leader transitions (i.e., coups) (Dell et al. 2012) and incumbents' electoral losses potentially speeding democratic turnover (Obradovich 2017).

A growing body of research examines the connections between natural disasters, i.e., storms, floods or droughts and conflict. By damaging public and private infrastructure, destroying crops and killing livestock, these events can cause or worsen scarcity, subsequently leading to conflict. The direct association between natural disasters and armed conflict is contested (Nel and Righarts 2008; Bergholt and Lujala 2012). However, there is some evidence that natural disasters increase the outbreak of armed conflict in highly ethnically fractionalized countries (Schleussner et al. 2016), lengthen civil conflict and communal conflict (Eastin 2015; Detges 2016; Ghimire and Ferreira 2016) and increase state-sponsored repression (Wood and Wright 2016) and the likelihood of transnational terrorism (Paul and Bagchi 2018). Feitelson and Tubi (2017) examine the effect of the extreme 2007–2010 drought on armed conflict in the Euphrates and lower Jordan River basins and find that, with the exception of Syria, and the consequent spillover into Iraq, droughts do not constitute a main driver of armed conflict in the Middle East. They conclude that droughts may lead to conflict when more fundamental factors, especially adaptive capacity, have been compromised. There is also some evidence that widespread disasters generate solidarity and cooperation rather than conflict (Theisen 2012; Nardulli et al. 2015; Tubi and Feitelson 2016).

A limited body of research examines the connections between climate change and small-scale violent conflicts, i.e., non-state conflict or communal violence. There is some agreement that both decreased rainfall (resource scarcity) and increased rainfall (strategic advantage) in resource dependent societies increase the risk of localized violence, particularly in pastoral societies in Africa (Fjelde and von Uexkull 2012; Theisen 2012; Detges 2014; Ember et al. 2014; Maystadt et al. 2015; Nordkvelle et al. 2017). Tubi and Feitelson (2016) examine the conflictive and cooperative interactions between Muslim Bedouin herders and Jewish agricultural settlements in Israel's semi-arid northern Negev region during the 1957–1963 drought. They find that while the interactions between these two groups ranged from violent clashes to extensive cooperation and assistance, conflict was limited and that the measures taken by state institutions to directly reduce frictions and to provide relief assistance were central to the overall limited level of conflict.

In response to the challenges of finding a direct association between climate changes and violent conflict, most recent research examines the effects of climate changes on conflict via their effects on well-known drivers of conflict, in particular economic conditions and migration. Starting with the economic conditions channel, research has not established a robust link between climate variables, economic growth, and conflict (Miguel et al. 2004; Ciccone 2011; Bergholt and Lujala 2012; Koubi et al. 2012; Hodler and Raschky 2014; van Weezel 2015). However, recent studies provide consistent evidence that climate changes, via their negative effect on agricultural production, livestock prices, and incomes, affect various types and dynamics of conflict (Bazzi and Blattman 2014; Maystadt and Ecker 2014; Fjelde 2015). Moreover, negative weather shocks occurring during the growing season of local crops increase the continuation and intensity rather than the outbreak of civil conflict (Jun 2017; Harari and Ferrara 2018), especially in regions with agriculturally dependent and politically excluded groups (von Uexkull 2014; Schleussner et al. 2016; von Uexkull et al. 2016). As an example of such shocks, dry spells during the wet season have been found to have serious economic consequences in rain-fed agriculture, which represents a significant fraction in many Mediterranean countries (>90% of cultivated regions in Algeria, Morocco and Tunisia, 57% in Turkey, 64% in Italy or 56% in Portugal (Tramblay and Hertig 2018). As an example, Morocco's 2007 drought reduced wheat production by 76% (Schilling et al. 2012), which has been shown to play a vital socio-economic role in Mediterranean countries (Páscoa et al. 2017).

Several recent studies identify a causal link between higher food prices caused by climate changes and urban social unrest in Africa (Berazneva and Lee 2013; Smith 2014; Bellemare 2015; Raleigh et al. 2015), while Buhaug et al. (2015) disagree. Rising food prices are considered to have played a significant role in fomenting the Arab Spring unrest across North Africa and the Middle East in 2011 (Johnstone and Mazo 2011; Sternberg 2012; Newman 2020). However, Sneyd et al. (2013) show that such forms of violence are triggered by a complex set of political and economic factors rather than by higher food prices.

By reducing the supply of water in transboundary river basins, climate events can increase the likelihood of interstate conflict. Despite the menace of "water wars" prominently discussed since the early 1990's, shared water, although it does lead to tensions, threats, and even to some localized violence, it does not lead to war (Wolf 2007). Joint precipitation scarcity reduces the likelihood of interstate militarized disputes (Devlin and Hendrix 2014), and water scarcity enhances the incentives of riparian states to cooperate rather than to fight (Dinar et al. 2011). In addition, research shows that riparian states' liberal institutional and economic structures (Kalbhenn 2011; Feitelson and Tubi 2017), commercial treaties (Dinar et al. 2015), the behavior of upper riparian (Feitelson and Tubi 2017) and upstream-downstream relations (Munia et al. 2016), the existence of transboundary treaties (Tir and Stinnett 2012), the number of agreements between riparian states (Dinar et al. 2019), the specific design of international water agreements (Dinar et al. 2015) and institutional frameworks for flexible but specific water allocation mechanisms (Dinar et al. 2015; Oktav 2017) further mitigate the risk of conflict. While hydrological disputes in the Jordan, Nile, and Tigris-Euphrates river basins are mostly seen as a part of territorial security and development-oriented concerns rather than a genuine water issue on its own, climate change is likely to further affect inter-state relations and even threaten the stability of existing water institutions, if these institutions are not able to accommodate change (Dinar et al. 2015; de Stefano et al. 2017).

Regarding the channel of migration, the literature argues that environmental migration can cause conflict in the receiving areas by increasing competition for resources and jobs between immigrants and the native population, upsetting ethnic balance when immigrants are of a different ethnicity than the native population; and by exacerbating fault lines, such as between highly employed and unemployed segments of society, rural and urban areas, etc. (Goldstone 2002; Reuveny 2007). Recent research shows that although residents in receiving areas, in particular urban centers in developing countries, view climate events (e.g., floods and storms) and conditions (e.g., drought and water/soil salinity) as legitimate reasons to migrate, yet environmental migrants are not seen as more deserving than economic migrants (Spilker et al. 2020).

However, despite the surge in the number of studies on the potential link between environmental change, migration, and conflict, this literature is still far from reaching a consensus on this relationship. For example, while some scholars provide evidence that mass population movements induced by climate shocks were an important factor leading to Syria's uprising and subsequent civil war (Kelley et al. 2015; Ash and Obradovich 2020), others conclude that the occurring drought had little if any impact on the outbreak of conflict (Fröhlich 2016; Selby et al. 2017) (see *Box 5.3.1*). Moreover, limited and often ambiguous empirical evidence based on large-N studies further adds to the difficulty to derive conclusive statements (e.g., Brzoska and Fröhlich 2016). Reuveny (2007), for instance, shows that migration caused by extreme events can induce more conflict in receiving communities, while Raleigh et al. (2008) do not find a significant effect. Bhavnani and Lacina (2015) find that greater rates of internal migration due to climate shocks are associated with a higher risk of riots in Indian states. Ghimire and Ferreira (2016), however, report that disaster-induced migration lengthens the duration of an existing civil conflict, but it does not affect the risk of new conflict outbreaks. Climate changes have also been shown to increase intercommunal violence by affecting pastoralists' copying strategies for access to water and foliage (Adano et al. 2012; Detges 2014). Finally, while long-term climate events, such as droughts, seem to enhance environmental migrants' conflict perceptions in their destination location (Koubi et al. 2018), they may not add to their willingness to support violence (Linke et al. 2018). Migrants who experienced short-term climate events, such as storms or heavy rains, on the other hand, are more likely to support violence if they were themselves victims of violence (Linke et al. 2018). Moreover, migrants to urban areas who had experienced both sudden and gradual climate events, e.g., a drought and a storm, at their location of origin are more likely to join and participate in social movements about migrant rights such as joining a migrant interest group and participating in protest rallies organized by the group even if these may cause violent clashes (Koubi et al. 2021).

Beyond economic and ethno-political conditions, as well as migration flows, the state of social and political institutions is often found to shape the likelihood of collective violence. Various aspects of the strength and, more often, weaknesses of governments but also conflict-related institutions have been repeatedly demonstrated in recent research (Butler and Gates 2012; Koubi et al. 2012; Böhmelt et al. 2014; O'Loughlin et al. 2014; Linke et al. 2015, 2018; Tubi and Feitelson 2016; Wood and Wright 2016; Detges 2016; Fair et al. 2017; Jones et al. 2017; Ide 2018b).

In summary, there is some evidence that climate change may increase the risk of armed conflict in countries and/or regions, which are poor and highly dependent on agriculture, have few capabilities to cope with climate changes, and are characterized by pre-existing tensions and conflict (Ide et al. 2014; Koubi 2019). However, there is very limited knowledge regarding the mechanisms that connect climate change to conflict (Buhaug 2015; Koubi 2019). There is also very little research on the effects of climate changes on conflict in the Mediterranean region. Consequently, there is an urgent need for research and data collection that can be used to study the processes that could lead from changes in climate to conflict in the Mediterranean Basin.

5.3.3 Projections, vulnerabilities and risks

5.3.3.1 Livelihoods, culture, human rights

Countries with high carbon emission potential directly and massively contribute to global warming, which is associated with substantial harms to poor and vulnerable populations, including indigenous people, through their multiple impacts and associated risks (i.e., increasing frequent extreme-weather events, spread of tropical diseases, desertification, rising sea levels, biodiversity loss, decrease of crop yield and food security, etc.) (Jodoin and Lofts 2013; IPCC 2018a). Poor people are much more vulnerable to these impacts and risks because they tend to live in the most exposed areas, typically cannot protect themselves, and lack the means to cope once a threat has materialized (Hallegatte et al. 2016; Hallegatte and Rozenberg 2017; IPCC 2018a; Wallemacq et al. 2018). Assuming that the global distribution of income and wealth will remain as uneven as today, present excess emissions are likely to cause vastly greater harms to poor and vulnerable populations in the future, than they are causing today (Burke et al. 2018; IPCC 2018a; Pretis et al. 2018; Tol 2018). In addition, climate change impacts threaten traditional knowledge about livelihoods in ways that endanger culture and sense of place attachment (Adger et al. 2012; Tucker et al. 2015; Tschakert et al. 2019). Climate change could increase migration flows. While it is challenging to project the scale of future migration flows as complex interactions between economic, political, social, demographic, and environmental factors shape people's movements (Black et al. 2011), experts agree that millions of people, especially in Sub-Saharan Africa, South Asia, and Latin America, could be forced to move within their countries in the medium term due to climate changes (Rigaud et al. 2018). The scale and geographic scope of this type of population displacement could be one of the greatest human rights challenges of our time. Most countries do not have any governance framework to manage the internal movement of people living within their boundaries and no binding international human rights instrument exists to guide national governments to prepare and respond, creating an enormous protection gap for hundreds of millions of people (McAdam 2016).

Climate change also poses a severe threat to many cultural heritage sites (IUCN 2017). Mediterranean UNESCO World Heritage sites are highly likely to be impacted by climate change over the coming decades, notably from coastal hazards due to sea-level rise. A basin-wide study investigated risks for coastal word Heritage Sites from flooding and erosion under four sea level rise scenarios until 2100. Of 49 sites located in low-lying coastal areas of the Mediterranean, 37 are at risk from a 100-year flood and 42 from coastal erosion, already today (Reimann et al. 2018). The results indicate the urgent need to better protect those sites that are already at risk. Risks will exacerbate in the course of the twenty-first century and beyond (until 2100, flood risk may increase by 50% and erosion risk by 13% across the Mediterranean region), with their magnitude depending on global-scale mitigation efforts in the coming years. For these sites, adaptation can only be implemented to a limited degree because their specific cultural values could be compromised by adaptation measures. If no steps are taken, world heritage sites could lose their values during the coming centuries and will consequently be removed from the UNESCO World Heritage list.

5.3.3.2 Conflict

The Mediterranean Basin is characterized by projections of extreme heat, drought and aridity conditions under climate change *(Chapter 2)*. The IPCC report on 1.5°C has stated that 'climate-related risks to livelihoods including food security, water supply and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C (Summary to Policymakers: B5) (IPCC 2018b).

In this context, climate change is likely to act as a threat multiplier (CNA 2007) in the MENA region by placing additional pressure on already scarce resources and by reinforcing preexisting threats such as poverty, unemployment, and political instability as well as competition over shared water resources along river basins, ultimately leading to violence and conflict. However, establishing a link between future climate change and conflicts in MENA countries is challenging due to the lack of research and consequently scientific knowledge regarding the connections between climate change and conflict in this region. Nevertheless, considering that although the whole region is subjected to climate change but very few countries are experiencing (have experienced) conflict, a few of the main findings of the climate-conflict literature might as well apply here: climate change is very likely to lead to conflict in MENA countries that are poor and are characterized by pre-existing tensions and conflict (Ide et al. 2014; von Uexkull et al. 2016; Waha et al. 2017; Koubi 2019).

Civil conflict is "development in reverse" (Collier et al. 2003). Armed conflict kills people, destroys infrastructure that affects development outcomes, and hampers economic growth that lifts people from poverty, thus reducing the incentives to fight (Chassang 2009; Cederman et al. 2013). Gates et al. (2012) estimate the effect of conflict on income growth. According to their simulations, five consecutive conflict years with more than 1,000 battle deaths reduce per capita incomes by 20% relative to a no-conflict counterfactual, whereas eight additional years of further conflict widen the gap by 5-10%. When it comes to assessing the speed and extent of post-conflict recovery, the analyses in Gates et al. (2012) reveal that the negative impact of short wars is reversed after roughly five peaceful years, whereas long wars are associated with a permanent reduction in per capita incomes of about 10%. Similarly, Costalli et al. (2017) employ synthetic control modelling for 20 conflict countries. On average, years of ongoing conflict see 17.5% lower per capita incomes than carefully constructed counterfactual peace years. Their analysis also reveals massive heterogeneity across conflicts, with estimates ranging from a 1.8% average effect in Egypt (1993-1998) to a staggering 74% for the Liberian civil war (1989-1997 and 1999-2003). Their analysis also shows that the GDP losses due to conflict are especially high in ethnically fractionalized countries and attribute this effect to disruptions to inter-ethnic cooperation and trade.

Conflict does not only undermine the capacity of governments and non-governmental actors to provide adequate protection from the impacts of climate change, but it is also a major driver of climate vulnerability via its negative effects on economic growth, education, food security and environmental destruction. Broader socio-economic development, expressed by higher growth in education and poverty alleviation, could help in offsetting most of the conflict risk in developing countries associated with reduced economic growth due to implementation of policies to curb GHG emissions (Hegre et al. 2016). Ending violent conflict may be one of the most efficient and cost-effective ways to improve social resilience to climate change.

Regarding future interstate conflicts in the MENA region's major river basins, i.e., Nile, Jordan, Tigris and Euphrates, the limited historic evidence for 'water wars' should not lead to complacency. These river basins will face a strong increase in demand for water due to demographic pressures, industrialization, and urbanization. Simultaneously, while in many cases supply will recede due not only to earlier mismanagement, but also to the impacts of climate change through, for instance, changes in precipitation, increased evaporation, shifts in the seasonality of rain, or droughts. These changes could have security implications at the international level. Consequently, it will take coordinated efforts by all, and especially the major riparian states to adapt to climate change in order to avoid increasing conflict in the future. To the extent that each country securitizes water –i.e., transforms water into a key aspect of its national security and development whose protection justifies the use of particular means such as dams, without taking into considerations the needs of its neighbors and especially downstream states, conflict could be more likely under future climate changes (Feitelson and Tubi 2017). International water agreements and more institutionalized forms of cooperation therefore need to be flexible and robust enough to cope with the emerging threats of climate change (Dinar et al. 2015; Link et al. 2016; de Stefano et al. 2017). There is very little research on the effects of future climate changes on conflict in the Mediterranean region. Consequently, there is an urgent need for research and data collection that can be used to forecast conflict in the face of climate change in the Mediterranean Basin.

5.3.4 Adaptation

5.3.4.1 Livelihoods, culture, human rights

Climate change acts directly to change natural weather patterns, but the effects cascade quickly through many sectors with implications for livelihoods (i.e., loss of revenues and subsistence assets), culture (cultural ties to the land, biodiversity and food patterns), and human rights (i.e., rights to food, water, health, etc.). For this reason, governments have a large stake in making adaptation a national priority (Tolba and Saab 2009), and this applies to the Mediterranean as well given the severity of climate impacts in this region, which is increasingly considered as hot spot in many IPCC reports (IPCC 2007, 2014, 2018a). In addition to prevention and mitigation, adaptation is increasingly becoming the focus of formal and informal discussions on human responses to climate change both on the international level and in the Mediterranean.

The effectiveness of different ways to address adaptation to climate change is dependent on the underlying cultural fabric of the human groups involved for their successful implementation (Heyd and Brooks 2009). There are important cultural dimensions to how societies respond and adapt to climate-related risks since culture mediates changes in the environment and changes in societies. Culture is no less central to understanding and implementing adaptation; the identification of risks, decisions about responses, and means of implementation are all mediated by culture. Cultures are dynamic and reflexive and are therefore in turn shaped by the idea of climate change. Hence culture, and its analysis, is central to understanding the causes and meaning of, and human responses to climate change (Douglas and Wildavsky 1982; Shove 2003; Hess et al. 2008; Hulme 2008; Brace and Geoghegan 2011; Adger et al. 2012). This is highly relevant to the Mediterranean context, which is a rich multicultural region composed of countries in Europe, the Middle East, and North Africa, with different, sometimes heterogeneous, cultural representations (The Anna Lindh Report 2018).

Heyd and Brooks (2009) define culture as comprising the ways of living, which involve values, beliefs, practices and material artefacts that condition the production of tangible as well as intangible goods and services needed for the satisfaction of a human group's needs and wants. The culture of any group has to be conceived of as dynamic, subject to constant transformation and in regular interaction with that of other groups, especially given the interrelationships of human populations in today's increasingly globalized context. Moreover, any set of values, beliefs or practices common to a human group is mediated by power relations, and is not simply the result of adaptation to objective conditions of the natural environment. Nevertheless, particular cultural patterns are among the factors that distinguish human groups, and may play a crucial role in the ability of these groups to cope with environmental/climate changes. In line with this perspective, Rull et al. (2016) tried to explain in a case study the concurrence of conspicuous climatic, ecological and cultural changes during the last millennia and how natural and anthropogenic drivers of change, as well as their potential synergies, might have been influential in determining some cultural shifts.

Climate adaptation policies have the potential to infringe on human rights in the Mediterranean region if their conception and implementation are not adequate or disconnected from some concerns such as justice, equity, poverty alleviation, social inclusion, and redistribution (Behnassi 2019). For instance, adaptation actions, such as relocation in response to sea-level rise or other environmental factors, may affect the right to culture, particularly for indigenous peoples, local communities and other vulnerable groups. Undeniably, relocation can have a particular impact on the right to culture of indigenous peoples whose cultural and spiritual practices are tied to the land, or for local communities who might lose access to significant sites such as ancestral burial grounds (Jodoin and Lofts 2013). Adaptation policies in the Mediterranean may have human rights implications, such as those pertaining to food, water, forest, and the availability of other resources to support the adaptation needs of vulnerable populations.

Governments' legal duty under universally recognized, international human rights instruments to protect people from harm, implies the mainstreaming of human rights into adaptation policy and governance (Behnassi 2019). States must therefore ensure that appropriate adaptation measures are taken to protect and fulfill the rights of all persons, particularly those most threatened by negative climate impacts (e.g., individuals and communities living in vulnerable areas of the Mediterranean such as small islands, riparian and low-lying coastal zones, and arid regions). In the context of adaptation, the protection of cultural rights requires that states avoid or minimize policies that could affect these rights. To this end, the protection of cultural rights is increasingly considered as part of adaptation – and even mitigation – policies, and appropriate scoping and risk assessment activities should be undertaken during the process.

To implement adaptation policies, Mediterranean countries need sufficient resources. Lower-income and climate-vulnerable countries, especially on the south shore of the Mediterranean, which are characterized by limited adaptive capacity due to poverty and political instability (Price 2017), are not generally in a financial position to efficiently deal with climate change and fully protect their populations from its adverse impacts. Their limited public budgets are usually dedicated to cover other vital sectors, such as infrastructure, health, nutrition, and education. Any attempt to allocate available resources to fund adaptation policies may negatively affect these sectors. The development and application of financial safeguards can prevent social and environmental harm and maximize participation, transparency, accountability, equity, and rights protection.

Although the UNFCCC established the Green Climate Fund (GCF), from which many Mediterranean countries are already benefiting to support their adaptation policies (Patel et al. 2016), mechanisms to ensure social and environmental safeguards are yet to be applied to the fund. To do so, institutions involved in funding climate-related activities are required to provide transparent processes, maintain policies and procedures that respect internationally recognized rights, and allow meaningful opportunities for public participation.

Many lower-income and climate-vulnerable Mediterranean countries lack the scientific and technological capacities to deal appropriately and efficiently with environmental change. Thus, science and technology transfer is increasingly considered critical to supporting sustainability and avoiding the shifting of polluting industries from developed countries to the developing world (CIEL 2008), including from northern Mediterranean countries to the southern ones. Establishing an institutional mechanism for science and technology transfer could help to implement a future climate framework in the region. In terms of effective implementation of adaptation strategies, the Sustainable Development Goals (SDG) framework can help ensure that scientific inputs required by the most vulnerable peoples and communities are systematically considered a priority (Behnassi et al. 2019).

5.3.5 Knowledge gaps

The evidence reviewed in this chapter shows that climate change poses risks to various dimensions of human security in the Mediterranean region, which arise through diverse causal processes, and which will manifest at different scales. However, many knowledge gaps remain.

The effects of climate change on migration are contingent upon the vulnerability of individuals and societies to such events. In turn, vulnerability is based on physical risk, political, economic and social characteristics, and individual factors such as gender, age, education, wealth, and social capital. In addition, government strategies designed to address vulnerability and to increase resilience can provide the basis for successful adaptation to climate change. Consequently, more widespread and rigorous research is needed in the following areas:

- The conditioning effect of socio-economic and political factors at different levels. Local contextual factors might even be more important in conditioning migration as vulnerability differs significantly across climate-affected communities/areas.
- Micro-level analysis aiming at identifying the climate and non-climate-related determinants of individual migration decisions.
- The compound effects of both slow-onset climate change and sudden-onset extreme events on migration.
- Collecting better data on migration and natural disasters as well as using better modelling techniques to predict future migration flows.
- The implications of migration on vulnerability, especially in the case of rural-to-urban migration.

One of the most critical problems faced by Mediterranean populations is violent conflict, which often triggers migration and loss of life. Climate change is likely to act as a "threat multiplier" in the Mediterranean region for these processes. However, our knowledge is limited regarding how natural disasters interact with and/or are conditioned by socio-economic, political, and demographic factors that cause conflict. Future research should examine:

- When and where are climate conditions and other environmental challenges likely to lead to conflict or social unrest?
- How and why is climate change associated with conflict, and how are other environmental change drivers involved?
- How will conflict patterns evolve over time under different scenarios of future anthropogenic climate and environmental change?
- Which and how could mitigation and adaptation policies amplify the likelihood of conflict?

BOX 5.3.1

Climate change and the Syrian conflict

Climate variability is popularly reported to be a significant cause of the Syrian conflict that began in 2011. Long-term drought and vulnerability of the population to drought led to large-scale internal migration that contributed to the 2011 popular unrest, which spiraled into Syria's civil war (Gleick 2014; Kelley et al. 2015; Werrell et al. 2015).

Several studies, however, dispute these claims (de Châtel 2014; Kelley et al. 2015; Hendrix 2017; Selby et al. 2017), and argue that the conflict in Syria was not caused by drought but rather was the result of several factors, including water resource degradation, income inequality and increasing poverty, pre-existing socio-economic grievances, long-standing natural resource mismanagement by the government, and the collapse of Syria's agrarian and rentier model of state–building and development. These studies identify government practices as being far more influential drivers than drought, especially since similar drought conditions did not stimulate conflict in neighboring countries (Hendrix 2017).

Authors of the original study on the Fertile Crescent rebut these claims and insist that overlap of acute vulnerability and the long-term drying trend was compounded with "population growth, poor agricultural policies, aggressive economic liberalization and the influx of Iraqi refuges" to create the suggested link between climate change, drought, displacement and unrest (Kelley et al. 2017). However, other critics suggest that the driving mechanisms between weather-related risks, the resource base and the subsequent risks through which climate-conflict-migration interaction occurs, as well as the evidence for exacerbation of displacement due to climate factors are rather poor (Challinor et al. 2018). In his review of the available literature on the Syrian civil war, migration and climate change relations, Ide et al. (2018a) conclude that despite the multidecadal drying trend and an exceptional drought before the onset of the conflict "comprehensive evidence through attribution studies of a (probabilistic) link to climate change is still lacking", and that that there is still a lack of knowledge regarding whether the drought induced "migration, intensified existing grievances and facilitated the onset of protests and the subsequent civil war."

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6

MANAGING FUTURE RISKS AND BUILDING SOCIO-ECOLOGICAL RESILIENCE

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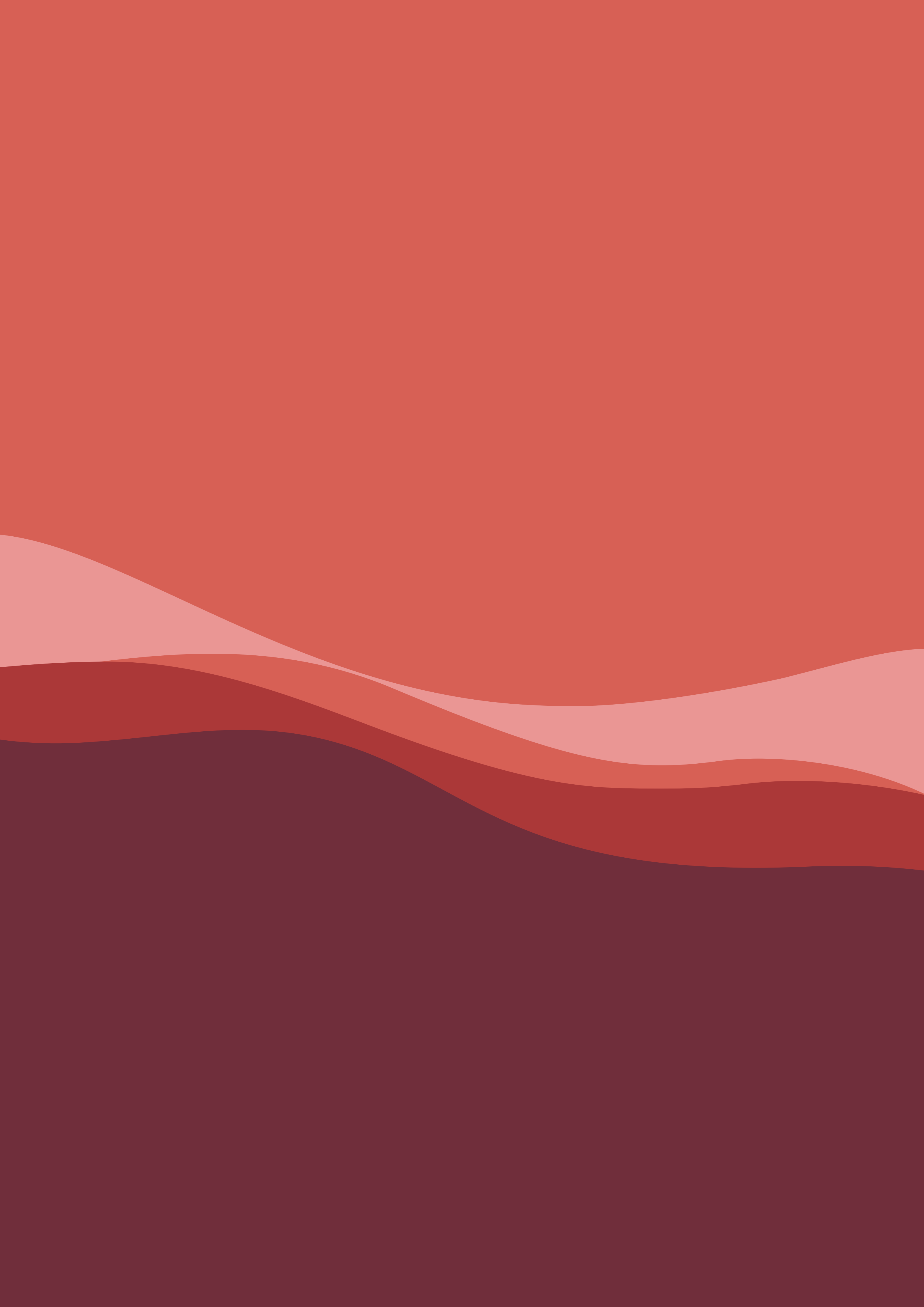
This chapter should be cited as: Vafeidis AT, Abdulla AA, Bondeau A, Brotons L, Ludwig R, Portman M, Reimann L, Vousdoukas M, Xoplaki E 2020 Managing future risks and building socio-ecological resilience in the Mediterranean. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 539-588, doi:10.5281/zenodo.7101119.*



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6 Managing future risks and building socio-ecological resilience

Executive summary

The Mediterranean Basin is experiencing major changes in environmental conditions, which can introduce new challenges to the resilience of its natural and human systems. This situation is combined with rapid and spatially diverse socio-economic development in the region, mainly in terms of demographic trends and settlement patterns, thus leading to higher exposure to environmental hazards. Furthermore, new risks are expected to emerge from interactions between drivers and impacts across sectors, thus increasing the vulnerability of natural systems and human populations.

Future risks in the Mediterranean region will be determined by hazard characteristics (intensity and frequency) and by developments in socio-economic conditions that determine a society's adaptive capacity to cope with these hazards. Current risks to human population, economies and ecosystems will increase as a result of changes in the patterns of droughts, wildfires, soil degradation, desertification, sea level rise, heat waves and river flooding, and other pressures, potentially leading to greater impacts. These impacts can be further exacerbated by the occurrence of compound and cumulative events, which can seriously challenge the adaptive capacity and resilience of biophysical and human subsystems. Coping with these risks, adapting to change and increasing the resilience of Mediterranean systems will be essential for ensuring sustainable development in the region.

Successful practices and initiatives for risk reduction and management, such as water-sensitive urban design, implementation of nature-based solutions, operational flood forecasting systems, or collaborations within cities' networks, are already being implemented across the region. However, these efforts are often slow in catching on or fail to consider the rising pressures in the light of changing environmental conditions and developmental demands. Understanding these changes and demands is essential for managing future risks. In this context, Mediterranean-wide initiatives such as establishing long-term monitoring schemes to obtain data missing in many parts of the basin; accounting for differences in monitoring and reporting between northern (EU), eastern, and southern countries of the region; advancing (climate) modeling techniques for the short-term prediction of extreme events (e.g., heat, flooding), and improvements in seasonal forecasts are essential for supporting future management and adaptation strategies and for enhancing resilience. Furthermore, public participation in the development and implementation of these strategies is necessary in order to increase local relevance and acceptance of proposed strategies, and is particularly important for building a resilient society.

The level of future risk in the Mediterranean Basin will largely depend on the timing of adaptation and on how soon and how effectively sustainable development is pursued. In particular, addressing more pressing natural and socio-economic challenges in several countries in the Middle East and North Africa is essential for avoiding the widening of the development gap between northern, southern, and eastern countries of the region. Therefore, developing joint, region-wide, and integrated management and adaptation approaches that treat multiple hazards in a holistic manner is of utmost importance for sustainable development in the entire region. Nonetheless, no one-size-fits-all strategy exists, but each measure needs to be tailored to the respective local conditions. Regional co-operations, e.g. in the form of active participation in regional-to-global initiatives and networks concerned with building socio-ecological resilience, will be an important step forward in transferring knowledge on successful practices and innovation across the Mediterranean nations.

6.1 Introduction

Scenarios of environmental and socio-economic change for this century suggest severe challenges to the resilience of natural and human systems worldwide. For climate, such challenges will be particularly posed by extreme events, such as increased temperature anomalies *(Section 2.2.4)* and potential changes in storm intensity *(Section 2.2.2.3)*, as well as by slow onset events such as sea level rise *(Section 2.2.8)*. From a management and policy perspective, this means that these changes increase the vulnerability of certain groups that are natural resource-dependent and increase the need to enhance the resilience of ecosystems and human systems. Finally, they will also increase the need for efforts to reduce local stressors and identify adaptation options.

The Mediterranean Basin is experiencing major changes in environmental conditions, combined with rapid and spatially diverse socio-economic development. These factors combined are exerting increased pressure on natural systems and human societies in the region. At the same time, new risks may emerge from interactions between drivers *(Section 2.6)* and from the interactions of impacts across sectors (Cramer et al. 2018), which may result in greater impacts, while increasing the vulnerability of less resilient natural systems and populations. These risks can affect the provision of services from natural systems and lead to severe disruptions in social systems.

Chapter 6 deals with managing future risks, identifying adaptation options and building capacity for resilience to climate and environmental changes. Addressing this aim, the chapter discusses three key components of emerging policy needs in the basin. The first component is the current understanding on the trajectory, intensity and spatial extent of future risk for the principal hazards, and associated policy considerations of the region. Secondly, the chapter outlines the current management and adaptation approaches and prevalent governance frameworks for coping with these risks. The third component critically reviews a range of examples of adaptation and mitigation for sectoral approaches, while considering case studies from Mediterranean-type environments.

Chapter 6 identifies a number of innovative and successful practices for achieving sound and sustainable development in countries of the Mediterranean Basin. Successful adaptation case studies involve stakeholder participation, structural political and economic change, gender considerations and weather-indexed insurance schemes. Successful mitigation involves options with clear societal benefits, such as energy cooperatives, energy efficiency, or regional cooperation. The final part of this section discusses potential interactions between hazards and sectors, which may lead to increased impacts. It further includes proposals to improve synergies between adaptation and mitigation practices and suggestions to promote Mediterranean cooperation and networking for building resilience, while also focusing on education and capacity-building.

6.2 Human health impacts

6.2.1 Future health risks

Environmental change can lead to a wide range of impacts on human health in Mediterranean countries (*Sections 5.2.3* and *5.2.4*). The most well-known impacts are direct impacts, e.g., extreme temperatures, cold and heat waves leading to cardiovascular and respiratory diseases and death (Gasparrini et al. 2017), wildfires leading to lethal injuries and respiratory diseases (Reid et al. 2016), and direct physical injuries and deaths resulting from extreme weather events, such as intense rainfall, river flooding, and storms (Forzieri et al. 2017). Impacts on human health can also be indirect, e.g., climate-related changes in food availability and quality that threaten food security (Deryng et al. 2016), increased variability of rainfall patterns that jeopardizes the availability and quality of freshwater (Koutroulis et al. 2016; Flörke et al. 2018), worsened air quality causing respiratory illnesses (de Sario et al. 2013; Doherty et al. 2017), and climate-driven increase in vector-borne diseases (Negev et al. 2015). The extent to which environmental change affects human health largely depends on the vulnerability of the exposed populations, that is, their ability to face and cope with climate-related hazards (IPCC 2012). Just as, for example, climate change is altering the climate system, socio-economic development and demographic growth are shaping the future vulnerability of populations in the Mediterranean Basin, with contrasting trends depending on the type of socio-economic trajectory (O'Neill et al. 2017; Reimann et al. 2018a; Kok et al. 2019). Urban areas along the Mediterranean coast are especially affected by climate change impacts on health because these areas concentrate people and assets (Watts et al. 2015). Urban areas often intensify climate-related hazards, e.g., hotter temperatures during heat waves due to the urban heat island effect (Papalexiou et al. 2018) and increase in run-off and flooding during extreme precipitation events due to soil sealing (Romero Diaz et al. 2017).

Heat-related morbidity and mortality are projected to increase substantially throughout the Mediterranean countries, under all climate scenarios *(Sec-*

tion 5.2.5.2). Impacts are expected to be the greatest in urban areas where people are concentrated and where the urban heat islands lead to higher inner-city temperatures (Yang et al. 2016). Future heat-related health risks are well-documented, with a large number of case studies spread across the Mediterranean Basin. Examples include (but are not limited to) a ~3- to 9-fold increase in the heat-related mortality rate in Cyprus (Heaviside et al. 2016); a 50-fold increase in mortality (compared to the current situation) on average across southern Europe by the end of the century (Forzieri et al. 2017) and a substantial difference in the increase of mortality between RCP2.6/RCP4.5 and RCP8.5 scenarios (Gasparrini et al. 2017; Kendrovski et al. 2017) *(Section 5.2.5.2).* In contrast, cold-related mortality is projected to decrease under all scenarios (Forzieri et al. 2017) *(Section 5.2.5.3).* It is also worth noting that changes in socio-economic and demographic conditions such as urbanization, demographic growth, and aging are also expected to further increase the burden of heat-related morbidity and mortality in Mediterranean countries (Rohat et al. 2019b, 2019a).

In contrast to other parts of the world, climate change is expected to lead to an overall increase in ground-level ozone- and fine particulate matter-related mortality in Mediterranean countries (Silva et al. 2016), with the exception of high-end climate change scenario RCP8.5, which leads to an increase in the health burden of air pollution in most Mediterranean countries (Silva et al. 2017). However, the significant uncertainties that exist in the trend directions and in risk estimates, that are primarily linked to the uncertainty in future types of emissions must be noted (Doherty et al. 2017).

Temperature rise will expand the habitat suitability for vectors, such as mosquitoes and sandflies (Negev et al. 2015; Semenza and Suk 2018; Hertig 2019) to most of the Mediterranean Basin by the end of the century and increase the transmission risk of the diseases they can carry, such as dengue, West Nile Fever and leishmaniasis (Bouzid et al. 2014; Semenza et al. 2016; Liu-Helmersson et al. 2019) *(Section 5.2.5.4).* One exception is the reduction of habitat suitability for *Aedes albopictus* in the southernmost parts of Europe (Caminade et al. 2012; Proestos et al. 2015), leading to a reduction of climatically suitable areas for the transmission of Chikungunya (Fischer et al. 2013). Changes to the hydrological cycle caused by climate changes are expected to further amplify such health issues and lead to increased fatalities. Erratic precipitation and extreme events and floods could support the flourishing of bacteria, parasites and algal blooms, including the protozoan parasites *Cryptosporidium,* hepatitis A viruses, *Escherichia coli* bacteria, and more than 100 other pathogens. The increase in human mobility also plays a crucial role in spreading vector-borne diseases throughout the Mediterranean Basin in newly suitable habitats (Thomas et al. 2014; Roche et al. 2015; Hertig 2019; Kraemer et al. 2019).

The combination of longer fire seasons and more frequent, large, and severe fires – triggered by increased droughts and land-use change (Turco et al. 2014; Knorr et al. 2016) – is projected to lead to greater fire risk and casualties, particularly in sub-urban areas (Forzieri et al. 2017) *(Section 2.6.3.3).* Similarly, more intense and frequent extreme precipitation events are expected to trigger a strong increase in flash flood-related injuries and mortalities throughout Mediterranean countries (Gaume et al. 2016) *(Section 3.1.4.1).* Floods can further damage water infrastructure, contaminate freshwater supplies, heighten the risk of water-borne diseases, and create breeding grounds for disease-carrying insects, especially threatening those with already limited access to water and sanitation (WHO 2017). The combination of demographic growth and changing diets is expected to lead to higher food demand across the region (Paciello 2015), while changes in extreme events such as droughts, heat waves, and extreme precipitation are projected to decrease crop and livestock yields substantially (Bernués et al. 2011; Deryng et al. 2016) *(Section 3.2.2.1).* This is particularly the case in the southern part of the Mediterranean Basin.

6.2.2 Management approaches, governance, and adaptation for health risks

National adaptation policies have been adopted in a large number of Mediterranean countries, often covering and acting on large-scale health topics such as extreme heat, air pollution, and vector-borne diseases (Negev et al. 2015). Although national governments have an important role to play in reducing the burden of climate change on human health, it is at the local scale that most actions and measures are taken (Paz et al. 2016). In fact, cities and municipalities in the Mediterranean Basin are at the forefront of climate change adaptation, particularly with regard to climate change impacts on human health, and often drive the regional effort to better anticipate and prepare for the adverse effects of climate change on human health and well-being (Reckien et al. 2018).

City-level adaptation is, more often than not, preferred to national-scale adaptation to decrease the vulnerability of the local population. This is accomplished through measures that include (but are not limited to) the improvement of housing and infrastructure, the education and awareness-raising of the most vulnerable communities, the implementation of early warning systems, the strengthening of local emergency and healthcare services, and the general strengthening of the community's and local institutions' adaptive capacity (Larsen 2015; Liotta et al. 2018). City-level adaptation can also directly target the reduction of climate-related hazards, such as building multi-usage buffer zones to reduce flood risk and to decrease the urban heat island (Yang et al. 2016).

Interestingly, management approaches sometimes attempt to develop adaptation measures that also affect climate change mitigation and/or that trigger health benefits, such as using green roofs to retrofit existing buildings (Gagliano et al. 2016) and transforming the transportation systems to mitigate emissions and reduce air pollution (WHO Europe 2017).

6.2.3 Case studies

It is important to note that most adaptation actions are impact-, context- and place-specific and there is no one-size-fits-all adaptation measure to reduce climate impacts on human health. Adaptation measures can take a wide range of forms, be triggered by different events, operate on different spatial and temporal scales, and be associated with different implementation constraints (Fernandez Milan and Creutzig 2015; Holman et al. 2018).

A number of Mediterranean cities have developed adaptation plans that specifically target the reduction of human health impacts. A significant part of the actions depicted in such climate adaptation plans are broad and unspecific (Reckien et al. 2018), which can constitute a bad practice and often do not mention potential negative effects, such as the increase in inner-city temperature and air pollution due to the systematic installation of air conditioning (Salamanca et al. 2014). Certain adaptation plans depict context-specific and quantified actions, such as in the city of Barcelona, which for instance, plans to increase its urban green areas by 1 m² per city resident by 2030 in order to decrease the urban heat island in case of extreme heat and increase water infiltration in the event of flash flooding (Barcelona Sostenible 2015).

For regional climate-related hazards, such as vector-borne diseases, a multi-country and transboundary approach to adaptation is crucial (Negev et al. 2015) and has been implemented over the past decades. In its current form, the MediLabSecure project[40] covers all Mediterranean countries and aims at preventing vector-borne diseases in these countries through scientific research and concrete actions.

6.2.4 Innovation

Climate change vulnerability assessments with a strong focus on human health have been undertaken over the past few years for cities without dedicated adaptation plans, including case studies for Cairo (Katzan and Owsianowski 2017), Nicosia (Kaimaki et al. 2014), and Antalya (Antalya Metropolitan Municipality 2018). These studies provide a strong scientific basis for the design of context-specific adaptation plans in the years to come. Collaboration within networks of cities with the goal to act on climate change (including adaptation to human health impacts) is promising in terms of identifying and sharing knowledge on best practices and concrete actions (Román and Midttun 2010; Rosenzweig et al. 2018). For example, cities such as Tel Aviv, Rome, Thessaloniki, Ramallah and Byblos are members of the "100 Resilient Cities"[41] network, Venice is a member of the "C40 Cities"[42] network and its program for connecting delta cities, and numerous cities are members of the Global Covenant of Mayors for Climate and Energy.

The integration of climate adaptation and mitigation plans within a unique climate plan is rarely achieved, but appears to be an efficient way to design measures that benefit both adaptation and mitigation (Reckien et al. 2018). The city of Athens has recently entered the circle of cities to have done so, with results on the reduction of human health impacts expected to come in the next few years (City of Athens 2017).

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[40] https://www.medilabsecure.com/home.html

[41] https://www.rockefellerfoundation.org/100-resilient-cities/

[42] https://www.c40.org/

6.3 Water security

The Sustainable Water Partnership (SWP)[43] defines water security as "the adaptive capacity to safeguard the sustainable availability of, access to, and safe use of an adequate, reliable and resilient quantity and quality of water for health, livelihoods, ecosystems and productive economies". This embracing definition reveals the pivotal role water security plays on all levels for reaching the ambitious goals laid out by the UN's Sustainable Development Goals (UN 2015; Bhaduri et al. 2016). Diametric to water security is water scarcity, a state reached when water demand can no longer be satisfied due to a lack of freshwater resources (Srinivasan et al. 2012). Physical water scarcity results in the depletion of water resources for both humans and natural systems and causes important transitions in the exploitation of different water compartments, e.g., from surface to groundwater sources, or even water transfers between basins. When excessive human consumption of water resources occurs under these circumstances, it may cause significant pressures on aquifers and surface waters, producing adverse effects on water quantity (over-exploitation) and quality (nutrient excess, pollution and lower biodiversity), which is detrimental to economic development and even compromises human health.

6.3.1 Future risks for water security

The Mediterranean Basin is particularly prone to limited water security due to its semi-arid to arid climates, especially as most important economies, such as tourism development *(Section 3.1.2.3)* and intensive agriculture *(Section 3.1.2.2)* are heavily water dependent and critically vulnerable to water scarcity and stress (Barceló and Sabater 2010). Thus, water security is at severe risk in the Mediterranean Basin. This susceptibility to scarcity is caused by strong human pressures, under the form of overexploitation, for agricultural, urban and industrial water uses, together with reduced availability of water due to climate change. Many Mediterranean water bodies, aquifer systems in particular *(Section 3.1.3.4)*, show over-exploitation associated with high seasonal water demand, and suffer from salinization, particularly in coastal areas and regions of intense irrigation and soil degradation. High human water demands in the region concentrate when water availability is at the lowest and exhausted aquifers co-occur with transformation of watercourses from permanent into intermittent. An increasingly common scenario in river basins includes headwaters becoming intermittent or even ephemeral, while lowlands bear aquifers that are depleted or contaminated by either salt or pollutants (Choukr-Allah et al. 2017). Growing human demands for water are leading to rapid increases in the frequency and severity of water scarcity, where there is insufficient water to simultaneously support both human and ecosystem water needs (Bond et al. 2019). With climate change and increasing demand for food and commercial services due to a growing population with higher demands, such patterns will very likely increase dramatically (Iglesias et al. 2012).

6.3.2 Management approaches, governance, and adaptation for water security

Observed trends and projections for the future indicate a strong susceptibility to changes in hydrological regimes, an increasing general shortage of water resources and consequent threats to water availability and management *(Section 3.1.1.1)*. However, it must be clearly stated that current uncertainties in climate projections and subsequent impact models, a yet incomplete understanding of the impact of a climate change signal on economic mechanisms or the lack of an elaborate and integrated human security conceptual framework, are imposing strong limitations on water-related decision-making under climate change conditions *(Section 3.1.5)*.

Climate, demographic and economic changes are expected to have strong impacts on the management of water resources, as well as on key strategic sectors of regional economies and their macroeconomic implications *(Section 3.1.5)*. Such developments bare the capacity to exacerbate tensions, and even intra- and inter-state conflicts among social, political, ecological and economic actors. Meanwhile, it is widely agreed that effective adaptation and prevention measures need multi-disciplinary preparation, analysis, action and promotion of collaborative strategies.

The complexity of the water cycle contrasts strongly with the low data availability, which (a) limits the number of analysis techniques and methods available to researchers, (b) limits the accuracy of models and predictions, and (c) consequently

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[43] https://www.swpwater.org/

challenges the capabilities to develop appropriate management measures to mitigate or adapt the environment to scarcity and drought conditions. The current potential to develop appropriate regional adaptation measures to climate change impacts suffers heavily from large uncertainties. These spread along a long chain of components, starting from the definition of emission scenarios to global and regional climate modeling to impact models and a subsequent variety of management options. Furthermore, the lack of awareness or understanding of the complex climate-resource-society dynamics often leads to inappropriate measures or no measures at all. Integrated water resources management is a holistic approach that focuses on both environmental as well as on socio-economic factors influencing water availability and supply, and seeks an efficient blend of all available conventional and unconventional water resources to meet the demands of the full range of water users, especially in agriculture, industry and tourism. However, the management approaches and solutions adopted, e.g., in form of decision support for specific water resources systems, are often highly specific for individual case studies *(Section 3.1.5)*.

An inventory of international, national and regional policies dealing with responses to climate change, water resources management, responses to hazards and disasters, and security in the region, is essential for proposing a suitable policy framework to integrate security, climate change adaptation and water management issues and specific recommendations for policy streamlining at the UN, EU, national and regional levels.

Political, economic and social factors seem to be more important drivers of water-related conflicts than climate-related variables *(Section 5.3.3.2)*. States and state-led adaptation play a prominent role in affecting human security: states can greatly facilitate adaptation, but policies are also prone to adverse effects. Adaptation can both increase and diminish water security for certain groups, although this depends to a great extent on factors such as power relations, marginalization and governance. There are also varying capacities of states to implement effective adaptation policies. Analyzing the political economy in an area or country helps to understand state-led adaptation. Impacts on key strategic sectors typically consider agriculture and tourism. These sectors show specific dependence on water security, which is of quintessential importance in the Mediterranean economy, with relatively high adaptation potential to strategic policies.

Most Mediterranean countries will likely face water shortages *(Section 3.1.1.1)*. This can have significant implications in terms of agricultural productivity, income and welfare. However, the water gap in the Mediterranean area will be affected by different external drivers. In northern Mediterranean countries, this will be due to increased temperature and decreased precipitation. Middle East and North Africa economies will likely find it difficult to put aside precious water resources for the purpose of environmental preservation. In southern Mediterranean countries, the growing non-agricultural water needs (induced by strong economic and demographic development) will be an additional challenge to water security, demanding management improvements in water efficiency. Innovations include highly successful efforts to increase water use efficiency. Smart metering, for example, is being deployed to improve accuracy in billing, evaluate consumption and increase users' awareness of their own consumption (Revolve Water 2017).

6.3.3 Case studies

Due to the already high and expected increasing pressure on water resources in the Mediterranean, the efforts to counteract water scarcity and establish water security are manifold in scope, action and scale. As the challenges can be very site-specific, and triggered by both natural and anthropogenic drivers in various constellations, significant uncertainties remain in identifying suitable programs of measures, which would be generally applicable for being independent of region and scale. Thus, related activities can be embedded anywhere from pan-continental to national levels, but often basin-scale and even highly localized programs and case studies are implemented. The range of measures *(Section 3.1.5)* includes water-saving technologies, such as new equipment in irrigation agriculture and households, often complemented by improved water efficiency (e.g., by means of adapted water management procedures), as well as direct measures to increase water availability through additional multi-scale storage solutions (ranging from cisterns to large reservoirs) or through the use of unconventional water sources stemming from recharging wastewater or seawater desalination. The latter may however, cause environmental concerns due to soil contamination or energy consumption (IWA 2012).

All these aspects can be useful components of an integrated water resources management approach (Choukr-Allah et al. 2012) *(Section 3.1.5.1)*. To date, there are several highly successful examples of such an approach, but negative case studies also exist. This highlights the prevailing need for further research and transdisciplinary collaboration to reach and maintain water security in the Mediterranean (Ludwig et al. 2011; Ludwig and Roson 2016; Saladini et al. 2018).

Several success stories of water security measures related to wastewater re-use experiments on local scale applications exist. The case of Oueljet El Khoder, Tunisia, is an exemplary effort, which succeeded in establishing a sound system for water re-use to provide reliable water resources for irrigation and ensuring sustainable conditions for the underlying aquifer. In this case, the collaborative project SWIM Sustain Water MED[44] has introduced a tertiary treatment unit including a slow sand filter alongside a monitoring and early warning system for monitoring the quality of the treated wastewater. The installations resulted in an increased rate of re-use of reclaimed water and an extension of the agricultural irrigation area.

A main challenge, however, is the fact that despite the evidence of water scarcity being felt by stakeholders and end-users, the role of climate change and the related future exacerbation of water stress is often ignored and not perceived as a key issue for water uses and water security (La Jeunesse et al. 2015), In the course of the CLIMB project[45], several circum-Mediterranean case studies (e.g., France, Italy, Turkey, Egypt and Tunisia) showed that the main response to increasing water demand in the Mediterranean region is a progressive externalization of water resources, with limits imposed by national borders and technological possibilities. This thinking, which does not consider climate change as a driving force, is not sustainable and prone to rising water conflicts.

6.3.4 Innovation

In recent years, great energy and investment has been placed in the modernization of installations and development of (sometimes integrated) water resources management *(Section 3.1.5)* (Cameira and Santos Pereira 2019). However, in many cases, these efforts seek to adapt to current state challenges and fail to consider the rising pressures in the light of climate change and growing domestic and industrial water demand. One of the expected consequences of climate change alone is a reduction in annual precipitation, paired with a very likely increase in rainfall variability and extremes *(Section 2.2.5)*. All of these factors contribute to increasing vulnerability and risk in potentially affected regions and can consequently jeopardize water security. Innovation is needed to reach beyond the current limitations of water resources management by introducing flexible mechanisms that not only include novel water (saving) technologies, but also build on targeted water system analysis and research *(Section 3.1.5.2)*. Important elements of these types of systems start with the (re-)establishment of environmental monitoring networks, composed of a dense in-situ observational network paired with operational remote sensing applications (e.g., for spatial drought monitoring, including vegetation status, soil moisture, water levels). Based on such regular time series of data products, spatially-explicit and process-based models can be built with sufficient predictive power to support long-term planning and decision-making to adapt to the impacts of a gradual climate and global change.

Great innovation potential lies in the development of regionally specified and flexible response schemes to water scarcity that reach beyond the state-of-art and provide integrated solutions for increased water efficiency by combining improved water-saving technologies (Wang and Polcher 2019) with the provision of unconventional water resources (e.g., by managed aquifer recharge or saline water for irrigation (Reca et al. 2018; Tzoraki et al. 2018)), to avoid water stress *(Section 3.1.5.2)*. It is further necessary to establish systems for short-term predictions of extreme events and seasonal forecasts that allow for extended reaction time of first responders (Haro-Monteagudo et al. 2017; Corral et al. 2019) and affected industries, such as agriculture (Martínez-Fernández et al. 2013; Kourgialas et al. 2019) or tourism (Hadjikakou et al. 2013; Toth et al. 2018). Water-sensitive urban design (WSUD) is approach to management that is starting to take hold in cities, although slow to catch on in the Mediterranean (Goulden et al. 2018). This paradigm is fueled by the interest in sustainable urban development and it aims to integrate best water management practices (many related to stormwater runoff), with mechanisms of urban planning. WSUD, developed in Australia, connects urban planning with stormwater management mainly for protecting groundwater in aquifers. In the United States, planners employ a similar approach, called low-impact development (LID), which focuses on maintaining a steady hydrological response (i.e., stormwater runoff vol-

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[44] https://www.swim-h2020.eu/

[45] https://cordis.europa.eu/project/id/244151

ume and discharge rate leaving the spatial unit before and after development), but also seeks to view stormwater as a benefit to the environment, rather than only as a disturbance (Carlson et al. 2015). While both LID and WSUD aim to minimize the hydrological effects of urban development on the surrounding environment, WSUD puts more emphasis on maintaining a water balance that considers waterway erosion along with the management of groundwater, stream flows, and flood damage. In Israel, this approach has been considered and implemented, but mostly on a local, site-specific basis, through such practices as retention pools, but it has been less successfully implemented to curb such problems as increased coastal erosion (Portman 2018).

In order to have practical impact, a crucial element in this endeavor is to fully take into consideration the political and institutional dimensions of dynamically changing priorities in water governance. This can be supported by novel ways of public participation and knowledge sharing between institutions and researchers (Bielsa and Cazcarro 2014), which in combination could and should lead to the development of smart water grids and efficient water licensing and metering.

6.4 Agricultural drought

6.4.1 Future drought risks in agriculture

Agricultural drought occurs when soil moisture availability to plants has dropped to such a level that it adversely affects crop and pasture growth (Mannochi et al. 2004). The Mediterranean region stands out as one meteorological drought hotspot where drought severity has increased in recent decades (Spinoni et al. 2019) *(Section 2.2.5)*. Regarding agriculture, climate warming exacerbates the impact of meteorological droughts through the increasing evaporative demand (Quintana-Seguí et al. 2016). The analysis of climate model ensembles in the Mediterranean consistently projects future meteorological droughts that translate into stronger soil moisture anomalies (Planton et al. 2012; Orlowsky and Seneviratne 2013; Dubrovský et al. 2014; Ruosteenoja et al. 2018) *(Section 3.1.4.1)*. More recently, Rojas et al. (2019) showed that climate models project negative precipitation trends outside the natural variability in the Mediterranean region in the mid-century, in all RCPs. A 10 to 30% decrease in precipitation is expected as early as 2040, in particular causing drier winters in northern Africa, and summer drying in southern Europe.

Already under “low” global warming levels of 1.5°C and 2°C, the exacerbation of drought conditions in the Mediterranean will be unprecedented since the last millennium (Guiot and Cramer 2016; Samaniego et al. 2018) *(Section 3.1.4.1)*. Furthermore, as Mediterranean drought events also imply hot summers (Zampieri et al. 2009; Hirschi et al. 2011; Russo et al. 2018), they drive a positive feedback that again enhances the frequency and the severity of agriculture droughts, directly challenging both crop and pasture management (e.g., Saadi et al. 2015; Scocco et al. 2016). Both rain-fed agriculture and irrigated agriculture are vulnerable to drought (García-Garizábal et al. 2014), because the availability of irrigation water may become limited by several factors, including depletion of overexploited groundwater (Famiglietti 2014), competition for water due to the expansion of irrigated agriculture (Khadra and Sagardoy 2019) or conflict with other water usages (e.g., Gössling et al. 2012) *(Section 3.2.2.1)*.

6.4.2 Management approaches, governance, and adaptation for agricultural drought

Farmers, who have been historically exposed to variable climate conditions, such as in the Mediterranean region, tend to be more prepared to cope with climate change (Reidsma et al. 2009). When it comes to droughts, several options are considered for avoiding water-stress in crops/pastures. Two main strategies can be identified: either ensuring that the water requirements are fulfilled (e.g., Fader et al. 2016), or requiring less water by modifying the agricultural system and its management so that the crops/pastures can better endure drought *(Section 3.2.3.1)*.

Adjusting irrigation water supply to satisfy water requirements

Rapid solutions for satisfying increasing water requirements, such as expanding irrigated areas or increasing groundwater and/or reservoir pumping, only have short-term effects and are often not sustainable when they lead to decreased groundwater levels, as reported from many regions (see Richey 2014 for the groundwater depletion of the major aquifers of the MENA region) or when only limited surface reservoirs are available *(Section 3.1.2.2).* This affects all competitive water users, including the environment, e.g., the wetlands in the Upper Guadiana Basin in Spain (Carmona et al. 2011). Other solutions include the deployment of improved irrigation and conveyance systems, which have a large water-saving potential (e.g., sprinkler or drip). In recent years, governments of a few Mediterranean countries have subsidized pressurized irrigation systems (Daccache et al. 2014). According to the study by Fader et al. (2016), the Mediterranean region could save up to 35% of water by implementing such irrigation techniques *(Section 3.1.5.2).* Nevertheless, these techniques alone are insufficient to face the increasing water demand resulting from climate change, demography, and socio-economic change (Malek and Verburg 2018).

Increasing attention is being given to wastewater reclamation and re-use, with important projects developed in countries all over the Mediterranean Basin since the end of the 20th century (Angelakis et al. 1999). From different experiments, it appears that treated wastewater re-use in integrated water resources management systems may provide significant benefits for irrigated agriculture and could be implemented in most water-scarce regions (Kalavrouziotis et al. 2015) *(Section 3.1.5.2).* Even the use of poorly controlled treated wastewater does not damage the agronomic quality of soils. It even increases the soil organic matter (Cherfouh et al. 2018). Consequently, it is possible to expect both potential agronomical benefits and improved water supply from wastewater management.

Desalination of seawater for irrigation has high costs and many negative environmental impacts (Sadhwani et al. 2005). Furthermore high-level desalination removes ions that are essential for plant growth (Yermiyahu et al. 2007). The above studies concluded that desalination facilities for irrigation need revised treatment standards. An alternative strategy looks at crop performance under deficit irrigation. Promising results indicate an enhancement of water productivity, leading to proportionally lower yield reduction than water deficit. Furthermore, in the case of tomatoes, fruit quality is improved (Patanè et al. 2011).

Reducing water stress

The development of intensive agriculture since the second half of the 20th century has changed soil properties in several ways, including change of structure, decrease in soil organic matter, and decrease in biological activity (e.g., García-Orenes et al. 2012; Aguilera et al. 2013; Morugán-Coronado et al. 2015). In addition, many arable soils with cereals are left bare for extended periods (Kosmas et al. 1997), and bare soil beneath the rows is also a frequent feature of industrial perennial crops (Gómez et al. 2011). Both aspects impact the soil hydrological cycle, i.e., the water resources for crops/pastures. First, besides increasing erosion (which has reached dramatic levels in some Mediterranean cropping areas), bare soils favor evaporation and intercept precipitation water less well than vegetated or mulched soil (Monteiro and Lopes 2007). Second, low organic matter content, tillage practices, and the decline of biological activities all imply soil structure changes such as porosity (Pagliai et al. 2004) *(Section 3.2.3.2).* In particular, the micropore to macropore ratio is modified: the proportion of micropores, which are considered the most important both in soil-water-plant relationships and in maintaining a good soil structure (Pagliai et al. 1983), is decreased by tillage, with a significantly reduced capacity to store water (Lampurlanés et al. 2016). Since the end of the 20th century, these phenomena have been studied in the Mediterranean Basin, using experiments on the effects of conservation agriculture (no tillage / reduced tillage, cover crops / mulching) on the soil-water dynamics for most of the Mediterranean cropping systems. These strategies are particularly promising in dry areas, and their average effect on Mediterranean agro-ecosystems, including yields, is beneficial, especially during water-stressed periods, despite the existence of contradictory results that may occur for many reasons (Mrabet 2002; Álvaro-Fuentes et al. 2007, 2008; Mrabet et al. 2012; Tomaz et al. 2017) *(Section 3.2.3).*

These adaptation strategies also have benefits for climate mitigation, since conservation agriculture emits less greenhouse gases and generally leads to soil carbon sequestration (Kassam et al. 2012; Aguilera et al. 2013; García-Tejero et al. 2020) (*Sections 3.2.3.2* and *3.2.3.3*). The net effect of this is still debated and clearly depends on other factors as well (Govaerts et al. 2009). There is also a finite time horizon as the agro-ecosystem soil carbon maximum capacity is often reached after a 20-50-year period (Lal and Bruce 1999). In any case, incentives from different institutions now exist in several countries in order to promote agricultural management strategies that rely on key principles of conservation agriculture (Calatrava et al. 2011). Water stress can also be reduced if several crops (or crops and flower/grass strips) are grown in combination on the same land, which may result in a deeper penetration of the roots into the soil. Such plasticity has been observed in vineyards with cover cropping, where the compensatory growth of the grapevine root system allowed the resources (e.g., water) of deeper soil layers to be exploited (Celette et al. 2008). In an agroforestry system mixing walnut trees and winter crops, the competition with the winter crops induces deeper rooting of the walnut trees (Cardinael et al. 2015). Besides revealing the adaptive capacity of plants, these agroforestry practices provide welcomed shade in summer in the Mediterranean Basin, which is beneficial for both crops and livestock (Sá-Sousa 2014). Agroforestry systems are multifunctional, currently re-discovered in temperate areas – only for the montado-dehesa system of the Iberian Peninsula, a savanna-like rangeland dominated by scattered Mediterranean evergreen oak trees, the positive role of the trees on the water balance has been shown since the 20th century (Joffre and Rambal 1993, 2006).

6.4.3 Case studies

Many studies on no tillage in the Mediterranean show that this practice has positive effects on the soil for keeping more water, therefore enhancing yields, especially in water-stressed years. A few studies on the similar positive effects of agroforestry are shown in *Fig. 6.1*.

6.4.4 Innovation

Mycorrhizal symbiosis

In the Mediterranean Basin, the alleviation of drought stress by mycorrhizal symbiosis has been studied for more than 25 years (Sánchez-Díaz and Honrubia 1994). Using soils of different Mediterranean locations, controlled experiments regularly report the beneficial effect of arbuscular mycorrhizal symbiosis for crops in drought conditions: Meddich et al. (2000) for clover, Ruiz-Lozano et al. (2001) for soybean, Marulanda et al. (2007) for lavender, Navarro García et al. (2011) for cane-apple bush, Armada et al. (2015) for maize (using also drought-adapted autochthonous microorganisms), and Calvo-Polanco et al. (2016) for olive among others. Field experiments confirm that mycorrhizal inoculation alleviates water deficit impact (e.g., in Hungary, Bakr et al. 2018), but we are not aware of such field studies in the Mediterranean.

Considerable progress has been made in understanding the role of arbuscular mycorrhizal sym-

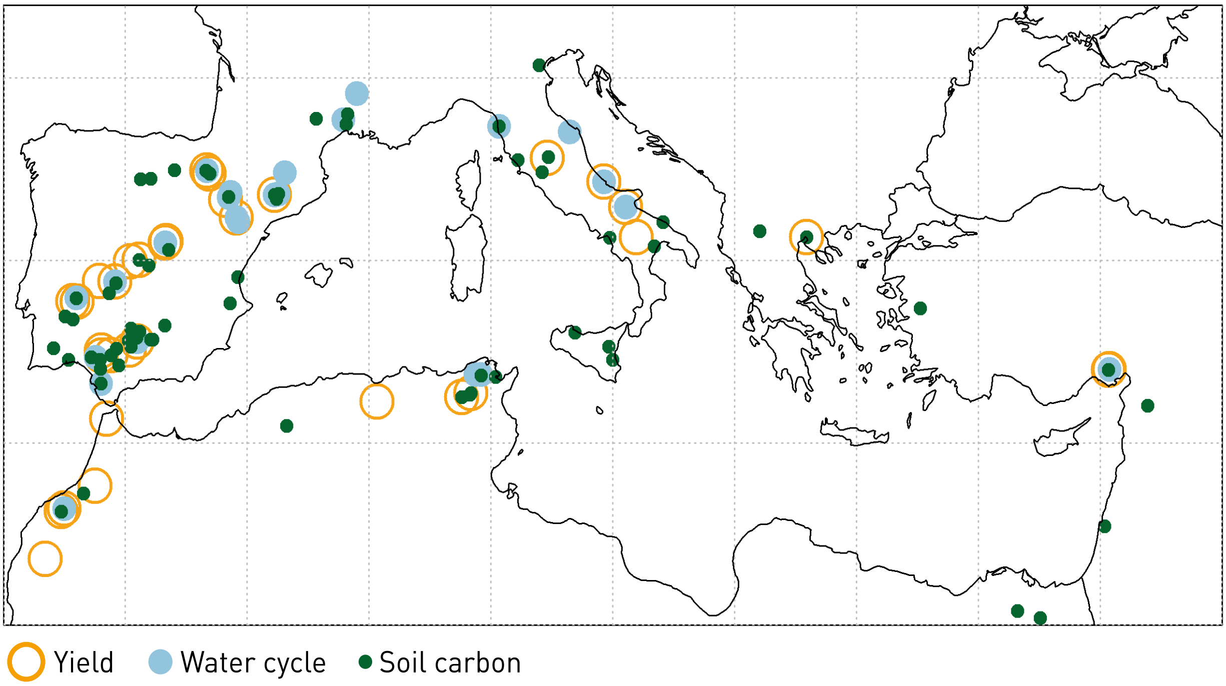

Figure 6.1 | Mediterranean sites where the impacts of innovative agricultural practices have been surveyed. These practices include "conservation agriculture", i.e., no or reduced tillage, organic amendments, cover crop, and two agroforestry sites. Dark green dots: sites where the impact of these practices on soil carbon have been measured, blue dots: sites where impacts on soil hydrology have been measured, orange circles: sites where the impacts on yields have been measured or surveyed.

biosis in reducing drought effects (Rapparini and Peñuelas 2014), but more studies are needed to elucidate the relevant mechanisms. Experiments are being carried out worldwide with different types of plants (Tyagi et al. 2017; Pavithra and Yapa 2018; Zhang et al. 2019), with particular focus on the efficient cooperation between nodulation and arbuscular mycorrhizal fungi (AMF) for legumes (Foyer et al. 2018). Understanding the AMF-mediated mechanisms that are important for regulating the establishment of mycorrhizal association and plant protective responses to unfavorable conditions will open up to new approaches to exploit AMF as a bioprotective tool against drought (Bahadur et al. 2019). Antagonistic interactions between barley and AMF have been observed under drought conditions, particularly at high AMF richness (Sendek et al. 2019) and suggest that unexpected alterations to plant-soil biotic interactions could occur under climate change.

Despite the benefits of AMF inoculation to crop production under water deficit, outcomes and challenges of AMF application for practical use in crop production may vary, e.g., in the event of possible colonization competition between the native populations of AMF in soils and the introduced symbionts (Posta and Duc 2019). Recent research has shown that compatible combination of AMF with other beneficial microbes such as plant growth-promoting bacteria offering synergistic effects on plant tolerance to stressful environments including drought stress is a promising perspective (Rahimzadeh and Pirzad 2017). Studies on quantitative trait loci involved in mycorrhizal plant responses to drought stress are needed for breeding programs to create new cultivars with a combination of drought-tolerant traits and AM benefits. Although biotechnology practices have already made the production of efficient arbuscular mycorrhizal fungal inoculants possible for the past 15 years (e.g., Barea et al. 2005), the farmers' awareness and acceptance of (relatively expensive) mycorrhizal inoculation remain low (Posta and Duc 2019). To conclude, while AMF inoculation in crop productions under water deficit seems promising, it has not yet proven its ability to be usable and successful for Mediterranean farming systems.

Composting

Composting technology is a modern technology that can produce a stable humus complex, used as high quality compost, providing plants with all required nutrients and micro-elements. Producers claim that the structure of this humus may increase the water holding capacity of soils by up to 70%, and have established composting facilities with organic farms in the Egyptian desert (Bandel 2009). However, results regarding water holding capacity development and enhanced resistance to drought are currently limited.

6.5 Wildfires

Mediterranean-type ecosystems are characterized by hot and dry summers and strong seasonality (Olson et al. 2001). Cool wet winters promote biomass growth and extended summer drought favors the regular occurrence of wildfires (Batllori et al. 2013). Historically, fires started by lightning during wet or dry storms, which can be very common in many Mediterranean-type ecosystems (Pineda and Rigo 2017). The geographic location of Mediterranean regions also benefits the frequency of strong wind events that further exacerbate fire activity. These ecosystems are dominated by fire-adapted vegetation resulting from a long evolutionary association with fire (Pausas and Keeley 2009), where usually crown and high-intensity fires largely prevail (Keeley et al. 2012a; *Section 4.3.3.1*).

Ever since prehistoric times, natural fire regimes have been altered by human activity in a multitude of ways, by modifying fuel structure, igniting new fires and extinguishing wildfires (Bowman et al. 2011; Keeley et al. 2012b). In highly populated areas, such as the Mediterranean Basin, it makes little sense to refer to a "natural" fire regime because the footprint of human dynamics has interacted with natural factors to mold fire regimes in time and space, and makes the characterization of a 'baseline' fire regime nearly impossible (Lloret and Vilà 2003). The alteration of ecosystems at unprecedented rates may lead to unidentified changes, making natural systems unable to persist within their natural variability regimes (Vitousek et al. 1997), potentially reaching no-return ecological states during this century (FAO 2013; Batllori et al. 2017).

6.5.1 Future wildfire risks

The present escalation of environmental changes is modifying fire regimes and producing new challenges for conservation management. In Mediterranean-type ecosystems of the European countries, afforestation linked to rural abandonment has occurred in recent decades *(Section 4.3.1.2)* and has shifted the systems to weather-limited fire regimes (Moreira et al. 2001; Pausas and Fernández-Muñoz 2012), in which the occurrence of fire-weather conditions drives fire activity (Pausas 2004), increasing the uncontrollability of fire events. The increase of adverse weather events associated with warming climate has stimulated an unsustainable fire regime perceived as a threat by society. Urbanization of rural areas during the second half of the 20st century has further modified fire dynamics, aggravating fire hazards due to the increase in ignition sources in these areas and an increased exposure of human activities to fire effects (Lampin-Maillet et al. 2011).

Direct human fire actions have also altered fire regimes (Bowman et al. 2011; Loepfe et al. 2011; Oliveira et al. 2012; Brotons et al. 2013; Chergui et al. 2017; Costafreda-Aumedes et al. 2017). Besides altering the spatial distribution of fuel, humans have also directly affected fire regimes by boosting anthropic ignitions and by suppressing fires with investments in huge fire-fighting structures *(Section 4.3.3.1)*. In European Mediterranean countries, fire management policies basically rely on the fire suppression principle, and the increasing effort made in this direction has strongly modified fire regimes (Brotons et al. 2013; Turco et al. 2013; Moreno et al. 2014; Otero and Nielsen 2017).

Climate change in the Mediterranean Basin is projected to increase summer heat wave events, extend fire seasons, increase yearly average temperatures and increase precipitation irregularities *(Section 2.2.5)* (Field et al. 2014). How these changes will impact wildfires is still being studied (Westerling et al. 2011; Batllori et al. 2013). While a warmer climate will upsurge fire activity by increasing water demand and decreasing fuel moisture, this increase in temperatures may also lead to a decline in ecosystem productivity and thus to an overall reduction of fuel biomass (Flannigan et al. 2009; Batllori et al. 2013), which can potentially counteract warming effects on fire activity. Climate change may also promote the occurrence of other disturbances (forest outbreaks, windstorms, non-indigenous etc.) that can result in new drivers of fire regime change *(Section 2.4.1.1)*. There is still a significant gap in the understanding and projection of future climate shifts and its impacts on ecosystems (Schoennagel et al. 2017; *Section 4.3.2.1*).

6.5.2 Management approaches, governance, and adaptation for wildfires

Changing fire regimes are now one of the most significant risks to natural systems and societies in places such as the Mediterranean Basin (Pausas et al. 2009). A deeper understanding of fire dynamics is therefore needed to enhance possibilities of successful biodiversity conservation strategies at the ecosystem level. In addition, a comprehensive understanding of fire regime patterns and processes will help to transform our societies within the resilience paradigm (Tedim et al. 2016). In recent decades, a rise in urbanization at the wildland-urban interfaces has led to an increasing number of fatalities (Moritz et al. 2014). The political response has been directed towards trying to eliminate fire from the system, with very limited success anywhere in the world (San-Miguel-Ayanz et al. 2013; Moritz et al. 2014; Archibald 2016; Tedim et al. 2016). There is an ongoing effort to promote development under which people are less vulnerable and more resilient to fire impacts *(Section 5.1.3)*.

The understanding on how the different drivers of change can further impact fire regimes is still limited (Flannigan et al. 2009; Westerling et al. 2011; Regos et al. 2014). However, there is no clear consensus on future land-cover change directions because they rely more on local economic drivers with high uncertainty in their long-term predictions (Rounsevell et al. 2006). In addition, the complex interactions of drivers, the cascading effects of sequential disturbances (Batllori et al. 2017), and the uncertainty of future conditions (Thompson and Calkin 2011) make the projection of future changes a major challenge. Fire research requires further tools and approaches that help to understand ongoing changes and provide solutions to help to make effective decisions.

Available evidence from recent decades show a steady increase in wildfire events leading to extreme wildfire events escaping from fire-fighting efforts, reaching acute fire intensities and often burning very large areas (San-Miguel-Ayanz et al. 2013) *(Section 2.6.3.3)*. Extreme wildfires have more significant consequences for societies and ecosystem properties than small fires (Adams 2013; San-Miguel-Ayanz et al. 2013; Tedim et al. 2013), and their occurrence is based on outstanding environmental conditions (San-Miguel-Ayanz et al. 2013). In European countries from the Mediterranean Basin, the appearance of these wildfires has been related to an expansion of forests interacting with increasingly hotter and drier weather conditions (Tedim et al. 2013). The high fuel loads accumulated in forests have resulted in intense fire behaviors (high flames, fire spotting capacity) that make them very difficult for fire-fighting brigades to control. Moreover, suppression systems often collapse when protecting dispersed human assets, diminishing direct fire suppression effectiveness. Under a climate change context, these extreme wildfires are projected to increase (Amatulli et al. 2013).

6.5.3 Case studies

Fire suppression strategies based on proactive opportunity search and advanced fire behavior (Castellnou et al. 2019) have been successful in some regions. However, increasing fuel loads and greater climate vulnerability make fire-fighting strategies prone to collapse in the event of extremely large or intense large fires, which has already happened in countries such as Greece and Portugal in recent years. Proactive systems may open the way for local stakeholders to participate in fire-fighting decisions (Otero et al. 2018). However, the key tractable factor behind potential reduction in future aggressive fire behavior is fuel availability. On these lines, different regions deploy prescribed fire techniques to decrease fuel loads in particular areas. However, contrary to other places with Mediterranean-type climate (such as Australia and California), deployment of prescribed fire over large tracts of land raises public concerns and is difficult to implement in Mediterranean countries, particularly in areas with a high percentage of private property (Fernandes 2018). In these cases, a combination of prescribed fire with other forest management techniques (such as using fuel for energy biomass) may be used (Regos et al. 2016). On the other hand, large tracts of conifer and eucalyptus plantations may increase the overall fire risk at the landscape scale, especially in comparison with mature native forests or more open farmland-dominated landscapes (Bowman et al. 2019).

6.5.4 Innovation

The key to sustainable, fire resilient landscapes is the development of sustainable socio-economic activities that allow local communities to thrive while ensuring low overall landscape risk and ensuring the persistence of other natural values (Smith et al. 2016). Such nature-based solutions to fire risk management (Duane et al. 2019) arise as an area where innovation, especially social innovation, is expected to develop in the coming years (Chergui et al. 2017). Technological innovation is also rapidly being introduced into strategic and operative fire-fighting, especially in relation to the use of remote sensors for data acquisition and remote control to predict extreme weather events leading to high-risk conditions conducive to intense fires (Peterson et al. 2017).

6.6 Soil erosion, degradation and desertification

6.6.1 Future risks for soils

Soil erosion, by water or wind, is the most widespread form of soil degradation worldwide (Panagos et al. 2017b). It is widespread in the Mediterranean region and includes sheet wash, rill and gully erosion, shallow landsliding, and the development of large and active badlands in both sub-humid and semi-arid areas (García-Ruiz et al. 2013). Soil erosion significantly alters the composition of soils, has a direct impact on the biogeochemical cycles that are responsible for supporting life on Earth and significantly reduces the ecosystem services and the economic systems that rely on them (Cherlet et al. 2018). The susceptibility of Mediterranean soils to erosion, degradation and desertification under changing conditions is exacerbated by a number of factors, such as deforestation, frequent forest fires, the cultivation of steep slopes and overgrazing (García-Ruiz et al. 2013) *(Section 2.4.1.2)*. According to the United Nations Convention to Combat Desertification (UNCCD, 2004), Portugal, Spain, Italy, Greece, Turkey and Morocco have a significant problem with desertification because of the occurrence of particular conditions over large areas. International and interdisciplinary research initiatives have come to support this statement and have provided ample documentation that large areas of the European Mediterranean region are being increasingly affected by desertification, e.g., the EU MEDALUS, DISMED, MEDACTION, LEDDRA projects (Kosmas et al. 1999; Drake and Vafeidis 2004; Kepner et al. 2006; Sommer et al. 2011) *(Section 2.4.1.1)*.

The assessment of future degradation and desertification risk and whether it can be reversed with land conservation and management practices, is affected by our ability to accurately set a baseline (Behnke and Mortimore 2016) or even decide on what constitutes an alarming rate. With the very slow rate of soil formation, any soil loss of more than 1 t ha^{-1} yr^{-1} can be considered as irreversible within a time span of 50-100 years. However, the concept of variable tolerable rates of erosion should be noted and requires further definition (di Stefano and Ferro 2016).

Numerous efforts to estimate current erosion rates have been reported in the literature, most commonly using empirical models (e.g., RUSLE) or physical process-based models (e.g., PESERA). A recent attempt to quantify soil erosion by water over the European region using the RUSLE model has reported very high soil loss rates for European Mediterranean countries of commonly over 50 t ha^{-1} yr^{-1}, mainly in southern Spain and Italy and to a lesser extent in Greece, Cyprus and France (Corsica) (Panagos et al. 2015). A more recent global modelling effort based on RUSLE by Borrelli et al. (2017) assessed the impact of land use change on soil erosion between 2001 and 2012. With regard to the Mediterranean Basin, it corroborated the previous findings and identified Morocco, northern Algeria, western Syria, Albania, Serbia, Montenegro and Bosnia Herzegovina as hotspots where erosion rates were predicted to increase according to a baseline scenario. Syria, Serbia, Croatia, Montenegro and Morocco were also projected to have increased soil erosion rates even with a conservation scenario. It is worth noting that soil erosion risk models contain erosivity and erodibility factors that reflect average-year rainfall. Therefore the currently available values for these factors may inadequately represent the more frequent and intense storms projected under most climate change scenarios (Jones et al. 2012). Moreover, Eekhout and de Vente (2019) have shown that applying different bias correction methods to contrasting Mediterranean conditions can lead to disparate soil erosion projections of either a future decrease or increase.

Other efforts have aimed at assessing the sensitivity of an area to degradation and desertification processes, using a system of indicators developed during the MEDALUS EU project (Kosmas et al. 1999), including soil erosivity, vegetation cover, climatic parameters (such as aridity), land use and land management. These studies have been applied in study sites throughout the Mediterranean, and have often identified hotspots of critical sensitivity to degradation and desertification (e.g., Lavado Contador et al. (2009) in Spain; Salvati and Bajocco (2011) in Italy; Symeonakis et al. (2014) in Greece; Kamel et al. (2015) in Lebanon; Boudjemline and Semar (2018) in Algeria, and Ait Lamqadem et al. (2018) in Morocco). Prăvălie et al. (2017) also applied this approach to the entire European Mediterranean for the years 2008 and 2017 and found widespread increases in sensitivity to desertification: the amount of territory with a high or very high sensitivity to desertification had increased, in less than a decade, by 177,000 km^2.

Adding to the complexity of assessing the future risks related to soil erosion and the reversibility of related degradation and desertification, climate change is expected to alter erosion rates in a complex, non-linear way. Rainfall changes (in either the intensity only or in the amounts as well), along with expected changes in temperature, solar radiation, and atmospheric CO_2 concentrations, will have significant impacts on soil erosion rates (Nunes et al. 2013; Li and Fang 2016; Zare et al. 2016; Zhou et al. 2016; Guo et al. 2019). Kirkby et al. (2004) describe a non-linear spatial and temporal response to climate change, with relatively large increases in erosion during wet years compared to dry years, and sporadic increases locally. However, the processes involved in the impact of climate change on soil erosion by water are complex, involving the abovementioned changes in rainfall amounts and intensities, the number of days of precipitation, plant biomass production and residue decomposition rates, soil microbial activity, evapotranspiration rates, and shifts in land use necessary to accommodate the new climatic regime (Nearing et al. 2004). Projections of changes in factors related to desertification indicate significant exacerbation of desertification risk in southern Europe and particularly in Spain, southern Italy, and Greece (Panagos et al. 2017a; Samaniego et al. 2018).

6.6.2 Management approaches, governance, and adaptation for soil protection

Soil erosion is greatly affected by human-environment interactions, most notably land use and land use changes. However, overly simplistic cause and effect approaches to what leads to degradation and desertification have now been abandoned (Cherlet et al. 2018) as the complex nature of non-equilibrium systems has been identified and acknowledged (Reynolds et al. 2007; Behnke and Mortimore 2016). A more integrated land management approach is currently driving policy-making, including the development and implementation of adaptive practices of sustainable land management. The World Overview of Conservation Approaches and Technologies (WOCAT) is a network that develops, archives, shares and disseminates sustainable land management knowledge to improve human livelihoods and the environment (Liniger et al. 2007), gaining broad appreciation from all involved stakeholders.

Sustainable land management approaches are continuously adapted in response to changing environmental conditions and human needs. From a list of hundreds of archived case studies of sustainable land management in the Mediterranean region, five types of measures are identified that can be taken to address land degradation (*Sections 3.2.3.2* and *4.3.3.3*): (i) agronomic measures: measures that improve soil cover (e.g., green cover), measures that enhance organic matter (e.g., manuring), soil-surface treatment (e.g., conservation tillage), and subsurface treatment (e.g., ripping); (ii) vegetative measures: plantation of trees and shrubs (e.g., live fences), grasses and herbaceous plants (e.g., grass strips); (iii) structural measures: terraces, bunds, banks, dams, pans, ditches, walls, barriers, and palisades; (iv) management measures: change of land use type, change in management/intensity level, change in timing of activities, and control/change of species composition, and (v) combinations of the other four types (Liniger et al. 2007; Cherlet et al. 2018).

With regard to policy, at the moment, only a few EU Member States have specific legislation on soil protection. Soil is not subject to a comprehensive and coherent set of rules in the European Union. Existing EU policies in areas such as agriculture, water, waste, chemicals, and prevention of industrial pollution indirectly contribute to the protection of soils. However, as these policies have other aims and scopes of action, they are not sufficient to ensure an adequate level of protection for all soils in Europe[46]. A limited number of countries or Autonomous Regions have Soil Protection Plans (e.g., the Basque Autonomous Country (Landeta 1995), Italy (Law 97 of 1994)) while a much larger number have ratified the UNCCD and have prepared a National Programme to Combat Drought and Desertification or National Action Plan, namely, Algeria, Egypt, Greece, Italy, Lebanon, Morocco, Portugal, Spain, Tunisia and Turkey.

6.6.3 Case studies

Based on the WOCAT classification of measures that address soil erosion and land degradation, the following is a successful example of a structure measure from Spain. Rodrigo-Comino et al. (2017) assessed agri-spillways as a soil erosion protection measure in Mediterranean sloping vineyards in southern Spain. Their results showed a great capacity by rills to canalize large amounts of water and sediments, and higher water flow speeds and sediment concentration rates than typically found in other Mediterranean areas and land uses (such as badlands, rangelands or extensive crops of olives and almonds). They concluded that agri-spillways can be a potential solution as an inexpensive method to protect the soil in sloping Mediterranean vineyards.

Another example for sustainable land management comes from Italy, a case of a vegetative measure. Bagagiolo et al. (2018) studied the effect of controlled grass cover on water and soil losses in different rain-fed sloping fields in northwestern Italy. Rainfall, runoff and erosion variables were monitored in hydraulically bounded vineyard plots, where the inter-rows were managed with tillage and grass cover. The grass cover proved to be effective in decreasing runoff and soil losses during most of the events, reducing soil losses especially when intense events occurred (i.e., during summer). Their results also showed the fundamental role of contour-slope row orientation in reducing runoff and soil losses, irrespective of the adopted inter-row soil management approach.

6.6.4 Innovation

Land Degradation Neutrality (LDN) is a new conceptual framework, introduced by the UNCCD to halt the loss of land due to unsustainable management and land use changes (Cowie et al. 2018). Its purpose is to maintain the land resource base so that it can continue to supply ecosystem services while enhancing the resilience of the communities that depend on the land (Metternicht et al. 2019). The LDN framework is designed to apply to all land uses and all types of land degradation. To achieve LDN, countries will need to assess the effect of land use decisions and undertake measures to restore degraded land so as to compensate anticipated losses (Cowie et al. 2018). The UNCCD suggests that countries should consider the social, economic and environmental outcomes of alternative land degradation and desertification mitigation options when planning LDN measures and should strive to engage relevant stakeholders. Some applications of the LDN framework have only just begun to materialize (e.g., in southeast Australia, Cowie et al. 2019), but none have yet been applied in Mediterranean countries or climates.

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[46] https://ec.europa.eu/environment/soil/index_en.htm

6.7 Heat waves

Temperature extremes occur on different time scales and need temporally high-resolution data to accurately assess possible changes (IPCC 2012). Temperature is associated with different types of extremes. It is of importance to distinguish between maximum, minimum and daily mean, as well as between cold and warm extremes, as they have different impacts on human health (*Sections 5.2.3* and *6.2*), the physical environment (Section 2.3), ecosystems *(Section 4.3)*, and energy consumption *(Section 3.3)*. Increases in the intensity, number, and length of heat waves have been reported for Mediterranean summers since the 1960s (Kuglitsch et al. 2010; Efthymiadis et al. 2011; Lelieveld et al. 2012) *(Section 2.2.4.1)*.

6.7.1 Future heat wave risks

Future projections for the Euro-Mediterranean area have shown spatial heterogeneity in increases in the intensity, frequency and duration of heat waves *(Section 2.2.4.2)*. Major increases in warm temperature extremes are expected across the Mediterranean region (Jacob et al. 2014; Russo et al. 2015; Zittis et al. 2016; Pereira et al. 2017) including hot days (T_{max} >30°C) and tropical nights (T_{min} >20°C) (Giannakopoulos et al. 2009; Tolika et al. 2012). Larger increases in intensity and duration are projected for southern Europe where heat wave days are projected to increase 20-fold by 2100 (Fischer and Schär 2010). Other projections over the Mediterranean include dramatic increases in the frequency of hot temperature extremes and heat stress by the end of the 21st century *(Section 2.2.4.2)*. Cities in southern Europe are expected to face longer heat waves (Guerreiro et al. 2018), thus increasing their vulnerability to climate impacts and the need for costly adaptation measures.

Projected changes in the characteristics of future heat waves are related to increasing risks in several sectors. Intense and long heat waves are related to increased morbidity and mortality in Mediterranean countries, especially in cities where the built environment amplifies the exposure to heat (*Sections 5.2.2.8* and *6.2*). Increasing temperatures affect overall energy demand for cooling, while heat waves may also affect peak demand that is mainly provided by electricity (EEA 2019a). The largest absolute increases in electricity peak demand are projected for Italy, Spain and France (Damm et al. 2017). The tourism sector plays an important role for the economic well-being and livelihoods of Mediterranean countries *(Section 5.1.1.3)*. Frequent heat waves may reduce tourist flows by the mid-21st century due to exceeded comfort levels (Hein et al. 2009) and could shift tourist demand outside the peak summer time (Perry 2003; Esteban-Talaya et al. 2005; Ciscar et al. 2009). Future increased extreme temperatures will increase the impact on transport infrastructure in the Mediterranean and will lead to damage to roads, rail, airports, and ports (Nemry and Demirel 2012; UNCTAD 2017; Vogel et al. 2017) with significant increases in adaptation costs (Nemry and Demirel 2012). High temperatures and drought will increase forest fire risk, which might lead to drastic damages in Mediterranean forests (Trigo et al. 2013; Gudmundsson et al. 2014; Turco et al. 2018) *(Section 4.3.2.1)*. High future temperatures and heat waves have a direct impact on crop growth conditions, crop productivity and crop distribution, agricultural pests and diseases, and the conditions for livestock production in the Mediterranean *(Section 3.2.1.4)*. These impacts will generate changing land-use patterns and will trigger economy-wide effects (Skuras and Psaltopoulos 2012). In southern Europe, yields for all the dominant (non-tropical) crops decreased by 5-60% because of climate change, depending on the country, the crop and the scenario *(Section 3.2.2.1)*. The combined effect of extreme heat events and shorter growing seasons will result in a loss of land suitable for agriculture (Fraga et al. 2016; Resco et al. 2016; EEA 2019b) in southern Europe (Section 3.2.2.1). Furthermore, the Mediterranean agro-climate zone is expected to experience pronounced increases in the areas affected by mild to strong heat stress, which will occur earlier and will impact winter wheat (Ceglar et al. 2019).

6.7.2 Management approaches, governance, and adaptation for heat wave risks

Reducing the direct impacts of extreme temperatures requires focus on information and preparedness associated with early warning (PPRD East 2013). The need for the implementation of early warning systems has risen since the 2003 summer heat wave (García-Herrera et al. 2010). Adaptation for heat waves in cities is a major challenge in design and costs estimation (Guerreiro et al. 2018). Prevention in the long term must further ensure that the vulnerability of the population and relevant infrastructure are reduced by improving urban planning and architecture (e.g., increasing the canopy cover in urban areas, cooling open public areas, adjustments in energy generation and transmission infrastructure), as well as through energy and transport policies (PPRD East 2013). Strategies are needed to reduce heat exposure of individuals and communities (especially vulnerable populations), to plan health and social services and infrastructure, and to provide timely information to the population (Future Earth 2019). Some of the adaptation measures for the projected changes entail fundamental, and expensive re-engineering of each city or water resource system. In the Mediterranean, significant adaptation measures to climate extremes, primarily in the form of structural protection measures, have already been implemented in the framework of the adaptation plans at the city, regional and national levels across the Mediterranean Basin.

6.8 River and pluvial flooding

6.8.1. Future flood risk

The Mediterranean region is characterized by numerous water courses with small and steep river catchments (Tarolli et al. 2012; Tramblay et al. 2019), although with notable exceptions, such as the Nile, Rhone, Ebro and Po rivers *(Section 3.1.1.1)*. The steep orography surrounding the Mediterranean Sea favors the occurrence of intense precipitation events triggered by spatially confined convective processes (Amponsah et al. 2018), especially in autumn (Gaume et al. 2016) *(Section 2.2.5)*. The resulting runoff can produce devastating flash floods in small river basins, i.e., less than 2,000–3,000 km² in size (Amponsah et al. 2018), especially where urbanized areas are located downstream of these small basins (Llasat et al. 2010; Gaume et al. 2016) *(Section 3.1.3.3)*.

The magnitude and impact of floods vary significantly over the Mediterranean region, with more frequent and severe events in the western part (Llasat et al. 2010; Gaume et al. 2016). Some sub-regions in southwestern Europe, including Liguria and Piedmont in Italy, Cévennes-Vivarais-Roussillon in France, and Catalonia and the province of Valencia in Spain are particularly prone to extremely severe events, due to geographic and climatological conditions (Gaume et al. 2016). Floods in Morocco, Algeria and Tunisia are less frequent but they are often associated with high mortality, while European countries suffer the highest economic damages (Llasat et al. 2010).

Trends in annual maximum peak flow in European Mediterranean countries have been decreasing in the past decades (Blöschl et al. 2019). However, no significant trend in the frequency and magnitude of extreme floods has been found for the Mediterranean as a whole (Gaume et al. 2016), or for large regions such as Catalonia and southern France (Llasat et al. 2005, 2014; Tramblay et al. 2019), even though local increasing trends have been observed (e.g., Genoa urban area, Faccini et al. 2018; *Section 3.1.3.3*). Future trends in flood patterns still appear unclear, with different studies reporting contrasting results (Kundzewicz et al. 2017), partly because of the limitations of regional- and global-scale models in representing small catchments (Tramblay et al. 2019) (*Sections 3.1.4.1* and *3.1.4.2*: Floods).

6.8.2 Management approaches, governance, and adaptation for flood protection

Flash flood risk management presents several challenges with respect to other types of flooding processes. The triggering meteorological and hydrological processes are difficult to monitor with traditional hydro-meteorological networks, given the small spatial and temporal scales involved (Amponsah et al. 2018). Moreover, flash flood risk can be associated with other hazards, particularly in mountain settings (e.g., landslides and debris flows). This complicates the implementation of forecasting and early warning systems as well as the design of physical flood defense infrastructure (Borga et al. 2011). Preparedness strategies need to be structured in accordance with these and other characteristics, such as short to negligible warning lead times, immediate threat to life and properties requiring quick response times, as well as the need for refuges and safe places (Borga et al. 2011). This requires effective coordination of response management by authorities and public awareness.

Good practices in flash flood risk management reported in the literature and applied in several case studies include: post-event surveys to collect information on flood-generating processes and impacts (Kreibich et al. 2017; Amponsah et al. 2018), development of dedicated early warning systems

(EWS) based on gauge and radar networks, numerical weather and hydrological predictions (Corral et al. 2019), construction of check dams and reforestation in upstream areas (Kourgialas and Karatzas 2017), floodplain restoration and bank erosion protection (Kourgialas and Karatzas 2017; Cortès et al. 2018), suitable agricultural practices to retain water and reduce flood damage to crops (Kourgialas and Karatzas 2017), improvement of drainage systems in urbanized areas (Cortès et al. 2018), increased citizen awareness (Borga et al. 2011; Cortès et al. 2018; Faccini et al. 2018), emergency management plans (Kreibich et al. 2017), and viable insurance schemes for damage compensation (Faccini et al. 2018).

6.8.3 Case studies and innovation

At the European level, the European Directive on Floods (Directive 2007/60/CE, European Parliament 2007) regulates flood risk management plans, focusing on prevention, protection and preparation. The implementation of the Floods Directive has driven notable improvements, also in flash flood risk management. According to Kreibich et al. (2017), vulnerability to flash floods was greatly reduced in recent events in Italy and Spain as compared to similar events that occurred several decades ago, due to improved awareness, preparedness and emergency management.

Cortès et al. (2018) report that in the Metropolitan Area of Barcelona, the implementation of prevention measures such as constructing rainwater tanks, or the establishment of warning systems, decreased the impacts of flood events between 1981 and 2015. Nowadays, different flash-flood forecasting systems are present in Catalonia (Spain), Liguria (Italy) and Southern France (Corral et al. 2019). Notably, the European Flood Awareness System (EFAS)[47] provides different flash flood indicators (Raynaud et al. 2015; Corral et al. 2019), and has recently been extended to the entire Mediterranean Basin, therefore offering the first pan-Mediterranean forecasting system for river and flash floods. Finally, in Spain and France, dedicated national insurance schemes against natural disasters exist, which cover losses through economic compensation.

However, not all Mediterranean areas benefit from recent advances. Information on flood hazard and risk is missing or scarce in some southern and eastern Mediterranean countries (Llasat et al. 2010), as well as in small and ungauged catchments in Europe (Kourgialas and Karatzas 2017). Adaptation plans in southern Europe suffer from a lack of funding in rural and low-populated areas (Aguiar et al. 2018). Challenges are still present even in large cities. For example, the city of Genoa, Italy, is particularly exposed to flash floods due to its geographical location, meteorological conditions and dense urbanization with inadequate planning (e.g., reduced or culverted river network in the river valleys) (Faccini et al. 2018). While progress has been made in increasing citizen awareness and improving early warning systems, structural solutions (e.g., diversion channels, relocation of the most exposed properties) appear unfeasible due to the large areas involved.

6.9 Sea-level rise: coastal erosion and flooding, saltwater intrusion

6.9.1 Future risk associated with sea-level rise

Mediterranean mean sea levels are projected to rise by 21 to 27 cm by 2050, under RCP4.5 and RCP8.5 scenarios, respectively (Jackson and Jevrejeva 2016; Jevrejeva et al. 2016). By the end of the century, the mean sea level would range between 20 cm and 110 cm above the present level (1980-1999), depending on the greenhouse gas emission scenario and the modeling system *(Section 2.2.8.2)*. Such sea-level rise, combined with variations in extreme weather and thus waves and storm surges, will substantially increase the frequency of extreme events as the present day event of the century is expected to occur every 10 years by 2050 and at least yearly by the end of the century (Vousdoukas et al. 2018b). All the above changes are projected to expose Mediterranean societies to unprecedented levels of coastal flooding and losses. Without considering socio-economic development, a 6 to 8-fold increase in annual damage is expected by 2050 and at least 25 times more annual damage is expected by the end of the century if no further investments in coastal protection are undertaken (Vousdoukas et al. 2018a). When climate change projections are combined with socio-economic scenarios, expected annual damage is projected to rise by 90 to 900 times, depending on

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[47] https://www.efas.eu/

the scenario. Adaptation in the form of dykes can cut damage costs in half, with countries such as France, Spain, Greece, and Italy having the highest damage costs in absolute terms (Hinkel et al. 2010), and Egypt and Tunisia facing the highest damages relative to their annual Gross Domestic Product (GDP) (Hinkel et al. 2012). Accordingly, Italy and France have the largest length of coasts where protection would be economically beneficial (Vousdoukas et al. 2020).

Most coastal regions globally are exposed on a daily basis to tidal water level variations of more than 50 cm, and ocean waves, which require wider active beach zones to act as a buffer against the ocean's forces. This is not the case in the Mediterranean, which is a micro-tidal area where a significant part of the coastline is not exposed to harsh marine storms *(Section 2.2.8)*. The above-mentioned characteristic makes the Mediterranean more susceptible to coastal hazards in view of climate change compared to other parts of the world. It is important to highlight that for many Mediterranean locations; the projected sea-level rise is of similar magnitude to the increase in sea levels during extreme events. At the same time, communities have developed lifestyles adapted to non-dynamic water levels, as several activities take place and infrastructure is located in close proximity to the sea (within few meters in many cases). This is also because apart from local-scale erosion, the coastline has been relatively stable for global standards with the exception of some cases of stronger shoreline retreat trends, observed in the Nile delta, Tunisia, Venice, and Albania (Luijendijk et al. 2018; Mentaschi et al. 2018).

Finally, interconnected hazards may exacerbate issues related to sea-level rise. For example, while the coastal environment encompasses particular characteristics distinct from general issues of water (such as shortages and drought) and precipitation (or lack thereof), there are numerous interconnections between water runoff, drainage and watershed management that are linked to hazards related to sea-level rise (O'Connor et al. 2009; Lichter and Felsenstein 2012; Portman 2018). Such hazards may result in compound effects that can lead to non-linear increases in the magnitude of individual hazards.

6.9.2 Management approaches, governance, and adaptation for coastal protection

It is important to highlight that coastal erosion in Mediterranean countries has been primarily driven by human interference with natural processes *(Section 4.2.1)*. For example, inadequate coastal management practices and, most importantly, unregulated construction have been reported in several regions (ERML 2012; de Leo et al. 2017; UNDP 2017). A recurring problem is the reduction or depletion of terrestrial sediment supply, that would naturally feed sandy beaches, resulting from the construction of upstream dams (Poulos and Collins 2002) *(Section 4.2.1.2)*. Such examples include the Beni Khiar and Dar Chaabane coasts and the Oued El Kebir river (Imen and Souissi 2018), Lesvos Island (Velegrakis et al. 2008), and Rhodope, Greece (Xeidakis et al. 2006).

Coastal adaptation practices can be classified into the following broad categories: protect, accommodate, advance, and retreat. Under protection practices, societies tend to "hold the line" by installing coastal protection elements. Traditionally these were mainly "hard structures" such as breakwaters and seawalls (Lamberti and Zanuttigh 2005). Dykes are another potential flood prevention solution, but they are very rare in the Mediterranean, as they are more common in meso-/macro-tidal environments. The same applies for surge barriers, with the only example being the MOSE system in Venice (CVN 2019). Submerged breakwaters reduce wave energy and mitigate erosion and have also become common practice along the Mediterranean coastline (Tomasicchio 1996; Sancho-García et al. 2013; Bouvier et al. 2017).

"Soft-protection", in the form of beach and shore nourishment as well as dune or wetland restoration, has become a more common alternative to hard structures in recent decades, with many examples, especially in France, Spain and Italy (Hamm et al. 1998; Hanson et al. 2002). Lately there is a tendency towards Ecosystem-based Adaptation (EbA) *(Section 4.2.3.5)*, also referred to as "soft protection", using ecological features such as reefs and/or coastal vegetation as coastal protection elements. Among the few examples of EbA is the coastal protection service provided by the Étang de Vic coastal lagoon in France (Conservatoire du littoral)[48] and the coastal dune reconstruction at the natural protection area of the Bevano river mouth in Emilia Romagna (Italy) (Giambastiani et al. 2016).

Until recently, advances through land reclamation has been more related to the need for more space to accommodate human activities (Mentaschi et al. 2018), but is also being increasingly considered

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[48] http://www.conservatoire-du-littoral.fr/siteLittoral/106/28-etang-de-vic-34_herault.htm

in the context of adaptation to sea-level rise. However, this practice is practically non-existent in the Mediterranean Sea. The same can be argued for accommodation i.e., increasing the resilience of infrastructure by making it less vulnerable to flooding. Recent studies have shown that flood fatalities have been reduced as societies are learning to live with flood hazards (Bouwer and Jonkman 2018), while there have been efforts to develop and implement Early Warning Systems for disaster risk reduction (Ciavola et al. 2011; Harley et al. 2011; Fernández-Montblanc et al. 2019). However, there are very few, if any, examples of large-scale efforts to develop flood-resilient buildings around the Mediterranean coastline. The same applies to the retreat option in which exposure to coastal hazard is reduced by removing assets and people from potentially vulnerable areas.

6.9.3 Case studies

Hard protection structures can be found all along the Mediterranean coastline and in most cases they contribute to sustaining a safe and functional coastal zone (Iskander et al. 2007; Becchi et al. 2014). However, as it has been already pointed out in other parts of the world (Cooper and Pilkey 2012), this comes at a price. Hard protection can alter nearshore sediment transport patterns and result in beach erosion. Such side effects have been observed in Greece and Cyprus (Tsoukala et al. 2015), Tunisia (Saïdi et al. 2012), and Egypt (Masria et al. 2015). In addition, hard structures can affect the nearshore ecology, as they can act as habitats for species which normally thrive in rocky shores (Munari et al. 2011). However such effects have been shown to depend on local conditions and not to be overwhelming (Colosio et al. 2007; Becchi et al. 2014).

There have been several beach nourishment projects along the Mediterranean coastline, some of which have been reported in the scientific literature (Hamm et al. 1998; Hanson et al. 2002; Masria et al. 2015) *(Section 4.2.1.1)*. These initiatives are ecologically milder but can still come with negative impacts (Colosio et al. 2007). For example, nourishment at Poniente Beach (Benidorm, Spain) has been shown to have caused the disappearance of the *Posidonia oceanica* meadows, which resulted in a strong beach erosion process (Aragonés et al. 2015). However, there are several studies which report that small-scale beach nourishments appear to be an eco-sustainable approach to combat coastal erosion (Borg et al. 2006; Danovaro et al. 2018). Geotextiles have been installed in several locations as a soft protection practice, but information on their performance is limited in the scientific literature with a few exceptions, such as the positive outcome in Lido de Sete, in France (Balouin et al. 2015). It is important to highlight that most of the literature shows that no universal solution exists and that robust planning and implementation is a prerequisite for any successful intervention.

6.9.4 Innovation

Risk and climate change adaptation efforts are inextricably linked. Having acknowledged risks, some countries have developed either "resilience toolkits" (e.g., US) or "adaptation toolkits" (e.g., Ireland) that address how civil society must prepare for hazards, with emphasis on coastal areas (Paterson et al. 2017; McDermott and Surminski 2018; Gardiner et al. 2019). Most Mediterranean countries are lagging behind in this respect. Recently there has been significant work on at least assessment of future risks pertaining to air, water, and sea (Navarra and Tubiana 2013). However, little has been done on the aspects of extreme hazards and the effects of climate change on society, which could encourage more resources (both human and financial) being dedicated to adaptation planning. Nevertheless, some examples of such actions exist. Countries such as Italy, France and Spain have established national and subnational initiatives on coastal adaptation and management[49]) (Losada et al. 2019) while multi-national initiatives such as the Bologna Charter[50] have introduced action plans for the protection and sustainable development of coastal areas in the region through e.g., the establishment of a network of coastal observatories.

At the same time, interconnections between different types of hazards need to be addressed in research, planning and management for adaptation. To some extent, such interconnections are recognized and have led to initiatives. One example is the DANUBIUS-RI (Bradley et al. 2018), which is a platform designed to support interdisciplinary research on rivers and seas by facilitating biogeochemical monitoring while also spanning various aspects of environmental, social and economic sciences. These types of initiatives will no doubt support projects and future risk assessments related to climate change.

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[49] www.erosionecostiera.isprambiente.it

[50] www.bolognacharter.eu

There is still a lack of information on the risks associated with the economic, livelihood and cultural consequences of coastal change (Reimann et al. 2018b) at the regional scale that would encourage progress towards the international and transboundary cooperation needed to address these challenges among Mediterranean countries. Transboundary cooperation is particularly difficult in the deep-sea areas, far from national jurisdiction. In these areas, cooperation is voluntary, often temporary and malleable at best, and non-existent at worst, even though it is compulsory for EU Member States based on Directive 2014/89/EU. Beyond the EU Mediterranean space, cooperation is voluntary. Much more oversight, accountability and especially monitoring is needed internationally (Neumann and Unger 2019), particularly in the Mediterranean. With regard to climate change, the "Our Ocean" Conference series, which has a strong topical relationship with SDG 14, has adopted climate change as one of its six areas of action (others are: marine protected areas, sustainable fisheries, marine pollution, sustainable blue economy, and maritime security).

6.10 Seawater temperature anomalies and extremes

6.10.1 Future risk of marine heat waves

Marine heat waves are periods of extremely warm sea surface temperature that persist from days to months and can extend up to thousands of kilometers *(Section 2.2.7.1)*. Recently observed marine heat waves demonstrated the strong influence of extreme climate events on marine organisms, including mass mortalities and shifts in species ranges (Rosenzweig et al. 2008), but also economic impacts on fisheries and aquaculture *(Section 4.2.1.1)*. In coastal areas at regional scales, little is known about the propagation at depth of a warming signal detected in sea temperature surface conditions. This is due to the scarcity of continuous observational data sets over the long-term (>10 years) from surface down through the water column (+40 m depth). Analysis of in situ temperature data available from different coastal sites confirmed warming trends in deeper layers consistent with those reported for surface waters (Bensoussan et al. 2019a). Thus, the warming is not limited to the surface, but propagates into deep coastal water layers (up to 80 m depth). Importantly, this warming displays significant variability along the depth gradient depending on local thermal regimes and seasonal stratification dynamics (Garrabou et al. 2019a). Likewise, marine heat waves have been recorded along depths with different intensity and duration depending on the years and concerned areas (Bensoussan et al. 2019b). Sustained observation in pilot sites will provide important information to validate models and track subsurface warming trends.

Like their atmospheric counterpart, Mediterranean marine heat waves are expected to increase in intensity, frequency and duration under anthropogenic climate change *(Section 2.2.7.2)* (Coumou and Rahmstorf 2012; Oliver et al. 2018). Darmaraki et al. (2019) used ensemble set of fully coupled Regional Climate Models (RCMs) from the Med-CORDEX initiative and a multi-scenario approach of different representative concentration pathways (RCPs), where marine heat waves become stronger and more intense under RCP4.5 and RCP8.5 than RCP2.6 by the year 2100. Under RCP8.5, a long-lasting Mediterranean marine heat wave appears at least once every year. Therefore, future marine heat waves appear up to three months longer, about four times more intense and 42 times more severe than at present *(Section 2.2.7.2)* and will affect the entire basin, predominantly in the warm and dry season from June to October. The main trigger can be attributed to the increase in the mean sea surface temperature (SST) and the daily SST variability. However, there is a lack of information on future trajectories of temperature conditions in coastal waters (from surface to 50 m depth and beyond) mainly due to the lack of customized modelling for these hydrodynamically complex areas. The results that are available point to an unambiguous increase in mean temperatures and frequency of extreme events, consistent with results obtained at the regional level (Garrabou et al. 2019b).

Current and future climate change trajectories are considered one of the major concerns for the conservation of marine biodiversity (Hughes et al. 2017; Cramer et al. 2018). In the Mediterranean, observed warming is already significantly affecting marine ecosystems (*Sections 4.1.1* and *4.2.1*), resulting in two main impacts: i) the shift in species distribution (indigenous and non–indigenous) and ii) the occurrence of unprecedented mass mortality events (MMEs). Besides these major impacts, other effects associated with warming are being reported as well, such as species proliferation and changes in species reproduction timing and migration patterns (Otero et al. 2013). Overall climate change is already dramatically affecting the abundance and distribution of species as well as the functioning of ecosystems (Sala et al. 2011; Givan et al. 2017; Cramer et al. 2018). It is difficult to foresee with precision to what extent the current climate trends will affect marine ecosystems and key species in the Mediterranean Sea in the coming decades. However, recent studies indicate that an increased extinction risk for endemic fauna, loss of habitat complexity and changes in ecosystem configurations is occurring (Ben Rais Lasram and Mouillot 2009; Ben Rais Lasram et al. 2010; Sala et al. 2011; Azzurro et al. 2019; Montero-Serra et al. 2019).

Three main patterns in species distribution associated with warming are being observed: i) northward expansion are extremely clear for warm-affinity native species such as the bluefish, *Pomatotus saltarix* (Dulčić et al. 2005; Sabatés et al. 2012), whose Mediterranean distribution was historically restricted to the southern and eastern sectors of the basin (Whitehead et al. 1986); ii) distribution contraction of cold-water affinity species in the northern areas such as the sprat *Sprattus sprattus* (Margonski et al. 2010), whose populations have drastically declined since the 1990s in the northern Adriatic and the Gulf of Lion (Lloret et al. 2001; Grbec et al. 2002; Hidalgo et al. 2020), and finally iii) west-eastward expansion of non-indigenous warm-adapted species of tropical origin, which are expanding their presence in the Mediterranean (Raitsos et al. 2010; Azzurro and Bariche 2017; Azzurro et al. 2019), for instance the case of the rabbitfish *Siganus luridus* and *S. rivulatus*, which are rapidly expanding their distribution and increase in abundance at the expense of their native counterpart *Sarpa salpa* (Marras et al. 2015) (*Sections 2.5.1* and *4.1.1*).

6.10.2 Management approaches, governance, and adaptation for ocean warming

Monitoring marine heat waves leads to a better understanding of their development, drivers and characteristics. Monitoring of near-time sea-surface temperature based on satellite data is possible, while the use of oceanographic arrays could provide information about heat penetration in deeper ocean layers. In the Mediterranean Sea, "T-MEDNet" was created in 2010 to develop an observation network on climate change effects and to spread standard monitoring protocols on seawater temperature and biological indicators. To date, continuous, quality checked temperature series are available at >70 sites and different ocean depths (5 to 40 m; T-MedNet 2019). They also evaluate satellite-derived sea-surface temperatures to track Mediterranean marine heat waves in near real-time.

6.11 Ocean acidification

Ocean acidification acts together with other global changes (e.g., warming, seawater expansion) and with local changes (e.g., pollution, eutrophication) *(Section 2.2.9)*. These simultaneous pressures and stresses lead to interactive, complex and amplified impacts for species and ecosystems *(Section 4.1.1.1)*. Globally, a pH change of -0.08 has occurred, on average, in the acidity of the oceans since the industrial age began *(Section 2.2.9.1)*, i.e. a 30% increase in acidity. If we continue on our present course, this will lead to a -0.46 increase by the end of the century *(Section 2.2.9.2)*, representing a 5-fold increase in acidity (Kolbert 2014). The term "ocean(s)" here is inclusive, encompassing marine and brackish water systems, from the open ocean to coastal waters, with the latter reflecting the immediate interface of land activities affecting the ocean, which has numerous implications for both eutrophication and acidification.

One of the issues generally underlined regarding research, and management to some extent, is the problem of ocean acidification being overshadowed by other more immediate, tangible and high-profile issues affecting the marine environment, such as marine litter (Tiller et al. 2019) *(Section 2.3.2.3)*. This is also true in the Mediterranean region where the marine plastic and marine litter issue is quite acute and where there are tangible and significant effects on economic well-being (i.e., tourism), health and well-being (Portman and Brennan 2017; Portman et al. 2019).

It is difficult to carry out long-term realistic manipulations of CO_2 levels, and therefore scientists have used areas with naturally occurring high CO_2 levels to forecast the effects of ocean acidification. In an elaborate census offshore of Naples, Italy, divers collected data around deep-sea volcanic vents to find out which species, habitats and processes are resilient to and/or adversely affected by ocean acidification. At several hundred meters from the vents, scientists observed seaweeds of different types, sea cucumbers and urchins (by counting both sedentary flora and fauna and observing the movements of creatures). Closer to the vents, they observed that the number of species dropped. As pH levels dropped in proximity to the vents (indicating higher acidity), macroalgal habitats were found to be significantly altered. Also, mollusks or limpets, which came close to the vents, exhibited dissolved shells (e.g., with holes in them) (Porzio et al. 2011). Similar work has also been carried out more recently at Mediterranean sea vents by Vizzini et al. (2019).

With regard to close-to-shore systems, there are high levels of uncertainty about how coastal ecosystems will be affected by rapid ocean acidification caused by anthropogenic CO_2, due to a lack of data. However, further study is needed to investigate whether the observed response of macroalgal communities can be replicated in different seasons and from a range of geographical regions for incorporation into global modelling studies to predict the effects of CO_2 emissions on the Earth's ecosystems (Porzio et al. 2011).

6.11.1 Future risk of ocean acidification

On a global level, not specific to the Mediterranean, some effects of CO_2 absorption can be explored by researching conditions with lower pH (representing greater acidity) in waters near hydrothermal vents (Portman 2016). Hall-Spencer et al. (2008) found that typical rocky shore communities with abundant calcareous organisms shifted to communities lacking scleractinian corals with significant reductions in sea urchin and coralline algal abundance. To our knowledge, this is the first ecosystem-scale validation of predictions that these important groups of organisms are susceptible to elevated amounts of pCO_2. Seagrass production was highest in an area at mean pH 7.6 (1,827 µatm pCO_2) where coralline algal biomass was significantly reduced and gastropod shells were dissolving due to periods of carbonate sub-saturation.

Some work in the Mediterranean region has translated expected changes in ocean chemistry into impacts, first on marine and coastal ecosystems and then, through effects on services provided by these ecosystems to humans, into socio-economic costs using economic market and non-market valuation techniques (Rodrigues et al. 2013; Peled et al. 2018). Initial evaluations suggest that the important sectors affected are tourism and recreation, red coral extraction, and fisheries (both capture and aquaculture production) (Rodrigues et al. 2013) *(Section 4.1.2.1).*

One way to assess the future impacts of ocean acidification, especially socio-economic impacts, is through the assessment of ecosystem services. A number of general studies have looked at the effects of climate change including acidification. This includes studies by Canu et al. (2015) for the general Mediterranean and by Peled et al. (2018) for the eastern Mediterranean in particular. The advantage to such approaches is that they estimate the monetary value of maintaining elements of the environment that have the potential to reduce acidification. The problem is incorporating these approaches into policy so that there is practical application (Portman, 2013).

One of the most harmful effects of acidification will be on fisheries, which are increasingly important and threatened in the Mediterranean Sea. Lacoue-Labarthe et al. (2016) contend that ocean acidification should therefore be factored into fisheries and aquaculture management plans *(Section 4.1.3.4).* Recruitment and seed production present possible bottlenecks for shellfish aquaculture in the future since early life stages are vulnerable to acidification and warming. Although adult finfish seem able to withstand the projected increases in seawater CO_2, degradation of seabed habitats and increases in harmful blooms of algae and jellyfish might adversely affect fish stocks (Lacoue-Labarthe et al. 2016).

6.11.2 Management approaches, governance, and adaptation for ocean acidification

One approach that has been applied to encourage actions that will counter acidification is that of ecosystem services assessment. This approach aims to encourage action by evaluating the costs of inaction. Peled et al. (2018) did such an evaluation for the Israeli Exclusive Economic Zone. One advantage to their approach is that they account for permanent and temporary carbon sequestration and the use of Social Cost of Carbon (SCC) values. Overall, they find that within the context of ecosystem services, the biological component within the oceanic carbon cycle acts as a sink, which in its hypothetical absence would cause higher levels of CO_2 outgassing back to the atmosphere, potentially leading to greater acidification once gases are reabsorbed (Peled et al. 2018) *(Section 4.2.2.2).*

Kelly et al. (2011) posit that ocean acidification can be curbed by focusing more attention on local and regional actions within terrestrial watersheds. Ramajo et al. (2019) and others have suggested that seagrasses may provide "refugia" from ocean acidification for associated calcifying organisms, as their photosynthetic activity may raise pH above the thresholds for impacts on calcification and/or limit the time spent below some critical pH threshold.

6.12 Non-indigenous species: marine, freshwater, and terrestrial

6.12.1 Future risks associated with non-indigenous species

Non-indigenous species may be a significant threat to biodiversity, economies and human health globally (Early et al. 2016; Tobin 2018) *(Section 2.5)*. Climate change and projected climate-driven biome and thermal niche shifts, along with increases in trade and mobility, are the main drivers of non-indigenous species expansion globally (Early et al. 2016) and in the Mediterranean.

Today, the highest numbers of non-indigenous species have been recorded in high Human Development Index (HDI) and economically developed countries, which are also able to collect the most information and mobilize the best efforts to manage them (Early et al. 2016). Studies show that countries which are the biggest agricultural producers (such as China and the United States) could be the main potential sources of non-indigenous species and experience the largest negative impacts from future non-indigenous species introductions (Paini et al. 2016).

Future trends in geographical distributions of non-indigenous species intrusions are likely to differ considerably from current patterns *(Section 2.5.1.3)* (Early et al. 2016). Although the level of non-indigenous species will remain high in developed countries in the coming decades, they will increase substantially in developing countries where biodiversity may be high but capacity to manage non-indigenous species is low. Developing countries, especially Sub-Saharan African countries, could be the most vulnerable to non-indigenous species expansion (Paini et al. 2016). In such places, non-indigenous species will increasingly threaten human livelihoods.

Water-borne infectious diseases are strongly associated with freshwater non-indigenous species that are linked to changes in environmental conditions produced by climate change (*Sections 5.2.3.3* and *5.2.3.4*). Some pathogens including West Nile Virus, dengue, yellow fever virus, chikungunya fever virus, malaria sporozoan protists, filariasis and dirofilariasis nematodes, require aquatic arthropod vectors that are extending their range due to climate changes, at least on the northern rim of the Mediterranean *(Section 5.2.5.4)*.

The number of non-indigenous plants (Doblas-Miranda et al. 2017) in the Mediterranean Basin seems to be lower than in other European regions (Vilà et al. 2007; Gassó et al. 2012), probably due to environmental constraints, the long history of anthropogenic disturbances and the lower economic development of the region until recently (Castri et al. 1990; Vilà and Pujadas 2001). With regard to non-indigenous, the first vertebrates established in the Mediterranean Basin date back from the Neolithic period, although there has been an extraordinary increase in the rate of introduction of non-indigenous species since 1850 and especially in recent decades (Genovesi et al. 2009). Establishment success seems to be higher than in other Mediterranean-type climate regions of the world, at least for birds (Kark and Sol 2005). However, information related to non-native terrestrial invertebrates is largely unknown (Roques et al. 2009).

Introduction patterns of non-indigenous species differ considerably amongst groups, although they tend to mostly occupy anthropogenically modified habitats *(Section 2.5.2.1)*, while contrary to other regions of the world, natural and semi-natural woody habitats are relatively resistant to non-indigenous species (Vilà et al. 2007; Kark et al. 2009; Roques et al. 2009; Arianoutsou et al. 2010). As in other regions of the world, the increase in the establishment of non-indigenous species in the Mediterranean Basin will continue due to the increasing rate of transport of goods and people. Delays in the management response therefore suggest that non-indigenous species will become of even greater concern in the future. Currently, the information available on non-indigenous species in the Basin is not complete and the number of non-indigenous species across taxonomic groups is underestimated (DAISIE 2009). Detailed information on their distribution and ecological impacts is necessary to accurately determine the current status of non-indigenous species in the Mediterranean region.

The ecological and economic consequences of non-indigenous species introductions in terrestrial ecosystems of the Mediterranean Basin are beginning to emerge. Non-indigenous plants compete with indigenous species, decreasing local diversity and changing community composition (Vilà et al. 2006). Changes in ecosystem functioning have been less explored but include alterations in decomposition rates (Castro-Díez et al. 2009) and changes in soil carbon and nitrogen pools (Vilà et al. 2006). Even though the number of successful non-indigenous species seems to be higher in plants, the impacts of non-indigenous animals are not of lower magnitude. The presence of non-indigenous vertebrates poses severe threats to native biodiversity through competition for resources, predation and hybridization with native species, and economic impacts mainly through crop damage (Genovesi et al. 2009). Besides the lack of knowledge on the number of non-indigenous terrestrial invertebrates present in the Mediterranean Basin, most species established in Europe are known to be potential pests for agriculture and forestry products, while around 7% affect human and animal health (Roques et al. 2009). Their ecological consequences have received minor attention, although certain non-indigenous insect predators, such as *Linepithema humile* or *Harmonia axyridis,* are known to have a dramatic effect on native invertebrate communities (Angulo et al. 2011; Roy et al. 2011a, 2011b).

The Mediterranean Sea has a long history of anthropogenic activity and introduction of non-indigenous species and currently has a large number of them *(Section 2.5.1).* In recent years, the expansion of non-indigenous thermophilic species (that originally began started to enter the Mediterranean from the Indo-Pacific region during the 20th century) has been linked to climate-driven hydrographic changes. In the Mediterranean, non-indigenous thermophilic biota used to be restricted to the Levantine Basin, but are now found in the central and western basins (Occhipinti-Ambrogi and Galil 2010). The speed at which non-indigenous species are spreading in the Mediterranean Sea due to climate change is much faster than the actual increase in temperature, which is a great threat jeopardizing the future of biodiversity in the Mediterranean Sea (Raitsos et al. 2010).

Biodiversity hotspots are highly vulnerable to non-indigenous species given that many of the nations that harbor them have low management capacity (Early et al. 2016). This is likely to be the case in eastern Mediterranean countries that have experienced a 150% increase in the mean annual rate of species introductions since 1924. Studies of long-term data since 1924 of 149 warm-water non-indigenous species in the Mediterranean Sea show that the Lessepsian introductions has been amplified by the warming of the eastern Mediterranean Sea (Raitsos et al. 2010).

The freshwater ecosystems of the Mediterranean Basin are considered a biodiversity hotspot with a high level of endemism and small natural ranges of native fish vulnerable to extinction (Ribeiro and Leunda 2012). Aquatic non-indigenous species have the potential to cause cascading disruption in entire food webs, cause biodiversity loss and do economic harm (Thomaz et al. 2014). The spreading of non-indigenous species in Iberian Peninsula freshwater rivers is a potent threat to native freshwater populations. Studies in the southwestern Iberian Peninsula freshwater rivers show that the quantities of non-indigenous species were the best forecaster of the decline of native fish species (Hermoso et al. 2011). In addition, the risk of exotic pathogens is threatening European Mediterranean countries through a continued introduction of non-indigenous disease vectors and changing climate and environments (Medlock et al. 2012) *(Section 2.5.2.3).*

STAGE OF INTRODUCTION	STRATEGY
ARRIVAL	• Risk Analysis • International Standards • Inspection
ESTABLISHMENT	• Detection • Eradication
SPREAD	• Quarantine • Barrier Zone
IMPACT	• Suppression • Adaptation

Table 6.1 | Overview of stages of non-indigenous species introduction and potential management strategies (based on Lockwood et al. 2007; Tobin 2018).

6.12.2 Management approaches, governance, and adaptation for non-indigenous species

Patterns of introduction, magnitude and expansion of non-indigenous species are currently at the most rapid rate of change ever recorded in human history (Early et al. 2016). Only a minority of non-indigenous species succeed in establishing in their new locations and become a threat but those that do can result in billions of dollars in costs (Tobin 2018). As a result, management strategies continue to be an important element in global discussions on non-indigenous species. Central to best practice efforts in developing and implementing management frameworks is assessing the introduction stage of the species being addressed to identify the appropriate strategy *(Table 6.1)*.

6.12.3 Innovation

Effective management strategies often involve preventing the arrival of non-indigenous species from the onset. Advances in risk analysis have led to refined estimates of likely introduction pathways and the time at which the pathway is most likely to result in successful establishment (Gray 2016). This has led to more optimized allocation of limited inspection resources. Other advances in risk analysis include use of new technologies for detection and surveillance of non-indigenous species such as eDNA (Valentin et al. 2018) and utilizing bioeconomic models to formally consider ecological and economic links and dynamics that allow us to assess the costs of different management strategies (Lodge et al. 2016; Epanchin-Niell 2017). Finally, models of non-indigenous species distribution developed on their biological characteristics and climate suitability can potentially be used to predict susceptible areas (Mainali et al. 2015; Barbet-Massin et al. 2018).

6.13 Interactions of hazards, synergies and trade-offs between adaptation strategies and mitigation

The previous sections present the risks of the main hazards in the Mediterranean region, which are expected to increase in the future due to changes in environmental and societal conditions. Each section analyzes these hazards in isolation, without considering potential interactions. However, when two or more hazards occur at the same time, for example heavy precipitation coinciding with storm surge flooding, potential impacts increase due to compounding effects (Zscheischler et al. 2018), even in cases when none of the individual events is extreme. Also, cascading effects of hazards occurring in succession and overlapping temporally or spatially (de Ruiter et al. 2020), such as heavy precipitation triggering landslides, can lead to increased impacts (Gallina et al. 2016; Terzi et al. 2019). To cope with the impacts of compound and consecutive events, a holistic approach to future risk is needed that considers the interaction between hazards and identifies management and adaptation practices that can be successful in coping with a wide range of hazards. Such approaches build socio-ecological resilience, preparing society for future environmental change in a sustainable manner.

A large number of the management and adaptation measures discussed for a single hazard or sector present synergies with other hazards or sectors. For instance, the implementation of green roofs against heat stress *(Section 6.2.2)* additionally increases infiltration during flood events. Similarly, managing agricultural drought by using agroforestry systems *(Section 6.4.2)* increases shade thus decreasing heat stress, decreases soil erosion due to a deeper penetration of roots, and has a positive effect on the water balance, which can counteract water scarcity. However, some strategies can lead to trade-offs with other hazards or sectors. While Ecosystem-based Adaptation (EbA) can be a successful strategy against sea-level rise-related hazards *(Section 6.9.2)* and can, at the same time, provide health benefits to the population, EbA measures have high space needs and are therefore only applicable to a limited degree in urban locations (Temmerman et al. 2013). Another example is the use of desalination plants for managing water scarcity *(Section 6.4.2)*, which can lead to severe soil contamination. Examples of potential synergies and tradeoffs between adaptation measures are presented in *Table 6.2*.

The majority of strategies discussed above have positive effects on mitigation. Water-sensitive urban design (WSUD), sustainable land management and EbA, and other strategies have the potential to enhance CO_2 sequestration due to an increase in biomass. Such primarily nature-based strategies manage and protect ecosystems and their functions. Nature-based solutions can increase socio-ecological resilience in a wide range of contexts as these strategies, along with the concept of ecosystem services, further help to raise awareness regarding the importance of ecosys-

ADAPTATION STRATEGY	HAZARDS: SYNERGIES (+) & TRADE-OFFS (-)	SYNERGIES (+) & TRADE-OFFS (-) WITH MITIGATION
URBAN PLANNING		
Green roofs	+ Reduces heat stress + Increases infiltration during floods + Health benefits	+ Increases CO_2 sequestration in biomass
Increase in canopy cover in cities	+ Reduces heat stress + Increases infiltration during floods	+ Increases CO_2 sequestration in biomass
Water-sensitive urban design (WSUD), e.g., retention pools	+ Counteracts water scarcity + Counteracts salt water intrusion + Counteracts soil erosion + Increases infiltration during floods	+ Increases CO_2 sequestration due to more open/green space
Hard protection, e.g., sea walls	+ Protects from sea-level rise impacts - Potential increase in river/pluvial flood risk due to damming effects	- Energy intensive production
NATURE-BASED SOLUTIONS		
Conservation agriculture	+ Counteracts agricultural drought + Reduces soil erosion	+ Increases CO_2 sequestration in soils
Agroforestry systems	+ Counteracts agricultural drought + Shade reduces heat stress + Deeper penetration of roots counteracts soil erosion + Positive effect on water balance	+ Increases CO_2 sequestration in biomass
Sustainable land management, e.g., green cover	+ Counteracts soil erosion and desertification + Increases infiltration during floods + Increases water storage capacity	+ Increases CO_2 sequestration in biomass
Prescribed fire techniques	+ Reduce wildfire risk - Difficult to implement due to high amount of private property	+ Avoid large wildfires and so increase CO_2 sequestration potential in biomass
Reforestation in upstream areas	+ Reduces river flooding + Reduces soil erosion - Increases fuel biomass for wildfires	+ Increases CO_2 sequestration in biomass
Ecosystem-based Adaptation (EbA)	+ Protects from sea-level rise impacts + Health benefits - High space needs: applicable in selected locations only	+ Increases CO_2 sequestration in biomass
ENGINEERED SOLUTIONS		
Desalination of sea water	+ Counteracts water scarcity - Soil contamination	- Energy intensive process
PUBLIC OUTREACH		
Early warning systems (EWS), e.g., the European Flood Awareness System EFAS	+ Warn against multiple hazards, especially extremes, e.g., wildfires, coastal and river flooding, heat stress	
Awareness raising through ecosystem service assessment	+ Potential to reduce ocean acidification + Increases EbA via ecosystem conservation	- Increases CO_2 sequestration in biomass (if ecosystems conserved)

Table 6.2 | Selected adaptation strategies discussed in this chapter grouped by type of strategy, along with synergies and/or trade-offs with other hazards/sectors, and climate mitigation.

tems as an adaptation strategy, with positive effects on human well-being (Keesstra et al. 2018; Seddon et al. 2019). On the other hand, a number of adaptation strategies are energy-intensive and their implementation may lead to an increase in greenhouse gas emissions. Examples are the use of desalination plants or the construction of hard protection measures against sea-level rise.

The potential synergies and trade-offs of adaptation strategies with mitigation illustrate the importance of developing integrated policies for responding to future risks that incorporate adaptation and mitigation strategies *(Section 5.1.3.1)*. This would allow synergies to be harnessed more strategically while, at the same time, avoiding potential trade-offs between mitigation and adaptation practices. In a study assessing adaptation and mitigation plans in European cities, Reckien et al. (2018) found that only a few Mediterranean cities have local climate plans that consider both mitigation and adaptation in a joint manner. These cities were primarily located in France, with a small number of cities in Spain. In most other European Mediterranean countries, the majority of cities have climate plans for mitigation only, very few for adaptation only, and some do not have any climate plans at all. Assuming that this finding can be transferred to southern and eastern Mediterranean countries, there is an urgent need for such local climate plans. Cities, in particular, need to become more resilient to environmental change as impacts will be disproportionally high in these locations due to the concentration of population and assets in combination with hazard-amplifying conditions (e.g., increased run-off through soil sealing, urban heat island effect (Rosenzweig et al. 2010).

A number of region-wide concerns and needs are raised across the chapter that, if addressed, can promote socio-ecological resilience and sustainable development in the entire region. Long-term monitoring data are missing in many parts of the basin, with particularly large differences in monitoring and reporting schemes between northern (EU), eastern, and southern countries of the region. There is also a need for advancing (climate) modeling techniques such as the representation of small river catchments, the short-term prediction of extreme events (e.g., heat, flooding), and improvements in seasonal forecasts. Furthermore, public participation in the development and implementation of management and adaptation strategies is important for their success. Stakeholders need to be involved in this process right from the start to increase local relevance and acceptance of the proposed strategies, thus facilitating implementation. Sharing and including local knowledge in the process is of prime importance in building a resilient society in a sustainable manner (Oppenheimer et al. 2019). Low-effort and low-cost strategies, e.g., promoting household-level adaptation, can play an important role in increasing resilience and coping with risk in the near future (Koerth et al. 2013b, 2013a).

Although national and local strategies are essential and successful in coping with risk and in increasing resilience, integrated management and adaptation approaches that treat multiple hazards in a holistic manner are required to address the above-stated concerns. Such approaches can be initiated in a top-down manner through region-wide policies such as the Barcelona Convention. The Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, established in 1976, provides a suitable basis for devising Mediterranean-wide policies. It was updated in 1995 and sets the basis for the Mediterranean Action Plan that is part of the UNEP Regional Seas Programme. One of its goals is to promote integrated management of the Mediterranean coastal zone. Considerable efforts have been undertaken in recent years with the aim to facilitate basin-wide planning and management such as the Protocol on Integrated Coastal Zone Management in the Mediterranean (UNEP/MAP/PAP 2008), the Mediterranean Strategy for Sustainable Development 2016-2025 (UNEP/MAP 2016) and the Regional Climate Change Adaptation Framework for the Mediterranean Marine and Coastal Areas (UNEP/MAP 2017) *(Section 5.1.1.2)*. These policy documents explicitly state the need for developing climate-resilient cities, acknowledging the importance of ecosystems for climate adaptation and mitigation, and enhancing regional and cross-border cooperation to promote sustainable development in the region (Benoit and Comeau 2005; UNEP/MAP 2012, 2016, 2017).

Active participation in regional-to-global initiatives and networks concerned with building socio-ecological resilience can be an additional important step forward. The "C40 Cities" network is concerned with achieving the goals of the Paris Agreement and currently has six members from the Mediterranean region (Barcelona, Rome, Venice, Athens, Istanbul, Tel Aviv). The "100 Resilient Cities" network aims to increase cities' resilience to a wide range of hazards, including drought, extreme heat, sea-level rise, but also other societal challenges such as corruption, demographic change, and poverty. Currently, ten Mediterranean cities are part of the network, including six from the northern Mediterranean and four from the South and East. Such initiatives can foster knowledge exchange, provide funding for specific projects, and promote ambitious action against climate and environmental change.

Lastly, the transfer of scientific knowledge to policy-making needs to be facilitated, for instance with the help of policy briefs and so-called "resilience toolkits" (such as RISC-KIT for coastal resilience[51]) in order to support well-informed decisions. Similarly, knowledge transfer concerning environmental issues and sustainable development needs to be an integral part of the curriculum in primary and secondary education, therefore increasing awareness and establishing sustainable lifestyles as a social norm (Otto et al. 2020).

This chapter illustrates that future risks in the Mediterranean region will be determined by hazard characteristics (intensity and frequency) and by developments in socio-economic conditions that determine a society's adaptive capacity to cope with those hazards. The level of risk will largely depend on how soon and how effectively sustainable development is pursued. With the tourism sector being a large source of revenue in most parts of the region, transforming this sector will be particularly challenging. War and social unrest pose an additional, currently more pressing challenge in several countries in the Middle East and North Africa. These current developments may lead to a widening of the development gap between northern, southern, and eastern countries of the region. Therefore, developing joint, region-wide, and integrated management and adaptation approaches that treat multiple hazards in a holistic manner is of utmost importance for sustainable development in the entire region. Nonetheless, no one-size-fits-all strategy exists, and each measure needs to be tailored to the respective local conditions.

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[51] www.risckit.eu

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APPENDIX

Appendix to Chapter 1 Introduction

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This chapter should be cited as: Lange MA, Llasat MC, Snoussi M, Graves A, Le Tellier J, Queralt A, Vagliasindi GM 2020 Introduction. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 589-598.*

A.1 MedECC Partners

In December 2017 the Secretariat of the Union for the Mediterranean (UfM) signed an agreement with the Plan Bleu Regional Activity Centre (UNEP/MAP) to jointly support MedECC. The MedECC Secretariat is supported and funded by UfM, through a grant provided by the Swedish International Development Cooperation Agency (SIDA), hosted by Plan Bleu in Marseille, France.

MedECC is also supported by: the French Agency for Ecological Transition (ADEME), Mediterranean Integrated Studies at Regional And Local Scales (MISTRALS), the Principality of Monaco, the Advisory Council for the Sustainable Development of Catalonia of the Government of Catalonia (CADS, Spain), Métropole Aix-Marseille Provence (France), Laboratory of Excellence OT-Med, Aix-Marseille University (France), the French National Research Institute for Sustainable Development (IRD), Association for Innovation and Research in Climate (AIR Climat, France) et ACTERRA Consulting (France).

The Union for the Mediterranean (UfM) is an intergovernmental institution created in 2008 which brings together all 28 countries of the European Union and 15 countries of the southern and eastern Mediterranean. UfM's mission is to enhance regional cooperation, dialogue and the implementation of projects and initiatives with tangible impact on citizens, addressing three strategic objectives: stability, human development and integration. The UfM Climate Change Expert Group (UfM CCEG) was established at the first UfM Ministerial Meeting on Environment and Climate Change in May 2014 in Athens, Greece. The UfM Ministerial Declaration of Athens expressed the need for a regional vulnerability assessment regarding climate change impacts in the Mediterranean. The role of the UfM CCEG is to advance discussions on climate change priority actions and accelerate the identification and development of concrete projects and initiatives. UfM CCEG has approved a Work Program (2017-2022) in which a specific activity "To promote a regional science-based consensus on climate impacts in the UfM region especially on the Mediterranean Basin" was included. The work undertaken by MedECC responds to this activity and is therefore supported by UfM under its Ministerial mandate.

Administered by the **United Nations Environment Programme (UNEP)** for more than four decades as the first Convention of its Regional Seas Programme and as a regional Multilateral Environmental Agreement, the **Mediterranean Action Plan (MAP)** was approved in 1975 by the Mediterranean States and the European Union (EU) and was amended in 1995 after the Rio Summit to better reflect the integrated approach and indivisible nature of sustainable development. The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention) was adopted in its original form in 1976 and amended in 1995 as a response to the MAP's revision. Today the UNEP/MAP – Barcelona Convention system represents the unique legally binding regime dedicated to the protection, depollution and preservation of the Mediterranean Sea and coast, and to sustainable development of its coastal area. The Barcelona Convention's 22 Contracting Parties adopted the Mediterranean Strategy for Sustainable Development (MSSD) in February 2016 at their 19th Meeting held in Greece, Athens, as a strategic guiding document for all stakeholders and partners to translate the 2030 Agenda for Sustainable Development (2030 Agenda) at regional, sub-regional and national levels. The MSSD provides an integrative policy framework for securing a sustainable future for the Mediterranean region consistent with the Sustainable Development Goals (SDGs). The creation of MedECC responds to needs and intentions expressed by the MSSD, in particular under the Flagship Initiative of its Objective 3 "Addressing climate change as a priority issue for the Mediterranean", which reads as follows: "Establish a regional science-policy interface mechanism, including the social and behavioral sciences, endorsed by all the Contracting Parties to the Barcelona Convention, with a view to preparing consolidated regional scientific assessments and guidance on climate change trends, impacts and adaptation and mitigation options".

Plan Bleu is one the UNEP/MAP Regional Activity Centers, located in Sophia-Antipolis and Marseille (France). Its program of work is approved every two years by the Contracting Parties to the Barcelona Convention. The main objective of Plan Bleu is to raise awareness of Mediterranean stakeholders and decision makers regarding environment and sustainable development issues in the region, through the following activities: a) Observing interactions between environment and development to support decision makers; b) Shaping possible futures for sustainable development (prospective studies, scenario building); c) Monitoring the implementation of the Mediterranean Strategy for

Sustainable Development; d) Integrating climate change as a priority; e) Supporting the transition towards a green and blue economy; f) Offering a socio-economic perspective for the appropriate management of Mediterranean resources.

MedECC has taken an active role as co-lead of the Climate Change chapter in the recent State of the Environment and Development Report (SoED 2019) coordinated by Plan Bleu.

The French **Research Institute for Sustainable Development** (IRD – *Institut de Recherche pour le Développement*) is a key French player on the international development agenda working primarily in partnership with Mediterranean and inter-tropical countries. It is based on the principle that scientific progress is necessary to further sustainable and human development, and uses an original model: equitable scientific partnership with developing countries to co-design solutions adapted to the challenges faced by humans and the planet, including pandemics, climate change, humanitarian and political crises, etc. It has been able to make an important contribution to MedECC thanks to its network and presence in fifty or so countries encouraging science and innovation as key drivers in their development.

The **Advisory Council for Sustainable Development of Catalonia** of the Government of Catalonia (CADS) is the advisory body on sustainability of the Catalan Government, whose main aim is to be an effective and successful interface between scientists, policymakers and stakeholders. The council is an active member of the European Environment and Sustainable Development Advisory Councils (EEAC), a network of advisory bodies established by national or regional governments or parliaments. Since 2005, CADS has overseen the elaboration of the periodic Report on Climate Change in Catalonia. The 3rd edition was published in September 2016 and involved 150 experts and more than 40 reviewers. A 4th edition is under preparation.

The **Ministry of Foreign Affairs and Cooperation of the Principality of Monaco** manages public policy in the following areas: immunity, diplomatic channels and consular affairs, European affairs, international and multilateral affairs and international environment.

The **French Agency for Ecological Transition (ADEME)** is active in the implementation of public policy in the areas of the environment, energy and sustainable development. ADEME provides expertise and advisory services to businesses, local authorities and communities, government bodies and the public at large, to enable them to establish and consolidate their environmental action. As part of this work the agency helps finance projects, from research to implementation, in its areas of action.

The **Association for Innovation and Research in Climate (AIR Climat)** aims to contribute to awareness-raising on climate change issues and to help, through research and innovation, to implement new solutions in the field of carbon economy, lifestyles and their evolution. AIR Climat brings together climate change scientists and technicians. The association leads the Regional Group of Experts on Climate in the "South Region" of France (Région Sud – Provence-Alpes-Cote d'Azur), GREC-SUD, which aims to centralize, transcribe and share scientific knowledge on climate and climate change in the region. The priority objective of the group is to inform decision makers (elected representatives, local authorities) of the territory, so that scientific results are considered in public policies. Eight thematic booklets on climate change in the region have been published so far.

ACTERRA is a consultancy firm dedicated to environmental policy and climate change. ACTERRA has expertise in designing and implementing adaptation measures at different scales: strategic approaches and institutions at international and national level, regional and interregional initiatives, research and consulting for local authorities, operational actions at local level, etc., in particular in southern Mediterranean countries.

Labex OT-Med *(Objectif Terre – Bassin Méditerranéen)* is a "Laboratoire d'excellence" (LABEX) selected by the French "Investissements d'Avenir" program that brings together 10 research laboratories and 1 research federation specialized in different fields: a) environmental sciences, law, economy and social sciences; b) global change and natural hazards in the Mediterranean Basin.

MedECC has also obtained support from the **MISTRALS** program (Mediterranean Integrated STudies at Regional And Local Scales). The main objective of this program is to bring together French researchers and to reinforce international collaboration between Mediterranean countries. MISTRALS is led by CNRS, with strong partnerships with several other French research institutions. The MedECC network of experts allows the dissemination of scientific results to stakeholders, policymakers and managers to help them address societal, environmental and economic challenges for the sustainable development of Mediterranean countries. MISTRALS addresses the following scientific questions, all of them included in the scientific objectives of MedECC: a) Links between past climate variability and evolution of Mediterranean civilizations and societies; b) Hydrological cycle in the Mediterranean and extreme rainfall events; c) Evolution of marine biogeochemistry under climate change and anthropogenic pressure; impacts on marine ecosystems; d) Change in atmospheric composition and air quality under climate change and anthropogenic pressure and impacts on health; e) Monitoring continental and marine biodiversity and their sensitivity to climate change and anthropogenic pressure; f) Changes in continental surfaces, from urban to countryside regions under climate change and anthropogenic pressure. Action b, in particular, is the objective of the research program HYMEX (Hydrological and Mediterranean Experiment) that has a strong relationship with MedECC, with some members of both corresponding steering committees and authors of this MAR1 report in common.

A similar relationship is maintained with **MEDCLIVAR** (Mediterranean Climate Variability and Predictability), which is a scientific network endorsed by the international CLIVAR Office, to promote better communication among different scientific disciplines and develop a multidisciplinary vision of the evolution of the Mediterranean climate through studies that integrate atmospheric, marine, and terrestrial climate components at time scales ranging from paleo-reconstructions to future climate scenarios.

A.2 Research activities in the Mediterranean region

A number of past and ongoing research programs and projects have objectives relating to the MedECC assessment process. The following compilation lists some of them, without attempting to be complete.

- The Mediterranean Experiment (MEDEX) is focused on cyclones in the Mediterranean, their impact and forecasting (Jansa et al. 2014).
- The Hydrological Mediterranean Experiment (HyMEX) aims to elucidate the hydrological cycle in the Mediterranean, with emphasis on extreme weather events, inter-annual to decadal variability of the coupled Mediterranean system, and associated trends in the context of global change (Drobinski et al. 2014).
- The Med-CORDEX initiative attempts to downscale global climate scenarios in the Mediterranean (Ruti et al. 2016).

Other large collaborative scientific projects and networks do exist and are actively engaged in enhancing the necessary scientific knowledge base, often through a multidisciplinary and integrated approach (i.e. CIRCE-Climate Change and Impact Research: the Mediterranean Environment). The MedCLIVAR network is a case in point. Results of the investigations have been published in three books (Bolle 2003; Lionello et al. 2006; Lionello 2012) and numerous scientific articles. While often conceived as scientific platforms for better communication and cooperation among scientists, these projects, networks and initiatives and their results are usually not easily accessible to decision- and policymakers.

The recent assessment reports of the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES) provide useful knowledge but they have not provided an integrated view on the Mediterranean Basin. These assessments cover only parts of the region in disconnected chapters or only some of the relevant topics (e.g. climate variability). In close cooperation with MedECC, the forthcoming Sixth Assessment Report of the IPCC will contain, for the first time, a "Cross-Chapter Paper" dedicated to the Mediterranean Basin.

A.3 Institutional context of MedECC

The origin of the MedECC initiative can be traced back to a meeting of the MedCOP 21 in Marseille, France, on 4-5 June 2015. In the context of the "Agenda of Positive Solutions", the idea of a network of Mediterranean Experts on Climate and environmental Change (MedECC) was first put forward and very positively received during this meeting. MedECC was envisioned as a Mediterranean derivative of both IPCC and IPBES. Just one month later, on July 9, 2015, MedECC was more officially established in the context of a side event at the international scientific conference "Our Common Future under Climate Change" (CFCC) in Paris under the auspices of the International Council of Scientific Unions (ICSU), Future Earth, the United Nations Educational Scientific and Cultural Organization (UNESCO) and a number of French research institutions. CFCC was the key scientific event to prepare for the UNFCCC COP-21 held in Paris on November 30 – December 12, 2015. The Mediterranean side event at CFCC brought together about 40 scientists and representatives of the initial supporting institutions, including Plan Bleu (United Nations Environment Programme/Mediterranean Action Plan Regional Activity Centre), Labex OT-Med, MISTRALS, UfM, the World Bank Center for Mediterranean Integration (CMI), Regional Group of Experts on Climate in the South Provence-Alpes-Cote d'Azur (GREC-SUD), French National Research Institute for Sustainable Development (IRD) and Advisory Council for the Sustainable Development of Catalonia of the Government of Catalonia (CADS) as well as decision- and policymakers.

Since 2015, MedECC has developed its network of voluntary contributions, aiming to contribute to a science-policy interface for Mediterranean sustainable development. Major steps in this context have included:

- Regular contributions to the meetings of the Union for the Mediterranean Climate Change Expert Group (UfM CCEG) since its meeting in Barcelona, Spain, on October 1 and 2 2015.
- Side events organized by MedECC during the 21st and 22nd Sessions of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 21 and COP 22 – UNFCCC) respectively in Paris, France, in December 2015, and in Marrakesh, Morocco, in November 2016.
- A substantive contribution to the implementation of the Mediterranean Strategy for Sustainable Development (MSSD) 2016-2025, approved during the 19th Meeting of the Contracting Parties to the Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean (Barcelona Convention) in Athens, Greece, in February 2016.
- Following the adoption of the 2017-2022 work program of the UfM CCEG, it was decided to rely primarily on MedECC to provide an assessment of the impacts of climate and environmental change in the Mediterranean Basin. Given the cross-sectorial scope of MedECC and its emphasis on environmental issues, it was decided that any possible UfM contribution to MedECC activities will be inclusive and involve Environment and Climate Change representatives of the UfM Member States, and will be pursued in coordination with all relevant UfM structures.
- The signature of an agreement in December 2017 between the Secretariat of the UfM and Plan Bleu Regional Activity Centre (UNEP/MAP) to jointly support MedECC, with the establishment of a MedECC Secretariat – financed in 2018-2020 by UfM through a grant from the Swedish International Development Cooperation Agency (SIDA) and hosted by Plan Bleu in Marseille, France, since May 2018.

A.4 The path towards the first assessment (MAR1)

A.4.1 Main steps in report preparation

The Secretariat of the UfM hosted the first meeting of the MedECC ad hoc SC on April 7 and 8 2016 in Barcelona, Spain. The purpose of this meeting, to which a few key scientists and representatives of the main user institutions were invited, was to debate the group's governance system and the foundations of the First Mediterranean Assessment Report (MAR1). This meeting was followed by a workshop in Aix-en-Provence, France, in October 2016, where participants from 16 countries, 50 scientists and 18 representatives of end-user organizations, met to develop the general structure and outline of MAR1. From May 2017 to March 2018, thematic workshops were organized in order to discuss the topics to be included in MAR1. More specifically the thematic workshops comprised: (i) a workshop on "Water, food, energy" (May 2017, Rabat, Morocco), (ii) a workshop on "Development, health and human security" (June 2017, Palermo, Italy), (iii) a workshop on "Ecosystems and ecosystem services" (July 2017, Marseille, France), (iv) a workshop on human impacts on Mediterranean marine ecosystems and the economy (October 2017, Monaco) and (v) a workshop on drivers of climate and environmental change (March 2018, Aix-en-Provence, France).

A call for self-nominations of Coordinating Lead Authors (CLAs) and Lead Authors (LAs) for MAR1 was widely distributed on May 31, 2018, with a deadline extended to June 22, 2018. This call was circulated widely in various scientific networks. MedECC invited self-nominations from experts from the full range of scientific, technical and socio-economic views and backgrounds linked with the Mediterranean. MedECC received 161 self-nominations from 24 countries (39% female and 61% male).

MedECC CLAs were appointed by the MedECC SC, giving priority to recognized scientific capacity and ensuring, to the highest degree possible, diversity in terms of scientific discipline, country of origin and gender. During a second phase LAs were appointed by CLAs in collaboration with the MedECC SC, using the same criteria. Contributing Authors (CAs) were selected by the CLAs, with the approval of the MedECC Coordinators. The drafting of MedECC MAR1 can thus be considered a highly participatory process.

All appointed authors are widely recognized experts who represent a broad range of subject areas and opinions in order to achieve scientific excellence. CLAs and LAs interact frequently with MedECC Assessment Coordinators, the MedECC Secretariat and the MedECC SC. In 2020, the final editing of the report and the Summary for Policymakers was undertaken by an ad hoc Editorial Committee consisting of MedECC coordinators and several CLAs and/or SC members.

In October 2018, a few scientists representing the MedECC network published the first synthesis of multiple changes in the environment that impact the livelihoods of people in the entire Mediterranean Basin (Cramer et al. 2018).

In December 2018, scientists representing the MedECC network, in collaboration with decision makers, published a preliminary assessment of risks associated with climate and environmental changes in the Mediterranean region (MedECC booklet) (MedECC 2018).

An event organized on 10 October 2019 by the UfM Secretariat as part of the IV UfM Regional Forum was a good occasion for presenting this MedECC booklet with updated information and draft key messages. The event was a very good opportunity for bringing the report to the attention of the representatives of major stakeholders, all sectors of society, and especially policymakers from across the region, ahead of its finalization and communication to the ministers in charge of environment and climate change at the upcoming UfM Ministerial meeting dedicated to these issues. It had a huge impact in the media across the region, and helped raising awareness.

A.4.2 Tasks and responsibilities

Role attribution in report drafting and definitions are generally based on IPCC procedures, with modifications due to more limited resources than IPCC.

Assessment Coordinators

The role of coordinating the assessment is shared between two scientists. An assessment coordinator's role is to assume responsibility for overseeing the preparation of an assessment report, as well as its Summary for Policymakers (SPM) and generally ensuring that the report is completed to a high standard, that the chapters feed into each other and that their messages are not contradicting.

The coordinators are both senior experts in their field and have experience in coordinating the work of experts. Besides overseeing the development of the assessment, the coordinators also contributed text to chapters.

The coordinators of MAR1 were Joël Guiot (CEREGE, CNRS, France) and Wolfgang Cramer (IMBE, CNRS, France).

Coordinating Lead Authors (CLAs)

CLAs take overall responsibility for coordinating major sections of an assessment report. CLAs have similar roles as LAs with the added responsibility of ensuring that major sections of the report are completed to a high standard, collated and delivered to the MedECC Secretariat in a timely manner. CLAs play a leading role in ensuring that any cross-cutting scientific or technical issues which may involve several sections of a report, are addressed in a complete and coherent manner and reflect the latest information available.

Lead Authors (LAs)

LAs are responsible for the production of designated sections on the basis of the best scientific, technical and socio-economic information available. LAs typically work in small groups, which have responsibility for ensuring that the various components of their sections are brought together in time, are of uniformly high quality and conform to any overall standards of style set for the document as a whole. During the final stages of the report preparation, when the workload may be particularly heavy, LAs are dependent upon each other to read and edit material, and to promptly agree on any changes deemed necessary.

The essence of the LAs' task is the synthesis of material drawn from all available literature. LAs are also required to take account of expert and government review comments when revising text. LAs must have the ability to develop text that is scientifically, technically and socio-economically sound and that faithfully represents, as much as possible, contributions by a wide variety of experts. LAs are required to record in the report views which cannot be reconciled with a consensus view, but which are nonetheless scientifically or technically valid.

Contributing Authors (CAs)

CAs are asked to prepare technical information in the form of text, graphs or data for integration by the LAs into the draft section. Input from a wide range of contributors is a key element in the success of the MedECC assessment report. Contributed material may be edited, merged and if necessary, amended, in the course of developing the overall draft text.

Expert Reviewers

Expert Reviewers provide comments on the accuracy and completeness of the scientific, technical and socio-economic content and the overall balance of the drafts. Expert reviewers comment on the text according to their own knowledge and experience.

MedECC Secretariat

The MedECC Secretariat assists with all matters related to the preparation of the MedECC MAR1, including communication, exchange of scientific information, management of documents and drafts, the review process and other matters. The MedECC Secretariat is also responsible for collaborating and coordinating with the CLAs to ensure that the chapters are delivered in a timely manner and to a high standard. The Secretariat collaborates closely with MedECC Coordinators and has been funded by UfM thanks to SIDA and based in Plan Bleu premises in Marseille, France, since May 2018.

The MedECC Secretariat is currently composed of the MedECC Science Officer, Katarzyna Marini. MedECC will seek to expand this support structure.

MedECC Steering Committee (SC)

The MedECC SC decides on the functioning of MedECC and focuses on strengthening the science-policy dialogue, as well as the visibility and credibility of MedECC. The SC participated in the development and validation of the structure and outline of MAR1, reviewed the CLA and LA nominations and validated the final list of CLAs and LAs.

At the time of MAR1 the SC included:

- **Magda Bou Dagher Kharrat** *(Saint Joseph University, Beirut, Lebanon)*
- **Ghani Chehbouni** *(IRD, Rabat, Morocco)*
- **Wolfgang Cramer** *(CNRS, IMBE, Aix-en-Provence, France)*
- **Marianela Fader** *(International Centre for Water Resources and Global Change (UNESCO), Federal Institute of Hydrology, Koblenz, Germany)*
- **Carlo Giupponi** *(Ca' Foscari University and Venice International University, Italy)*
- **Arnault Graves** *(Union for the Mediterranean, Barcelona, Spain)*
- **Samir Grimes** *(National High School of Marine Sciences and Coastal Management, Algiers, Algeria)*
- **Joël Guiot** *(CNRS, CEREGE, Aix-en-Provence, France)*
- **Manfred A. Lange** *(The Cyprus Institute, Nicosia, Cyprus)*
- **Elen Lemaitre-Curri** *(Plan Bleu, Marseille, France)*, until July 2020 ; **François Guerquin** (Plan Bleu, Marseille, France), after July 2020
- **Julien Le Tellier** *(UNEP/MAP – Barcelona Convention Secretariat, Athens, Greece)*
- **Piero Lionello** *(University of Salento, Lecce, Italy)*
- **Maria Carmen Llasat** *(University of Barcelona, Spain)*

- **Cyril Moulin** *(National Institute for Earth Sciences and Astronomy (INSU), CNRS, MISTRALS, Paris, France)*
- **Shlomit Paz** *(University of Haifa, Israel)*
- **Arnau Queralt Bassa** *(Advisory Council for the Sustainable Development of Catalonia (CADS), Barcelona, Spain)*
- **Maria Snoussi** *(Mohammed V University, Rabat, Morocco)*
- **Andrea Toreti** *(European Commission – Joint Research Centre (JRC), Ispra, Italy)*
- **Ethemcan Turhan** *(Environmental Humanities Lab, Kungliga Tekniska Högskolan (KTH), Stockholm, Sweden)*
- **Elena Xoplaki** *(Justus-Liebig Universität Gießen, Germany)*

A.4.2 Key stages of MedECC report production

Development of the detailed outline of the report – March 2018

The overall structure of the report was discussed and validated during the scoping workshop, which took place in Aix-en-Provence, France, in October 2016. Detailed outlines of chapters were developed during thematic workshops: (i) on "Water, food, energy" (May 2017, Rabat, Morocco), (ii) on "Development, health and human security" (June 2017, Palermo, Italy), (iii) on "Ecosystems and ecosystem services" (July 2017, Marseille, France) and (iv) on drivers of climate and environmental change (March 2018, Aix-en-Provence, France).

Development of the First Order Draft (FOD) – April 2019

Numerous on-line and on-site meetings between the MedECC SC members were held, starting with the Barcelona meeting in 2017. The MedECC Secretariat was established in May 2018. The first LA on-line meeting (on-line) was held in October 2018 to discuss the report production procedure and timeline. The 1st physical Mediterranean Assessment Report (MAR1) LA meeting was held in Milan (Italy), on March 4-7 2019. The meeting gathered 58 participants from 16 countries: MAR1 CLAs and LAs, MedECC SC Members and MedECC Partners. The main objective of this meeting was to work together on the 1st Mediterranean Assessment Report (MAR1). Authors discussed and further developed the contents of each chapter. The discussions in cross-chapter groups made it possible to verify the consistency of information provided across the whole report and identify overlaps.

The First Order Draft (FOD) of all chapters was finalized in April 2019. The FOD had at least 70% completed text for all major sections. It underwent a review internal to the assessment (Co-coordinators, CLAs, LAs, SC) in May 2019, which provided an opportunity to understand where the overlaps are between chapters, and gaps in text and expertise.

Development of the Second Order Draft (SOD) – September 2019

Between June and September 2019 LAs held numerous on-line meetings. The SOD was the first complete draft of the technically and scientifically balanced assessment. Each chapter was required to include an Executive Summary. At this stage, authors had thought about graphics and had either identified existing graphics for inclusion or identified where graphics will be developed. Authors were also asked to be mindful of the language used in the preparation of the SOD and to present the range of scientific, technical and socio-economic evidence clearly and concisely.

In preparing the SOD and at subsequent stages of revision after review, CLAs were requested to clearly identify disparate views for which there is significant scientific or technical support, together with the relevant arguments.

The Executive Summary located at the beginning of each chapter of the report outlines the key findings arising from the assessment process. The summaries are crucial in how the outcomes of MedECC assessment are communicated to its primary audience. They are not abstracts, but a synthesis, analysis and collective expert judgment of the chapter findings. A key statement in the SPM should be readily traceable back to an Executive Summary statement(s) which in turn must be readily traceable back to a section(s) of the chapter text, which in turn should be traceable where appropriate to the primary literature through references.

Peer-review of SOD by scientific experts – October-November 2019

An open call for independent reviewers was launched. The MedECC Coordinators and the Secretariat selected the reviewers. The reviewers come from a variety of institutions but are required to have a scientific background in the field of the assessment. The role of the reviewers was to comment on the accuracy and completeness of the scientific, technical or socio-economic contents and the overall scientific, technical or socio-economic balance of the draft report. Expert reviewers provided the comments to the CLAs through the MedECC Secretariat in an agreed format. The MedECC Secretariat received 113 reviews.

Comments were collated and sent to authors of the assessment. Upon request, the Secretariat made available any material that is referenced in the document being reviewed that is not available in the international published literature. Authors needed to have this material available in case a request is made.

MedECC Steering Committee and Coordinating Lead Authors meeting – December 2019

The objective of this meeting was to discuss the results of the external peer review by scientific experts, develop the Summary for Policymakers and to plan next steps for producing the Final Draft (FD). The SPM (of about 20 pages) was produced by a team consisting of Coordinators, CLAs and selected LAs. The SPM is primarily based on the chapters' Executive Summaries. It contains the main policy-relevant, but policy-neutral findings of the assessment in synthesized and less technical language, generally in the form of top key messages and presented without reference to the main chapters. These messages represent the highest level of synthesis of the assessment and may be structured differently from the set of main findings in the SPM.

Development of the Final Draft (FD) – February-April 2020

The FD incorporated further development of the assessment by chapter teams as well as the results of the peer-review of SOD by scientific experts. All review comments require a written response – the resulting tables will be made publicly available upon request. Where authors reject a comment, they will provide written justification for doing so.

Review of the draft SPM by stakeholders – May-June 2020

The draft of the SPM was reviewed by governments and other relevant stakeholders through an open and transparent process. Drafts of report chapters were also provided as a source of the findings provided in the SPM.

The SPM approval procedure is organized with the UNEP/MAP – Barcelona Convention Secretariat and its Plan Bleu Regional Activity Centre, through their Focal Points and/or the Members of the Mediterranean Commission on Sustainable Development (MCSD), as well as with UfM Member State representatives within the regional Climate Change Expert Group (CCEG). The exact procedure has been established in close cooperation with UNEP/MAP and UfM.

During review and approval by policymakers, the scientific content of the report and the clarity of its presentation were discussed.

Finalization of draft Assessment Report and SPM for Plenary discussion – July-August 2020

The final draft will take into consideration all comments from the review by stakeholders and policymakers. Where authors reject a comment, they will provide written justification for doing so. A final draft of the SPM including key messages and graphics was also developed during this period.
The preparation of the final version of the report, considering all stakeholder and expert comments, was undertaken by the Coordinators, CLAs and LAs in consultation with the MedECC Editorial Committee. This stage is critical for the coordination of key findings and policy relevant messages in the SPM, for developing graphics, for quality assurance of chapters and ensuring consistency and traceability of confidence statements between the SPM and the chapters.

The final draft should reflect comments made by policymakers, stakeholders and scientific experts. If necessary, authors, together with review editors and reviewers can try to resolve areas of major differences of opinion. Reports should describe different, possibly controversial, scientific, technical and socio-economic views on a given subject, particularly if they are relevant to the policy debate. The final report will credit all Coordinators, CLAs, LAs, CAs, reviewers and MedECC Editorial Committee and other contributors, as appropriate, by name and affiliation.

Plenary consultation on the SPM – 22 September 2020

The revised Summary for Policymakers (SPM) of the First Mediterranean Assessment Report (MAR1) was the subject of the plenary consultation with policymakers, governments, decision makers and stakeholders, which took place on 22 September 2020 (in Marseille, France and on-line). Due to the health crisis, the plenary consultation was predominantly held virtually. The particular aim of the plenary consultation was to ascertain that

MAR1 findings, as presented in the SPM, are fully comprehensible and unambiguous and that the remarks from the on-line consultation were well integrated. This meeting gathered more than 100 participants. It was attended by representatives from 15 countries. The agreed changes were implemented in the SPM, which should no longer be changed (except for editorial and technical modifications). At the end of the meeting the conclusions and recommendations were adopted. Participants in the plenary session were: Focal Points of the Union for the Mediterranean Climate Change Expert Group (UfM CCEG) and the UfM Environment Task Force, Focal Points of Plan Bleu/Regional Activity Centre (United Nations Environment Programme / Mediterranean Action Plan (UNEP/MAP)), Members of the Steering Committee of the Mediterranean Commission on Sustainable Development (MCSD), MedECC Coordinators, Secretariat, Steering Committee members and MAR1 Coordinating Lead Authors, Plan Bleu, UNEP/MAP and UfM Secretariat representatives.

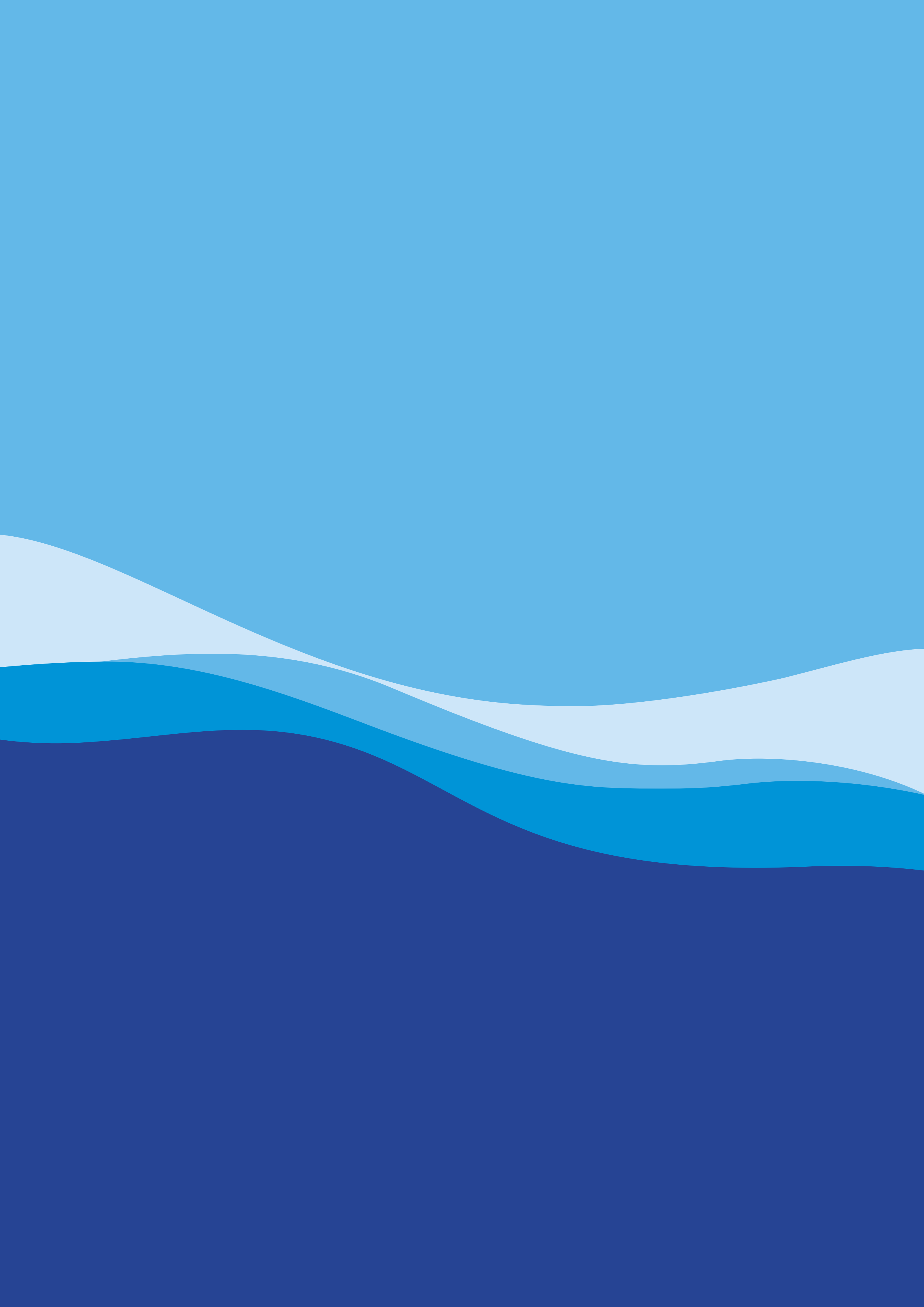
B

APPENDIX

Maps of seasonal temperature and precipitation changes for the Mediterranean Basin

Authors:
George Zittis *(Cyprus)*, **Samuel Somot** *(France)* and **Filippo Giorgi** *(Italy)*

This chapter should be cited as: Zittis G, Somot S, Giorgi F 2020 Appendix B – Maps of seasonal temperature and precipitation changes for the Mediterranean Basin. In: Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report *[Cramer W, Guiot J, Marini K (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, pp. 599-612, doi:10.5281/zenodo.5794071.*



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Introduction and scope

Projected changes of key meteorological variables (for example, precipitation and temperature) are not, in terms of magnitude, expected to be consistent throughout the Mediterranean region. Similarly, according to global and regional model projections and due to several climatic feedbacks, these changes will not be uniformly distributed throughout the year. While changes in seasonal temperature and precipitation were also discussed in *Chapter 2* of the First Mediterranean Assessment Report (MAR1), here we present a complementary but more informative assessment that could provide useful information for impact and adaptation studies and also motivate mitigation actions. This is presented in the form of an atlas that includes all the Mediterranean countries, a range of future periods and the two greenhouse gas emission pathways (RCP2.6 and RCP8.5) that were discussed primarily in MAR1.

Data and methods

At the time of writing, the most comprehensive and populated ensemble of regional climate projections, that adequately includes most of the Mediterranean region, is the EURO-CORDEX (Jacob et al. 2020), which is the European initiative of the Coordinated Regional Downscaling Experiment (Giorgi and Gutowski 2015). This set of state-of-the-art regional projections, available in a horizontal resolution of about 12 km is the basis of the present assessment. The full list of experiments taken into account as well as the availability per variable and scenario are presented in *Table 1.*

When assessing future climate change, it is important to specify the reference period to which climate projections are compared, along with future "time slices" of particular interest. In MAR1 and the present atlas, we use 20-year periods. This length is sufficient to smooth part of the high-frequency natural climate variability that may otherwise mask the forced trend, but it is short enough to assume that climate does not change much during the 20 years covered. For the reference period, we chose the last decades of the 20th century (1980-1999). For the future, we kept 20-year time slices in order to sample the same level of internal variability as in the reference period. We divided the 21st century into 20-year time slices with a near-future period (2020-2039), a mid-term period centred in 2050 (2040-2059) and a far-future period close to the end of the 21st century (2080-2099). The mid-21st century period is arguably of particular interest for many stakeholders, especially for mid-term adaptation. The end of the 21st century period is also of interest for stakeholders working on mitigation targets and involved in very long-term planning (e.g., for the design and planning of dams, forests or cities).

In terms of seasons, we use the boreal hemisphere definition for winter (December-February), spring (March-May), summer (June-August) and autumn (September-November), for analysis of both temperature and precipitation. Maps of future projections on an annual basis are discussed in the main text of MAR1 and are therefore not presented here.

For future climate, an important part of the uncertainty is related to the evolution of socio-economic development. To be able to propose future climate projections according to various possible socio-economic and climate policy trajectories, we follow the Representative Concentration Pathways or RCPs, defined in *Box 2.1* of MAR1 (Meinshausen et al. 2011). Here, we focus mostly on two of such pathways which encompass the range of IPCC-AR5, CMIP5 and CORDEX simulations: the 'business as usual' scenario of high emissions (RCP8.5) and a more optimistic pathway closest to meeting the UNFCCC Paris Agreement main targets (RCP2.6). These scenarios have been chosen also due to model projection availability constraints at the regional scale.

GLOBAL MODEL	REGIONAL MODEL	TEMPERATURE AT 2M		PRECIPITATION	
		RCP2.6	RCP8.5	RCP2.6	RCP8.5
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	CLMcom-CCLM4-8-17_v1		●		●
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	CNRM-ALADIN53_v1	●	●		
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	CNRM-ALADIN63_v2	●	●	●	●
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	DMI-HIRHAM5_v2		●		●
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	KNMI-RACMO22E_v2	●	●	●	●
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	RMIB-UGent-ALARO-0_v1	●	●	●	●
CNRM-CERFACS-CNRM-CM5 (r1i1p1)	SMHI-RCA4_v1		●		●
ICHEC-EC-EARTH (r12i1p1)	CLMcom-CCLM4-8-17_v1	●	●	●	●
ICHEC-EC-EARTH (r12i1p1)	DMI-HIRHAM5_v1		●		●
ICHEC-EC-EARTH (r12i1p1)	KNMI-RACMO22E_v1	●	●	●	●
ICHEC-EC-EARTH (r12i1p1)	SMHI-RCA4_v1	●	●	●	●
ICHEC-EC-EARTH (r3i1p1)	KNMI-RACMO22E_v1		●		●
ICHEC-EC-EARTH (r3i1p1)	SMHI-RCA4_v1		●		●
IPSL-IPSL-CM5A-LR (r1i1p1)	GERICS-REMO2015_v1	●		●	
IPSL-IPSL-CM5A-MR (r1i1p1)	SMHI-RCA4_v1		●		●
MOHC-HadGEM2-ES (r1i1p1)	CLMcom-CCLM4-8-17_v1		●		●
MOHC-HadGEM2-ES (r1i1p1)	DMI-HIRHAM5_v1		●		●
MOHC-HadGEM2-ES (r1i1p1)	KNMI-RACMO22E_v2	●	●	●	●
MOHC-HadGEM2-ES (r1i1p1)	SMHI-RCA4_v1	●	●	●	●
MPI-M-MPI-ESM-LR (r1i1p1)	CLMcom-CCLM4-8-17_v1		●		●
MPI-M-MPI-ESM-LR (r1i1p1)	MPI-CSC-REMO2009_v1	●	●	●	●
MPI-M-MPI-ESM-LR (r1i1p1)	SMHI-RCA4_v1	●	●	●	●
NCC-NorESM1-M (r1i1p1)	DMI-HIRHAM5_v2		●		●
NCC-NorESM1-M (r1i1p1)	GERICS-REMO2015_v1		●		●
NCC-NorESM1-M (r1i1p1)	KNMI-RACMO22E_v1		●		
NCC-NorESM1-M (r1i1p1)	SMHI-RCA4_v1	●	●	●	●
NOAA-GFDL-GFDL-ESM2G (r1i1p1)	GERICS-REMO2015_v1	●		●	
	TOTAL	14	25	13	23

Table B.1 | List of EURO-CORDEX experiments taken into account in the presented assessment and availability of variables.

Projected temperatures

Winter temperature

Projected winter temperature changes for the Mediterranean are presented in *Figure B1*. For pathway RCP2.6, the EURO-CORDEX multi-model ensemble suggests a relatively mild increase that is not expected to exceed 1°C-2°C for all sub-periods *(Fig. B.1 – left panels)*. Particularly for the middle and late-21st century, the projected winter warming is slightly higher over the eastern part of the Mediterranean. Nevertheless, the regional differences are not so evident. For the business-as-usual RCP8.5, the near-future winter temperature projections are of the same magnitude as the worst-case ones for RCP2.6 *(Fig. B.1 – top right)*. Already by mid-century, winter warming is expected to reach 3°C, with respect to the historical reference, in many parts of the region. This is the case mainly in high-elevation regions, such as the Atlas Mountains, the Alps, Anatolia and parts of the Balkan Peninsula, highlighting that winter warming could be enhanced by positive snow-albedo feedbacks. For the end of the current century *(Fig. B.1 – bottom right)*, warming is projected to intensify and exceed 4°C in most of the region. In the hotspot mountainous areas, this warming is projected to reach 6°C with respect to the reference period.

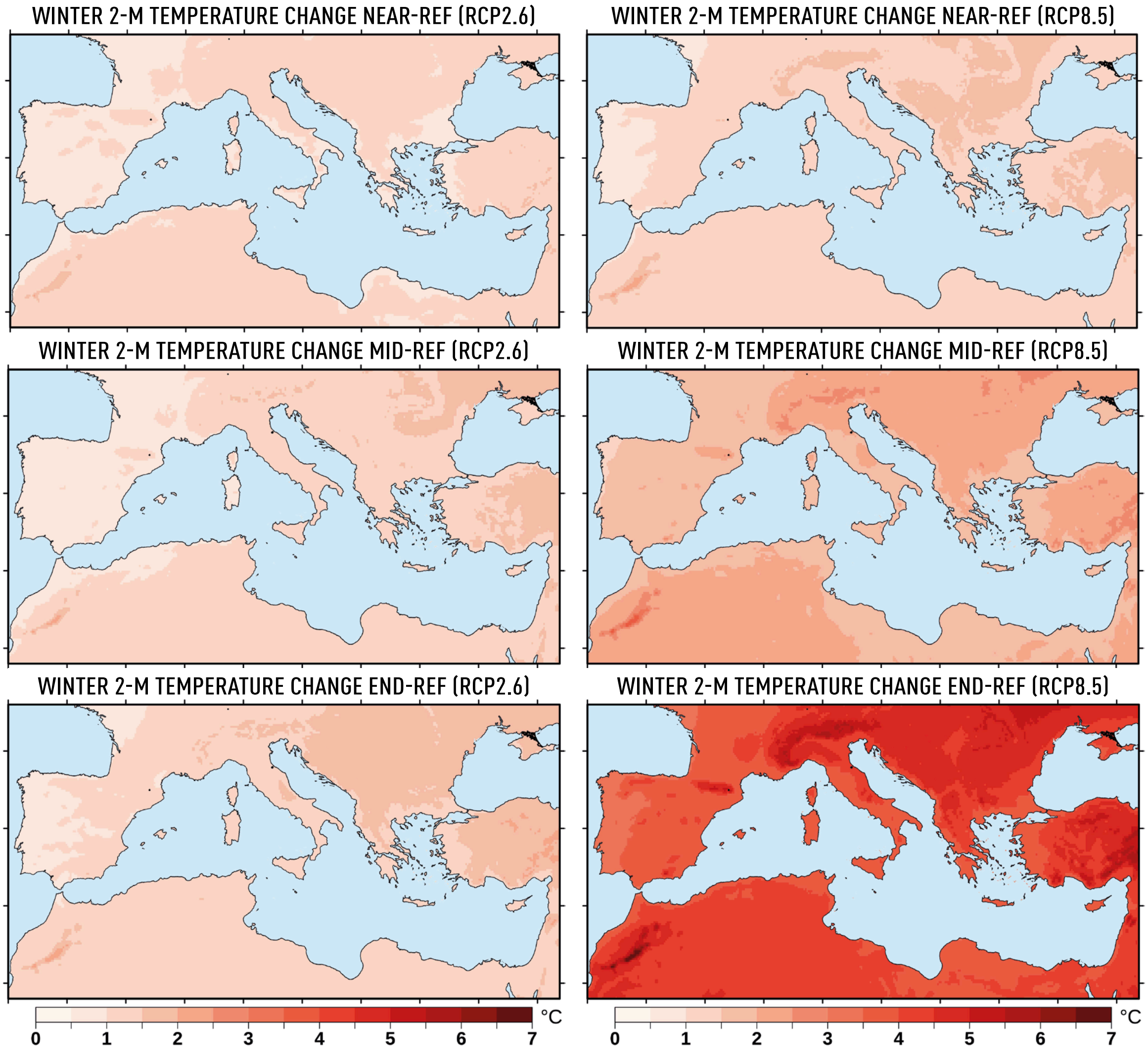
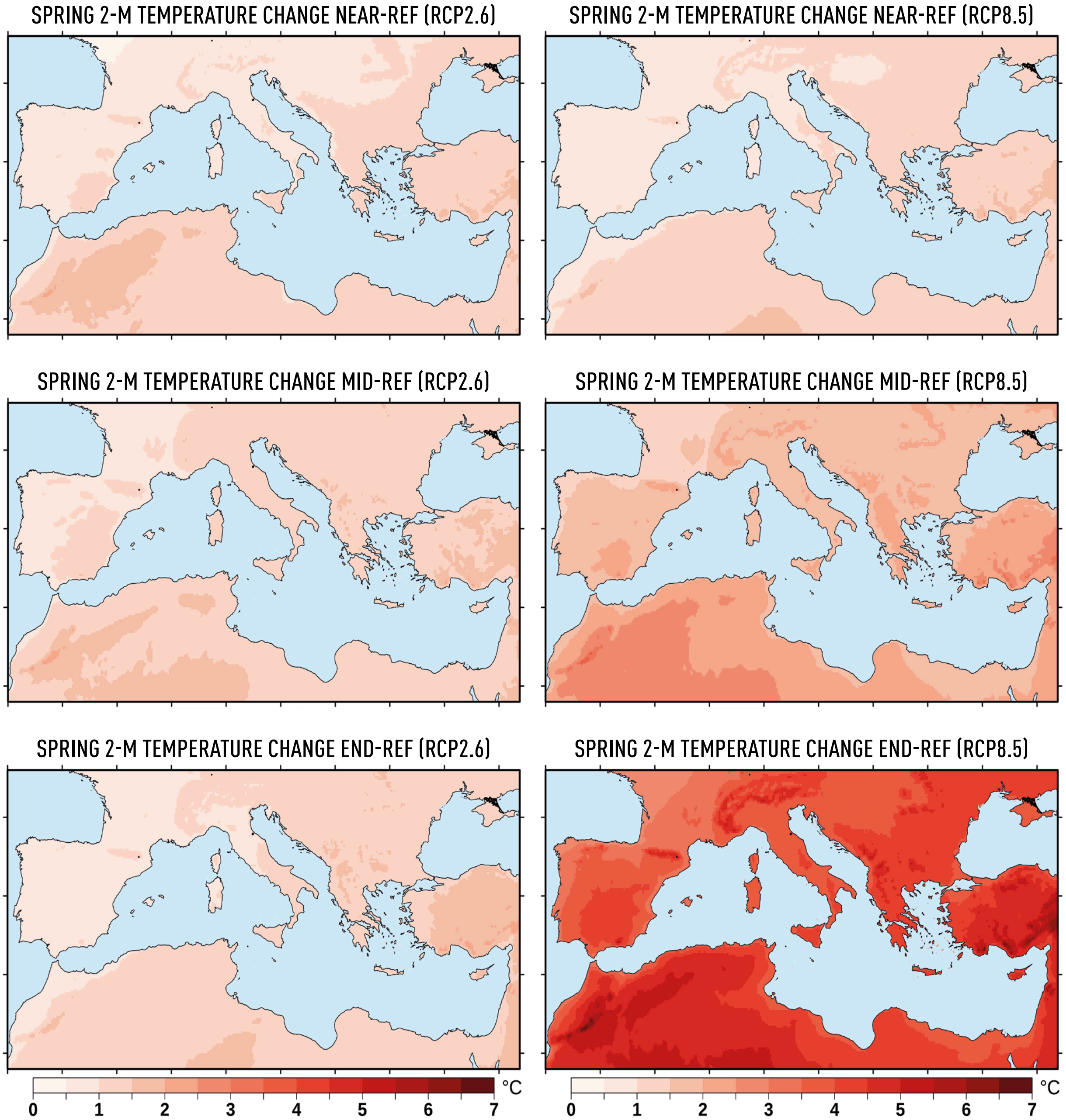


Figure B.1 | Projected changes in winter (December, January, February) temperatures between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Spring temperature

The projected changes during boreal spring are presented in *Fig. B.2*. Under pathway RCP2.6 and for near-future and mid-century, the projected spring warming is somehow higher than during the winter season. For southern Mediterranean regions, such as the Maghreb, this warming will reach 2.5°C-3°C. By the end of the century, the warming is not projected to exceed 2°C in most of the Mediterranean, with the exception of Anatolia. As expected, under the business-as-usual pathway *(Fig. B.2 – right panels)*, the spring warming is projected to follow the same spatial patterns. The EURO-CORDEX ensemble suggests warming between 4°C and 5°C, with higher values in North Africa and the mountainous regions of the Mediterranean.



SPRING 2-M TEMPERATURE CHANGE NEAR-REF (RCP2.6)

SPRING 2-M TEMPERATURE CHANGE NEAR-REF (RCP8.5)

SPRING 2-M TEMPERATURE CHANGE MID-REF (RCP2.6)

SPRING 2-M TEMPERATURE CHANGE MID-REF (RCP8.5)

SPRING 2-M TEMPERATURE CHANGE END-REF (RCP2.6)

SPRING 2-M TEMPERATURE CHANGE END-REF (RCP8.5)

Figure B.2 | Projected changes in spring (March, April, May) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Summer temperature

As discussed in MAR1, the projected summer temperature increase in the Mediterranean region, mainly in the South, is particularly high. This is the case mostly for RCP8.5 *(Fig. B.3 – right panels)*. By mid-century, summer warming will likely exceed 3°C in many parts of the region. The late-21st century RCP8.5 projections suggest that this warming will further intensify and locally exceed levels of 6°C-6.5°C. This is expected mainly for southern latitudes and regions such as the Maghreb, the Iberian Peninsula and Anatolia, as well as the Alps. Soil-atmosphere interactions have been found to play a role in this summer warming amplification (e.g., Zittis et al. 2014). In contrast, under the more moderate RCP2.6 pathway, summer temperature changes will likely be less than 2°C throughout the Mediterranean *(Fig. B.3 – left panels)*.

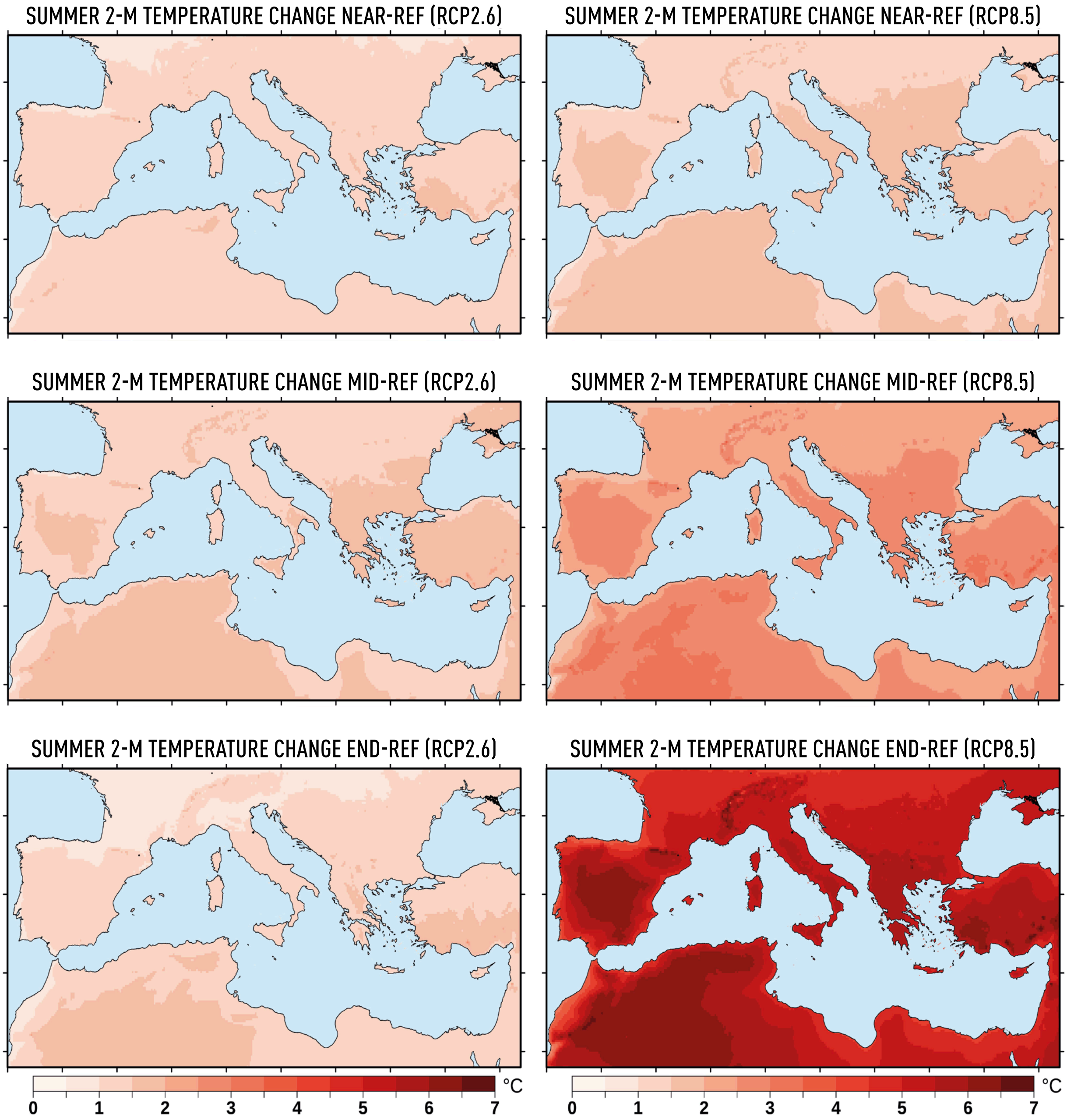
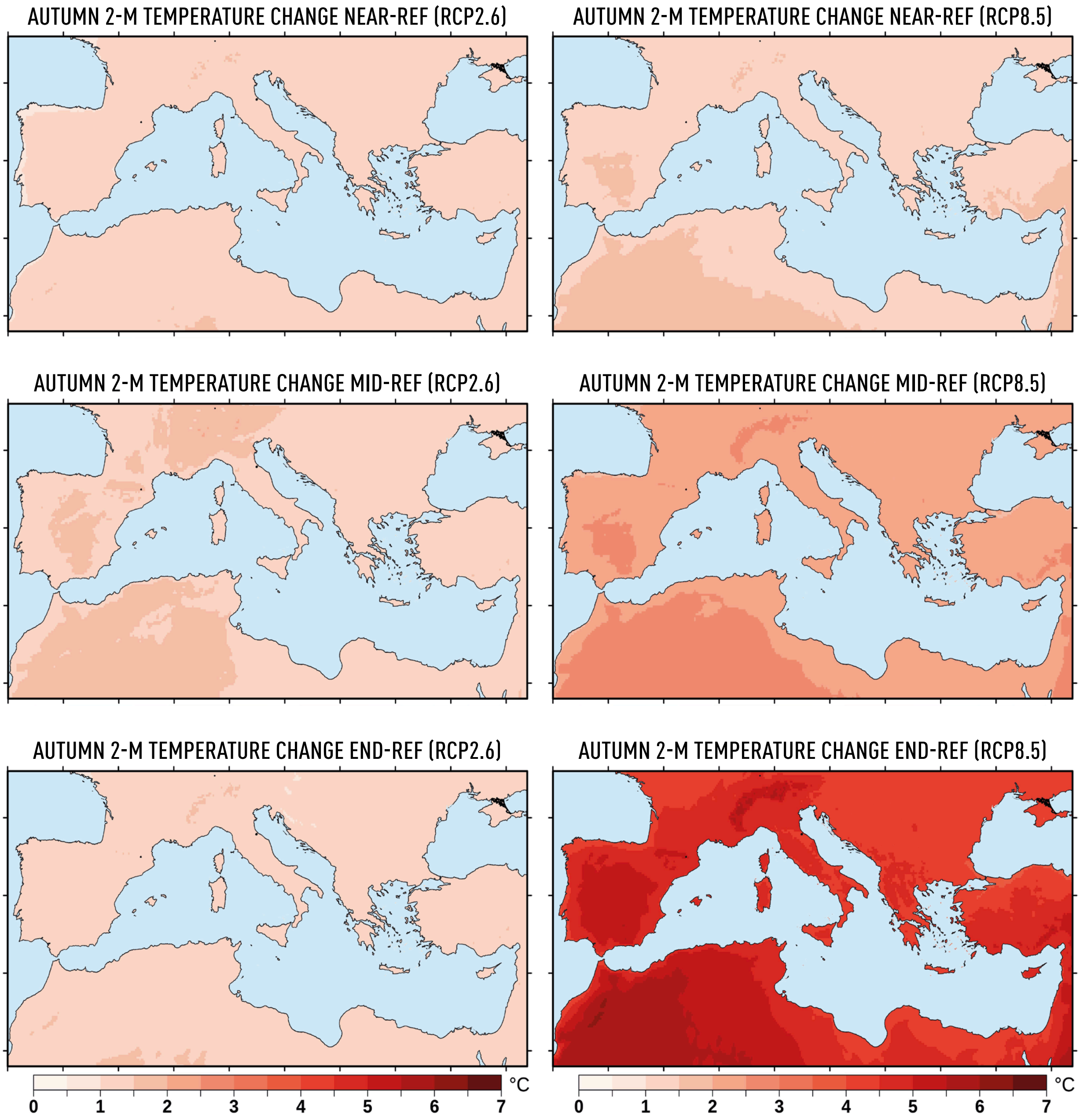


Figure B.3 | Projected changes in summer (June, July, August) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Autumn temperature

Maps of projected changes for the transitional season of autumn are presented in *Fig. B.4.* The spatial patterns are very similar to those for the summer season, however, the magnitude of warming is lower. For RCP2.6, future changes range between 1°C and 1.5°C for all future periods *(Fig. B.4 – left panels)*. The only exception is the western part of the Mediterranean and middle century projections that are expected to be somehow higher (up to 2°C). Under the high-emission pathway *(Fig. B.4 – right panels)*, the near future changes are comparable to those for RCP2.6, while the middle century projections indicate that the autumn warming, with respect to the reference period, is not expected to exceed 3°C. The end-of-century projections under RCP8.5 indicate further warming of up to 5°C-6°C, expected mainly for the southern Mediterranean (for example, the Maghreb, the Iberian Peninsula and Anatolia), as well as the Alps.


AUTUMN 2-M TEMPERATURE CHANGE NEAR-REF (RCP2.6)

AUTUMN 2-M TEMPERATURE CHANGE NEAR-REF (RCP8.5)

AUTUMN 2-M TEMPERATURE CHANGE MID-REF (RCP2.6)

AUTUMN 2-M TEMPERATURE CHANGE MID-REF (RCP8.5)

AUTUMN 2-M TEMPERATURE CHANGE END-REF (RCP2.6)

AUTUMN 2-M TEMPERATURE CHANGE END-REF (RCP8.5)

Figure B.4 | Projected changes in autumn (September, October, November) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Precipitation

Winter precipitation

Projected changes for boreal winter (December, January and February) precipitation are presented in *Fig. B.5* as percentage differences from the historical reference period. Under both emission pathways, and all future periods a North-South gradient of the climate change signal is evident. For southern Europe and the northern Mediterranean territories, winter precipitation is expected to change slightly or increase up to 10%-30%. In contrast, for the drier southern parts of the region, winter precipitation, which is more critical for replenishing water resources, is projected to decrease between 20% and 50%. For the Maghreb region, which is a hotspot of drying, the projected winter precipitation decrease could even exceed 60%. The projected changes are higher for the end of the current century and this is likely the case for both pathways under investigation.

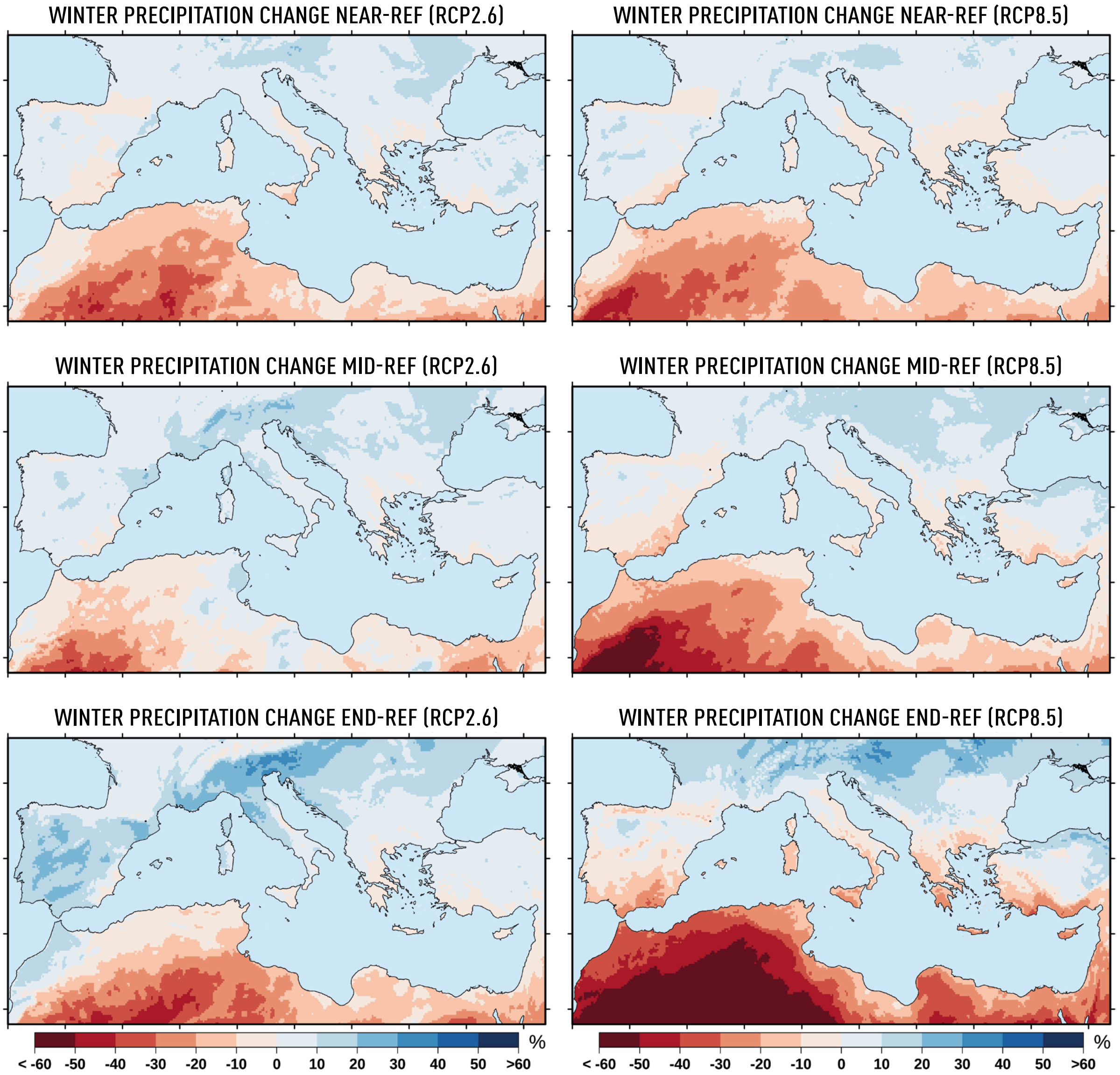


Figure B.5 | Projected changes in winter (December, January, February) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Spring precipitation

For spring (March to May) precipitation changes, the North-South gradient is still evident, however, this pattern is less pronounced *(Fig. B.6)*. Noteworthy, for the next two decades (i.e., the near future sub-period), the projected changes are higher for RCP2.6, indicating that even under low-emission pathways, global warming could introduce changes with high impact at regional scales. This is the case mainly for the Maghreb region *(Fig. B.6 – top panels)*. For the mid-21st century, the EURO-CORDEX ensemble suggests similar changes for both pathways. Small changes are expected for southern Europe, while for North Africa, a decrease of 10%-30% in spring precipitation is expected. Under RCP8.5, seasonal drying is expected to intensify towards the end of the century.

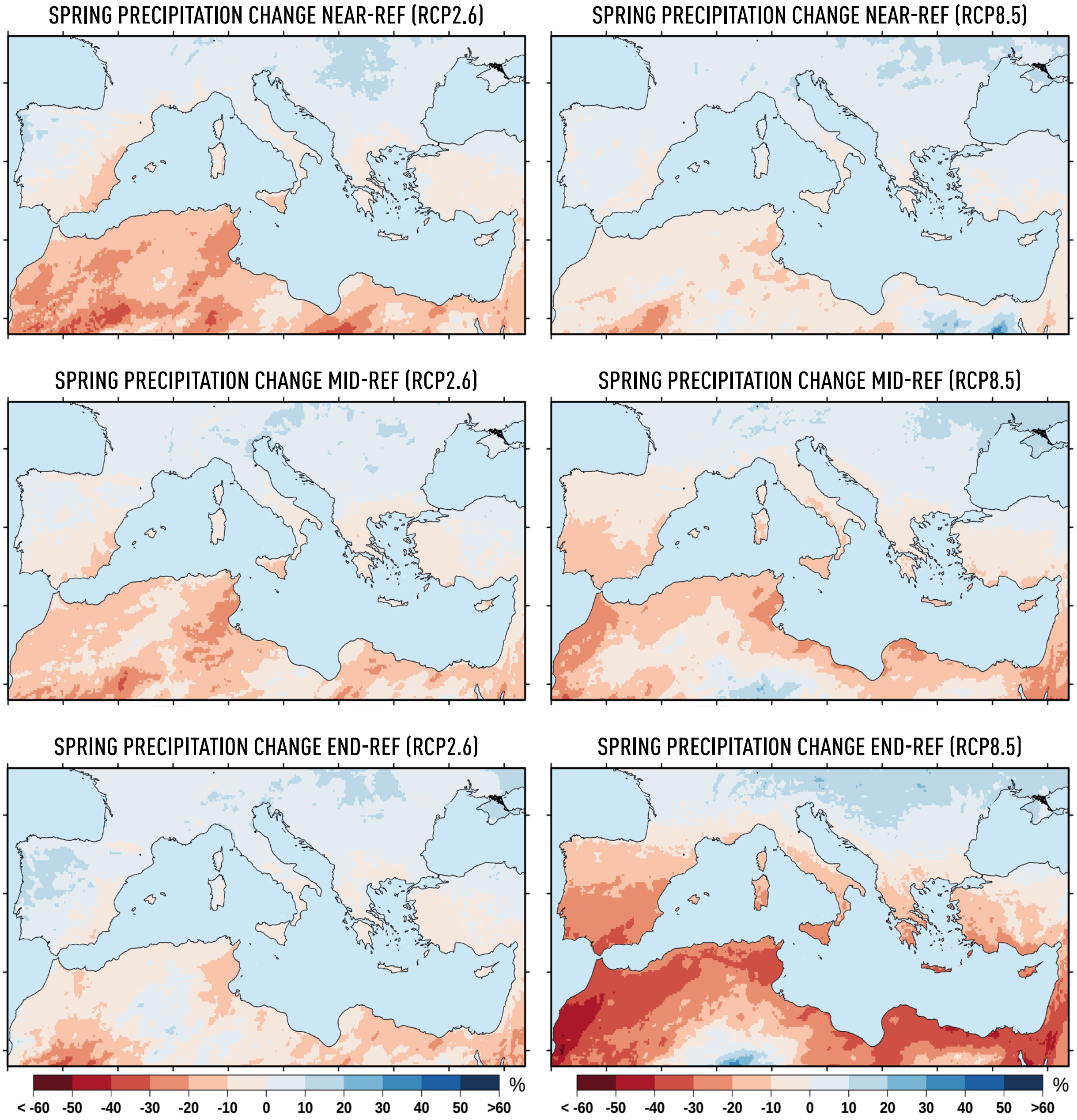


Figure B.6 | Projected changes in spring (March, April, May) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Summer precipitation

The projected precipitation changes of the summer season are presented in *Fig. B.7.* For the northern Mediterranean and southern Europe, the projected changes are relatively mild and were found to range between ±10%. For parts of the southern Mediterranean, a precipitation increase is projected, however, this is not always significant in actual precipitation amounts since summer precipitation is limited (not shown). This increase, that varies in magnitude between the different pathways and time periods, is likely related to a northward expansion of the inter-tropical convergence zone (Evans 2010). A strong summer precipitation decline is evident only for the end of the current century and the RCP8.5 pathway *(Fig. B.7 – bottom right).* This is apparent for most of the Mediterranean and southern Europe.

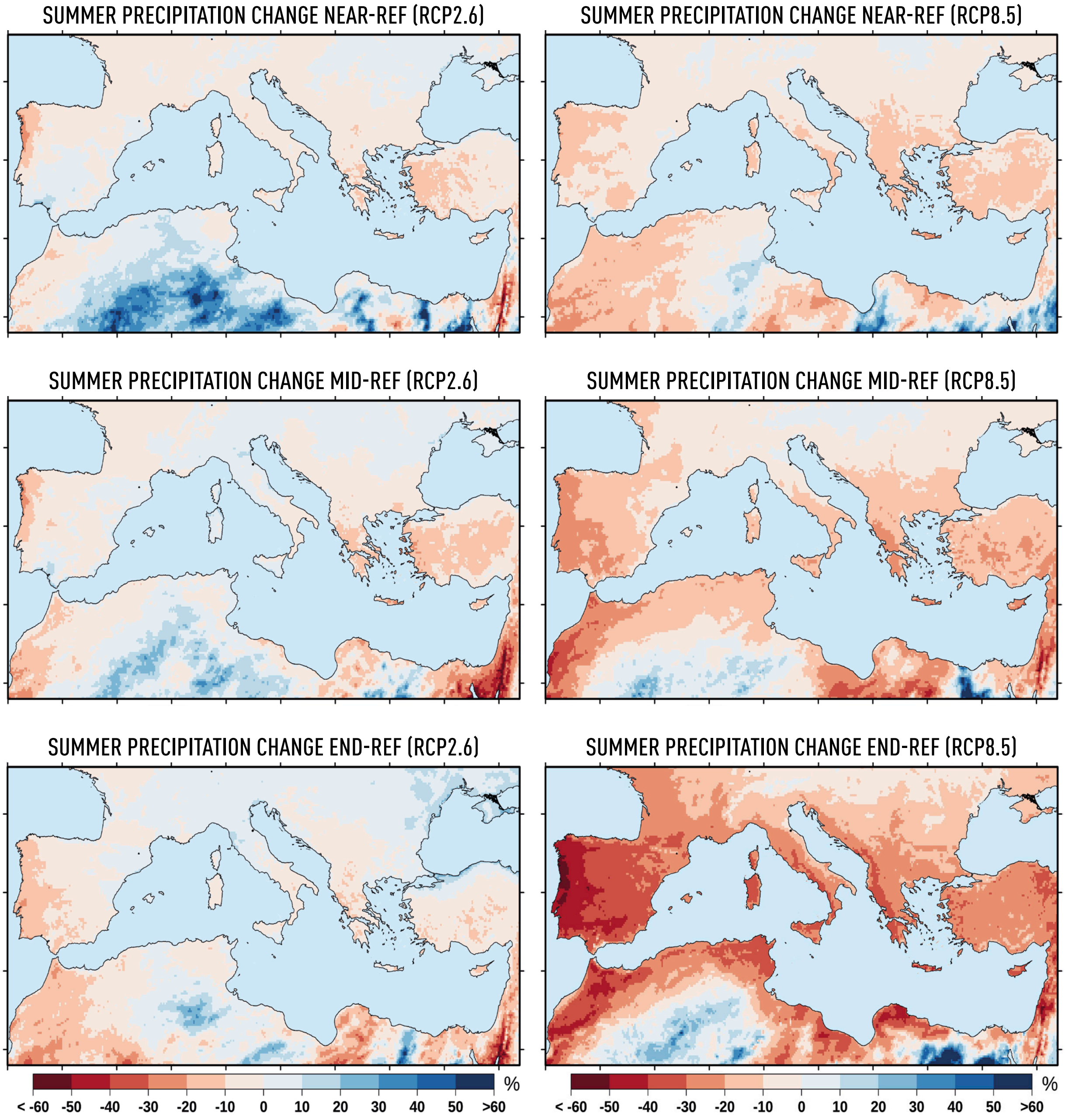


Figure B.7 | Projected changes in summer (June, July, August) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

Autumn precipitation

For the northern Mediterranean, the projected change in autumn precipitation is limited (±10%). For other regions (e.g., Southwest Mediterranean), the future change signal is not consistent between the two pathways. For the Maghreb, precipitation increases (10%-30%) have been projected under RCP2.6 *(Fig. B.8 – left panels).* On the contrary under RCP8.5, this region is projected to be subject to strong drying trends (up to 40%-50%), particularly towards the end of the current century *(Fig. B.8 – right panels).*

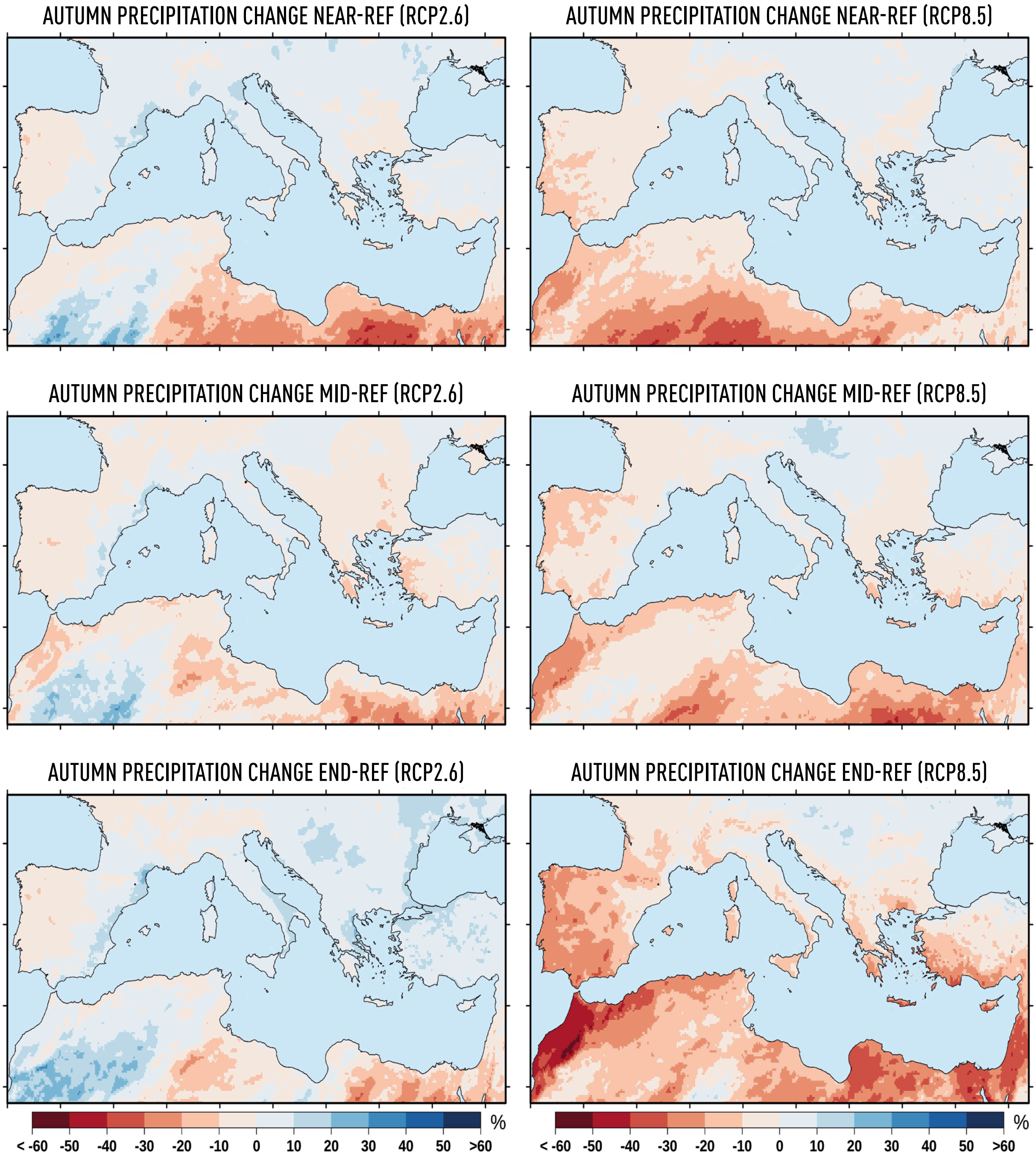


Figure B.8 | Projected changes in autumn (September, October, November) precipitation between the recent past reference period (REF: 1980-1999) and three future sub-periods (NEAR: 2020-2039, MID: 2040-2059, END: 2080-2099), based on the ensemble mean results of the EURO-CORDEX high-resolution simulations for pathways RCP2.6 (left panels) and RCP8.5 (right panels).

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C

APPENDIX

List of acronyms, chemical symbols and scientific units

%	Percent, part per hundred
‰	Per-mil, part per thousand
°C	Degree Celsius
$	American dollar
€	Euro
A1	IPCC SRES storyline and scenario family: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies
A2	IPCC SRES storyline and scenario family: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines
ACP	Asbestos Cement Pipeline
AD	Anno Domini
ADEME	French Agency for Ecological Transition
AGCM	Atmospheric General Circulation Model
AI	Aridity Index
AIR Climat	Association for Innovation and Research in Climate
Al	Aluminum
AMF	Arbuscular mycorrhiza fungi
AMO	Atlantic Multidecadal Oscillation
Approx.	Approximately
AR3	IPCC Third Assessment Report
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AR6	IPCC Sixth Assessment Report
Art.	Article
As	Arsenic
a.s.l	above sea level
ASP	Amnesic Shellfish Poisoning
atm	standard atmosphere (unit of pressure)
B	Boron
B1	IPCC SRES storyline and scenario family: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies
B2	IPCC SRES storyline and scenario family: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.
BC	Before Christ
BiOS	Bimodal Oscillating System
BP	Before Present
C	Carbon
CA	Contributing Author
ca.	circa, meaning approximately
CAAGR	Compounded Average Annual Growth Rate
$CaCO_3$	Calcium carbonate
CADS	Advisory Council for the Sustainable Development of the Government of Catalonia
cal	calibrated years

cap	capita
CAP	Common Agricultural Policy
CBD	Convention on Biological Diversity
CCA	Climate Change Adaptation
CCEG	Climate Change Expert Group
Cd	Cadmium
CDM	Clean Development Mechanisms
CE	Common Era or Current Era
CEDAW	Convention on the Elimination of All Forms of Discrimination against Women
CFCC	Our Common Future under Climate Change
CH_4	Methane
CIMPAL	Cumulative IMPacts of invasive ALien species
CIRCE	Climate change and impact research: the Mediterranean environment
CL	Cutaneous Leishmaniasis
CLA	Coordinating Lead Author
cm	centimeter
CMEMS	Copernicus Marine Environment Monitoring Service
CMIP3	Couples Model Intercomparison Project Phase 3
CMIP5	Couples Model Intercomparison Project Phase 5
CNR-ISMAR	Italian National Research Council, Institute for Marine Science
CNRM	French National Centre for Meteorological Research
CNRS	French National Centre of Scientific Research
Co	Cobalt
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CO_3^{2-}	Carbonate ion
COP	Conference of the Parties
CORDEX	Coordinated Regional Climate Downscaling Experiment
CP	Contracting Party
CPRCM	Convection-Permitting Regional Climate Models
Cr	Chromium
CRI-MED	Coastal Risk Index
CRU	Climatic Research Unit
CRU TS	Climatic Research Unit Timeseries
CS	"Conservative" Scenario
CSO	Civil Society Organisation
CSP	Concentrated Solar Power
CT	Conventional Tillage
CTD	conductivity-temperature-depth
Cu	Copper

DAISIE	Delivering Alien Invasive Species Inventories for Europe
DI	Development Index
Dii	Desert industrial energy initiative
DJF	December-January-February
DSP	Diarrheic Shelfish Poisoning

e.g.	for example
EC	Emerging Contaminants
EC	European Commission
ECtHR	European Court of Human Rights
ED	Endocrine Disruptors
eDNA	environmental deoxyribonucleic acid
EEA	European Environment Agency

EEAC	European Environment and Sustainable Development Advisory Councils
EF	Emission Factor
E	Exa (10^{18})
ELA	Equilibrium Line Altitude
EMT	Eastern Mediterranean Transient
ENSO	El Niño Southern Oscillation
EPPO	European and Mediterranean Plant Protection Organization
ESD	education for sustainable development
etc.	et cetera meaning "and other similar things"
EU	European Union
EWG	Expert Working Groups
EWS	Early Warning Systems
F	Fishing mortality rate i.e. the catch relative to the size of the stock (the proportion of fish caught and removed by fishing).
FAO	Food and Agriculture Organisation
FD	Final Draft
Fe	Iron
Fig.	Figure
FMSY	The maximum rate of fishing mortality (the proportion of a fish stock caught and removed by fishing)
FOD	First Order Draft
FPS	Flagship Pilot Study
FRA	Fisheries Restricted Area
G	Giga (10^9)
g	gram
GCM	Global Climate Model
GDI	Gender Development Index
GDP	Gross Domestic Product
GFCM	General Fisheries Commission for the Mediterranean
GHG	Greenhouse Gases
GII	Gender Inequality Index
GIS	Geographic Information System
GNH	Gross National Happiness
GNI	Gross National Income
GOA-ON	Global Ocean Acidification-Observing Network
GOLT	Gill-Oxygen Limitation Theory
GRACE	NASA's Gravity Recovery and Climate Experiment
GREC-SUD	Regional Group of Experts on Climate in the "South Region" of France (Provence-Alpes-Cote d'Azur)
GWL	Global Warming Level
h	hour
H^+	Hydrogen ion
ha	hectare
HAB	Harmful Algal Bloom
HCO_3^-	Bicarbonate ion
HD	Human Development
HDPE	High-Density Polyethylene
Hg	Mercury
i.e.	that is
IBT	Inter-Basin Transfer
ICCPR	International Covenant on Civil and Political Rights

ICESCR	International Covenant on Economic, Social and Cultural Rights
ICRC	Convention on the Rights of the Child
IGO	Intergovernmental Organization
IHDI	Inequality-adjusted Human Development Index
IIASA	International Institute for Applies Systems Analysis
IPBES	Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IRD	French National Research Institute for Sustainable Development
ISBA	Interactions between Soil, Biosphere, and Atmosphere
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management

J	Joule
JJA	June-July-August

K	Potassium
ka	kilo annum, thousand calendar years ago
k	kilo (10^3)

l	liter
LA	Lead Author
LabEx OT- Med	Laboratory of Excellence "Objectif Terre - Bassin Méditerranéen"
LCOE	levelized Cost Of Energy
LDC	Less Developed Country
LDN	Land Degradation Neutrality
LID	low-impact development
LIW	Levantine Intermediate Water
LMPA	Large Marine Protected Area
LPI	Living Planet Index

M	Mega (10^6)
m	meter
m	milli (10-3)
MAES	Mesophotic Assemblages Ecological Status
MAP	Mediterranean Action Plan
MAR	Managed Aquifer Recharge
MAR1	1st Mediterranean Assessment Report
max	maximum
MCSD	Mediterranean Commission on Sustainable Development
MECIDS	Middle East Consortium on Infectious Disease Surveillance
Med	Mediterranean
MedCLIVAR	Mediterranean CLImate VARiability and Predictability
MedCOF	Mediterranean Climate Outlook Forum
MedECC	Mediterranean Experts on Climate and environmental Change
MEDENER	Mediterranean Association of National Agencies for Energy Management
MEDREG	Association of Mediterranean Energy Regulators
MENA	Middle East and North Africa
MEP	Mediterranean Energy Perspectives
min	minimum
MISTRALS	Mediterranean Integrated STudies at Regional And Local Scales
MMEs	Mass Mortalities Events
Mn	Manganese
MP	Microplastics (plastic particles with a longest dimension <5 mm)
MPA	Marine Protected Area

MPI	Multidimensional Poverty Index
MS	Mediterranean Sea
MS	Member States
MSFD	Marine Strategy Framework Directive
MSSD	Mediterranean Strategy for Sustainable Development
Mt	Mountain
MTE	Metal Trace Elements

n	nano (10^{-9})
N	Nitrogen
N_2	molecular nitrogen
N_2O	Nitrous oxide
NAO	North Atlantic Oscillation
NDC	Nationally Determined Contributions
NGO	Non-Governmental Organization
NH_3	Ammonia
NH_4^+	Ammonium ion
Ni	Nickel
NI	Nitrification and urease inhibitors
NIS	Non-Indigenous Species
no	number
NO	Nitric oxide
NO_2	Nitrogen dioxide
NO_3	Nitrate

NO_3^-	Nitrate ion
NO_x	Nitrogen oxide
Nr	Reactive nitrogen
NRW	Non-Revenue Water
NT	No Tillage
NW	NorthWestern
NWFP	Non-Wood Forest Product

O_3	Ozone
OAR	Ocean Acidification Refugia
OCP	Organochlorinated phenyl
OECD	Organisation for Economic Co-operation and Development
OHCHR	Office of the High Commissioner for Human Rights
OME	Mediterranean Energy Observatory
OPHI	Oxford Poverty & Human Development Initiative
Osm	Osmole

P	Penta (10^{15})
P	Phosphorus
p	probability value (significance)
PAE	Phthalic Acid Ester
PAH	Polycyclic Aromatic Hydrocarbon
PAI	Pesticide Active Ingredients
Pb	Lead
PCB	Polychlorinated biphenyl
pCO_2	Partial pressure of carbon dioxide
PES	Payments for Ecosystem Services
PET	Potential Evapotranspiration
pH	Figure expressing the acidity or alkalinity of a solution on a logarithmic scale on which 7 is neutral, lower values are more acid and higher values more alkaline

PI	Precipitation Index
PM	Particulate Matter
PM10	PM with diameter below 10 µm
PM2.5	PM with diameter below 2.5 µm
POP	Persistent Organic Pollutant
ppb	parts per billion
PPP	Public-Private Partnership
PRA	Pest Risk Analysis
PS	Proactive Scenario
PSP	Paralytic Shellfish Poisoning
Psu	Practical salinity unit
PV	Photovoltaic
PVC	Polyvinyl chloride
R&D	Research and Development
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RCSM	Regional Climate System Model
RES	Renewable Energy Sources
resp.	respectively
RS	Reference Scenario
s	second
SC	Steering Committee
SD	Sustainable Development
SDG	Sustainable Development Goal
SDM	Species Distribution Models
Se	Selenium
SE	SouthEastern
SEMC	Southern and Eastern Mediterranean country
SIDA	Swedish International Development Cooperation Agency
SLM	Sustainable Land Management
SLP	Sea-Level Pressure
SO_2	Sulfur dioxide
SOC	Soil Organic Carbon
SOD	Second Order Draft
SoED 2019	State of the Environment and Development Report coordinated by Plan Bleu
SOM	Soil Organic Matter
SPI	Standardized Precipitation Index
SPM	Summary for Policymakers
SR1.5	IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways
SRES	IPCC Special Report on Emissions Scenarios
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SROCC	IPCC Special Report on the Ocean and Cryosphere in a Changing. Climate
SSP	Shared Socio-Economic Pathway
SST	Sea Surface Temperature
T	Tera (10^{12})
t	tonne
Ti	Titanium
toe	tonne of oil equivalent

TS	Transition Scenario
TWW	Treated Waste Water

UDHR	Universal Declaration of Human Rights
UfM	Union for the Mediterranean
UfM CCEG	Union for the Mediterranean Climate Change Expert Group
UHI	Urban Heat Islands
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
USD	American dollar

VBD	Vector-Borne Disease
VL	Visceral Leishmaniasis
VNR	Voluntary National Review
vs.	versus
VW	Virtual Water

W	Watt
WCRP	World Climate Research Programme
WDM	Water Demand Management
WeMO	Western Mediterranean Oscillation
WF	Water Footprint
WFD	Water Framework Directive
WFP	Wood Forest Products
WFPS	Water Filled Pore Space
WHO	World Health Organization
WMT	Western Mediterranean Transition
WNV	West Nile virus
WOCAT	World Overview of Conservation approaches and Technologies
WSUD	Water-Sensitive Urban Design
WUE	Water-Use Efficiency
WWTP	Wastewater Treatment Plant

yr	year

Zn	Zinc

$\delta^{11}B$	Boron isotope
$\delta^{13}C$	Carbon isotope
µ	micro
µM	micromolar, micromole per liter

ISO2
country codes

Iso Code	Country	Iso Code	Country
AL	Albania	**LB**	Lebanon
AT	Austria	**LT**	Lithuania
BA	Bosnia and Herzegovina	**LU**	Luxembourg
BE	Belgium	**LV**	Latvia
BG	Bulgaria	**LY**	Libya
CH	Switzerland	**MA**	Morocco
CY	Cyprus	**MC**	Monaco
CZ	Czech Republic	**ME**	Montenegro
DE	Germany	**MK**	The Republic of North Macedonia
DK	Denmark	**MR**	Mauritania
DZ	Algeria	**MT**	Malta
EE	Estonia	**NL**	The Netherlands
EG	Egypt	**NO**	Norway
ES	Spain	**PL**	Poland
FI	Finland	**PS**	State of Palestine
FR	France	**PT**	Portugal
GB	The United Kingdom of Great Britain and Northern Ireland	**RO**	Romania
GR	Greece	**RS**	Serbia
HR	Croatia	**SE**	Sweden
HU	Hungary	**SI**	Slovenia
IE	Ireland	**SK**	The Slovak Republic
IL	Israel	**SY**	Syrian Arab Republic
IT	Italy	**TN**	Tunisia
JO	Jordan	**TR**	Turkey

Table D.1 | ISO country codes

E

APPENDIX

Lists of Figures, Tables and Boxes

FIGURES

TABLES

BOXES

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MedECC
Mediterranean Experts on Climate and environmental Change

Union for the Mediterranean
Union pour la Méditerranée
الاتحاد من أجل المتوسط

UN environment programme

Mediterranean Action Plan
Barcelona Convention

Plan Bleu

ISBN: 978-2-9577416-0-1
DOI: 10.5281/zenodo.7224821