Climate change, tropical fisheries and prospects for sustainable development

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Abstract

Fisheries substantially contribute to the well-being of societies in both the tropics and extra-tropics, the latter through 'tele-coupling' – linkages between distant human-natural systems. Tropical marine habitats and fish stocks, however, are vulnerable to the physical and biogeochemical oceanic changes associated with rising greenhouse gas concentrations. These changes to fish stocks, and subsequent impacts on fish production, have substantial implications for the UN Sustainable Development Goals. In this Review, we synthesize the effects of climate change on tropical marine fisheries, highlighting the socio-economic impacts to both tropical and extra-tropical nations, and discuss potential adaptation measures. Driven by ocean warming, acidification, deoxygenation and sea level rise, the maximum catch potential of tropical fish stocks in some tropical Exclusive Economic Zones is projected to decline up to 40% by 2050s relative to 2000s under the RCP 8.5 emissions scenario. Climate-driven reductions in fisheries production and alterations in fish species composition will increase the vulnerability of tropical countries with limited adaptive capacity, including countries in the Pacific Island region. Thus, given the billions of people dependent on tropical marine fisheries in some capacity, there is a clear need to account for the effects of climate change on these resources and identify practical adaptations, when building climate-resilient sustainable development pathways.

Key Points:

- Tropical oceans will be the first where anthropogenic signals in physical and biogeochemical quantities exceed natural variability, with resulting impacts on socio-ecological systems
- Maximum catch potential in some of the tropical Exclusive Economic Zones is projected to decline by up to 40% by 2050s under continued high greenhouse gas emissions.
- Climate change impacts on tropical fisheries will affect sustainable development of both local economies and communities, and extra-tropical regions through ‘tele-coupling’ of human-natural systems such as seafood trade and distant-water fishing.
- The key impacts for developing tropical nations will be reduced capacity to achieve the UN Sustainable Development Goals related to food security (SDG2), poverty alleviation (SDG1) and economic growth (SDG8).

- Effective and practical adaptation solutions for both small-scale and industrial fisheries, built on the involvement of all appropriate stakeholders and supporting policies, are needed to sustain fisheries productivity in the tropics.
- The substantial predicted biological and social-economic impacts on tropical fisheries would be prevented if GHG mitigation actions keep global atmospheric warming below 1.5 ^{o}C relative to pre-industrial levels.

[H1] Introduction

Marine fisheries contribute substantially to the wellbeing of people and society, particularly in the tropics, where coastal communities depend on fisheries for food security, livelihoods, economic development and culture [1–3]. About 1.3 billion people live in tropical coastal areas, many of which rely on fisheries for food[4–6]. Indeed, fish is of major nutritional importance for both coastal and urban communities in many small island developing states (SIDS), contributing 50–90% of dietary animal protein in Pacific Island countries and territories (PICTs)[7], compared with 50% in West Africa[8,9], and 37% in Southeast Asia[10]. Communities in these regions are further highly dependent on wild-caught fish for micro-nutrients, such as zinc, iron, and omega-3 fatty acid[2,8], to avoid the 'hidden hunger' that results from micronutrient malnutrition[9] .

Tropical marine fisheries also make a significant contribution to the global fish catch. Between 2007 and 2016, for example, ~50% of the annual global fish catch (worth on average US$ 96 billion), was derived from tropical marine fisheries[11], which therefore underpin the economies of many SIDS[10,12]. For instance, the landed value **[G]** of the four main tuna species caught in the western and central Pacific Ocean was US$ 6.0 billion in 2018 (Ref[13]). Moreover, tuna-fishing license fees paid by the distant water fishing nations to operate in the exclusive economic zones (EEZs) **[G]** of several PICTs provides 30% to 90% of all (non-aid) government revenue[14]. It is not only large-scale industrial fisheries that are important, however. Small-scale fisheries contribute ~29% (US$ 31 billion) of the total landed value of fish in the tropics[11], and involve ~90% of the estimated 216 $\pm$ 6 million people[15] employed in marine fisheries[12]. Thus, in regions where employment opportunities are limited, industrial- and small- scale tropical fisheries provide numerous opportunities for coastal communities to earn income through harvesting and post-harvest operations[15–18].

Tropical marine fisheries also provide benefits for people in extra-tropical societies through 'tele-coupling'[19] — that is, environmental and socio-economic interactions between two or more linked areas over distance[20] (**Fig. 1**). Tele-coupling interactions between tropical fisheries and elsewhere include distant water fishing, the international seafood supply chain, transboundary fisheries resources and their governance. Any changes in the tropics therefore have the potential to propagate globally.

Indeed, the livelihoods dependent on tropical fisheries are increasingly threatened by multiple factors: overfishing[21,22], habitat degradation[23], pollution[24], sedimentation[25,26], invasive species[27], as well as various physical and biogeochemical responses to climate change, including warming, sea level rise, deoxygenation, acidification and altered nutrient concentrations. These latter CO_2-driven changes to the ocean — which are expected to increase in the coming decades —affect the physiology, behavior and interactions of both coastal and oceanic tropical marine fish species, leading to changes in their spatial distribution and abundance[28,29]. The very high vulnerability of tropical marine fisheries to climate change[30–32] could therefore undermine efforts to build sustainable development pathways for societies that depend strongly on the benefits from these fisheries, both within and outside of the tropics. Thus, there is an urgent need to comprehensively understand the risks of climate change to tropical fisheries to better inform adaptation measures.

In this Review, we consider the effects of climate change on tropical marine fisheries and discuss how these changes affect the use of fish in extra-tropical regions. The climate adaptation and mitigation measures most needed for tropical marine fisheries are described, highlighting options that could both support effective action and reduce the risk of adverse consequences on the tropical marine fisheries sector and their dependent human communities. The implications of climate change for sustainable development goals are also addressed.

Throughout this Review, the tropical regions are defined as regions between the Tropic of Cancer and the Tropic of Capricorn.

[H1] Climate impacts on tropical fisheries

Climate change threatens tropical marine fisheries, and in turn, the communities and economies that depend on those resources, both within and outside the tropics. Here, we begin by outlining the physical and biogeochemical changes associated with anthropogenic warming, followed by the response of tropical marine fish resources to these changes.

[H2] Physical and biogeochemical changes

Tropical marine fisheries are increasingly exposed to changes in the physical and biogeochemical properties of the ocean (including warming, sea level rise, deoxygenation, acidification and altered nutrient concentrations) attributed to rising concentrations of anthropogenic greenhouse gases, in particular to CO_2 emissions[33–35]. Indeed, tropical oceans are among the first places to show the emergence of anthropogenic signals of climate change, that is, variation in physical and biogeochemical parameters exceeding the historical natural range[36–38]. As many socio-ecological systems are naturally adapted to variability, any changes in ocean properties outside the range of observed natural variability will trigger impacts than have not occurred in the recent past[39].

For instance, the ocean is warming because it absorbs >90% of the excess energy accumulated through rising anthropogenic greenhouse gas concentrations[40,41]. Since the beginning of the 20th century, for example, sea surface temperature (SST) in the tropical ocean has risen by ~0.75°C (Refs [34,42]), with accelerated warming observed since 1980[43]. Tropical ocean warming is further modeled to continue and amplify throughout the 21st century (Ref [36]). By 2100, for instance, projections under RCP2.6 **[G]** and RCP8.5 **[G]** indicate tropical SSTs will be 0.8 ± 0.3°C and 2.9 ± 0.6°C higher than the 1986-2005 average, respectively[44]. However, even larger SST changes are expected in the equatorial Pacific compared to the southern subtropics owing to changes in regional wind patterns and ocean circulation[45].

Superimposed on the long-term warming are short-term extreme warm temperature events, so-called marine heatwaves[46], which have devastating impacts on marine ecosystems[47,48]. During the strong El Niño events of 1997-98 and 2015-16, for example, extreme ocean temperatures in the tropics and subtropics triggered unprecedented pan-tropical mass bleaching of corals[49]. The number of marine heatwaves days exceeding the 99th percentile have doubled in frequency over the period 1982 to 2016, and now occur four times in contrast to twice a year in 1982 (Ref[50]). Although better understanding on the physical drivers is still needed for forecasting marine heatwaves effectively[51], marine heatwaves are further projected to be 20 and 50 times more frequent under RCP2.6 and RCP8.5, respectively, when comparing 1850-1900 to 2081-2100, with the largest changes expected in the tropics[29, 50]. Extreme El Niño events, which also represent a form of marine heatwaves, are also projected to increase over the course of the 21st century under both RCP2.6 and RCP 8.5 (Ref[52–54]).

Warming of the tropical ocean also increases stratification of the upper water column[44,55], thereby reducing the exchange of oxygen-rich and oxygen-depleted water bodies above and below the thermocline, respectively. As the solubility of oxygen is reduced in warmer waters, these changes have decreased oxygen content by 0.09 to 0.34 μ mol kg^{-1} year^{-1} for 300-700m depths since the 1950s, also strengthening the oxygen gradient between the surface and the subsurface ocean layers[56–59]. Over the same time period, oxygen minimum zones — regions in the water column with the lowest oxygen concentrations, which are located in eastern parts of the tropical Pacific and Atlantic Oceans and the Arabian Sea —have expanded by 3–8% per decade[58–60]. While projected changes in oxygen minimum zones are uncertain[61,62], total oceanic oxygen content is projected to decline by 1.6–2.0% under RCP 2.6 and 3.2–3.7% under RCP 8.5 by 2100 (Ref [34]).

The ongoing oceanic uptake of anthropogenic CO_2 from the atmosphere has also increased acidity of tropical and other waters[34,63]. For example, ocean surface water pH has decreased by 0.013–0.03 units per decade over the past 25 years (Ref [44]), with the largest changes observed in the eastern equatorial Pacific and the Indian Ocean[36]. Surface ocean pH is projected to fall by 0.03–0.042 units (Ref [61]) and the seasonal amplitude of global mean surface ocean pH to increase by 16 ± 7% by 2100 under RCP 8.5 relative to present-day values[64]. As a consequence, extreme ocean acidity events will also become more frequent, more intense and last longer under increasing atmospheric CO_2 concentrations[65].

Rising sea levels -- caused by thermal expansion of the ocean, changes in ocean dynamics and loss of land ice -- also pose a threat to many tropical fish habitats, such as mangroves, seagrasses and coral reefs[66]. Sea levels have risen in all tropical ocean basins and are projected to continue in the 21st century[66–72]. The threats to coastal habitats and fisheries from sea level rises are exacerbated by increase in coastal extreme events such as tropical cyclone winds and rainfall.

[H2] Changes in net primary production

The marine food webs that support fisheries in oceanic and coastal areas are based on the net primary productivity (NPP) of phytoplankton, which in turn, is dependent on an adequate supply of nutrients, light and appropriate temperature. However, increased stratification of the water column, owing to upper ocean warming and freshening (increased precipitation), might inhibit the supply of nutrients to the photic zone (surface waters) [73,74], as observed in the tropical Pacific[74,75]. In combination with changes in light, nutrients, grazing and SST, such ocean stratification changes are projected to decrease tropical NPP by 7-16% under RCP8.5 by 2100 relative to 2006-2015 (Ref [44]), consistent with global reductions of <10% (Ref [61,75,76]). The warming-related decrease in NPP is projected to be amplified at higher trophic levels, resulting in a larger percentage decrease in fisheries catch than is accounted for by effects on NPP alone[76].

[H2] Changes in marine ecosystems

Physical and biogeochemical stressors are also affecting the distribution, abundance and reproduction of fish and invertebrate species, via ecosystems, with direct and indirect effects on the production of marine fisheries[39,77]. Coral reefs, mangroves and seagrasses — which provide feeding areas and habitats for part or all of fish lifespans — illustrate examples of such ecosystems vulnerable to anthropogenic stressors, including marine heatwaves[48,50] (**Fig. 2a**).

Coral reefs, which often dominate tropical coastal fish habitats, are among the marine ecosystems most vulnerable to ocean warming. The majority of reef-building corals are already near their upper thermal limits[78], and the median return time between pairs of severe coral bleaching events has diminished steadily since 1980 to 6 years[79]. Even if global warming is limited to 1.5°C, 70–90% of existing reef-buiding corals are expected to be lost by the end of the century[80]. In addition, ocean acidification is reducing calcium carbonate saturation levels, limiting coral capacity to build calcareous skeletons. Indeed, the critical threshold for chronic effects of climate change on coral reefs might already have been (or soon will be) reached[80] (**Fig. 2b**). Similarly, half the world's coastal wetlands, including seagrass meadows, salt marshes and mangroves, are thought to have been lost since the 19th century[81] through climatic and non-climatic drivers[48,50]. There is high confidence that these ecosystems will continue to be lost through warming and sea level rise, with some estimates of 20-90% loss by the end of the century depending on the emission scenario[36] (**Fig. 2b**).

Much like corals, marine ectothermic species (including all fishes and invertebrates) can only grow, reproduce and survive within specific temperature ranges, as determined by their physiology and ecology[82]. For tropical marine species, these thermal tolerances are more limited than temperate species[83], making them particularly sensitive to ocean warming[84]. As a result, the distribution of many marine fishes and invertebrates has shifted poleward, to deeper waters, or following ocean isotherms[85,86] where the prevailing environmental conditions (particularly temperature) favour growth and survival[85,86]. Observed and projected distributional shifts are estimated to be 30–130 km per decade poleward and 3.5 m per decade toward deeper waters[86–92]. These projected range shifts away from the tropics might decrease species richness in areas where environmental conditions have exceeded the tolerance limits of endemic species[86].

The aerobic capacity of fishes and invertebrates is also affected by decreasing water oxygen content and its interactions with ocean warming[93,94]. Ocean deoxygenation can limit important metabolic functions that impair growth and reproduction in fishes and invertebrates, as well as reducing their temperature tolerances and thus geographic ranges[95–97]. Ocean warming and deoxygenation also reduces the body size of some marine fishes and invertebrates, particularly in the tropics[98–101]. For example, the average maximum body size of marine fish in the tropics is projected to decrease by ~20% by 2050 relative to 2000 under RCP 8.5 (Ref [101]).

Collectively, the various stressors associated with climate change have widespread effects on tropical fisheries resources[36]. Thus, direct and indirect effects of continued greenhouse gas emissions are expected to substantially reduce the biomass of living marine resources in the tropics[102]. For example, projections from global-scale models of fisheries and marine ecosystems indicate that the total marine animal biomass in the tropics will decrease by 7.3 ± 3.1% under RCP 2.6 and 23.2 ± 9.5% under RCP 8.5 by 2100, relative to the 2000s[36]. Such decreases in animal biomass are largely driven by ocean warming and the decline in NPP in tropical waters resulting from climate change[103], illustrating a substantial risk to marine stocks.

[H2] Changes in marine fish stocks

Global marine fish catch has averaged between 80 and 91 million tonnes per year since 1990 (Refs [104,105]), with mean gross revenues fluctuating around US$ 100 billion annually[106]. These values do not include unreported catches and the 'true' annual average global fish catch is estimated to be 100-130 million tonnes since the 1980s (Ref [105]). However, post-2016 fish catches seem to have levelled off because many fish stocks are considered to be either fully exploited or over-exploited (that is, spawning biomass is below the reference values to achieve maximum sustainable yield **[G]**)[104,107–113]. Tropical fisheries have also expanded rapidly: annual catch has increased from 7.1 million tonnes (US$ 7.3 billion) in the 1950s, to 50 million tonnes in 2016 (US$ 89.7 billion) and the annual average catch estimates become 53.6 million tonnes when unreported catches are taken into account.

However, climate change threatens these fish stocks. Changes in temperature and phytoplankton production are related to the changes in fisheries catches and species composition in many tropical marine ecosystems since 1950[114–116]. Furthermore, analysis of fish population data shows that the maximum sustainable yield of 235 fish populations over 38 ecoregions has been reduced by 4.1% over the past 80 years[116] and increases in SST have led to negative changes in marine fisheries production in 8 of 47 large marine ecosystems between 1998 and 2006 (Ref

[114]). Historical catch data from tropical ecosystems also show substantial increases in the dominance of warm-water tolerant species since the 1970s that are related to ocean warming[116,117].

These observed changes are also projected to continue and amplify in the future. Global impact models, for example, predict decreases in maximum catch potential **[G]** of up to 40% in some tropical EEZs in 2050s [33] (**Fig. 3a/b**). The decrease in catch potential, driven largely by ocean warming and decrease in NPP, is projected to be particularly large in tropical Pacific and eastern tropical Atlantic regions under high emissions scenario. For instance, in the Indo-Pacific region, 3.5°C atmospheric warming is projected to decrease maximum catch potential by 46.8 ± 1.2%, as well as cause species turnover **[G]** of 36.4 ± 2.1% (Refs [31,118]). In the tropical Pacific region, more than half of (mainly coastal) the fisheries important fish and invertebrate species are also projected to become locally extinct by 2100 under RCP 8.5 (Refs [29,44]), contributing to the large decrease in the catch potential. Overall, by 2100, changes in biomass, catch potential and species composition are projected to be 2–4 times greater under RCP 8.5 compared to the RCP 2.6 (Ref [34]). Similarly, an index that integrates the projected effects of ocean warming, deoxygenation and acidification for exploited fish stocks in the tropics indicates that the risk of impacts increases from moderate-to-high under the RCP 2.6, to very high risk under the RCP 8.5 (Ref [119]).

[H2] Effects on communities and economies

The previously discussed impacts of climate change on tropical ecosystems and fish stocks will have profound economic[120] and social[121] effects. In the absence of improved management, marine fisheries revenues are projected to decline in 89% of the world's fishing countries under the RCP 8.5 by 2050, relative to their current status[31]. The greatest negative impact on maximum revenue potential (MRP) **[G]** is in tropical regions, with EEZs in the central Pacific and central Atlantic being affected the most (**Fig 3c**). The MRP is projected to decline by an average of 33% in the tropics by the 2050s under RCP 8.5[31] (Fig. 3c). The EEZs with the largest average decrease in MCP mostly belong to SIDS[31]. However, projected reductions in MCP in a country's EEZ do not necessarily translate to proportional losses in revenue[31], for example, if national vessels fish not only in their own EEZs but also in those of other countries or in international waters.

The implications of climate change for the socio-economic benefits derived from fisheries also vary by region, with the greatest effects occurring in low-income, food-deficit tropical countries, including SIDS, African and Asian countries or regions, for example, West Africa and Southeast Asia[31]. These developing countries usually rely heavily on fish and fisheries as a major source of micronutrients for healthy diets as well as for livelihood and employment opportunities[122,123], but have a relatively low capacity to adapt[121,124]. Therefore, adverse effects of climate change on the catch and total fisheries revenues in these countries are proportionally greater than in countries with a high human development index **[G]** and a large, diverse economy[2,125].

Climate change might also lead to the loss of 10–40% of species suitable for marine aquaculture in the tropics and subtropics by 2050 (Ref [126]). The losses in richness of potential mariculture species are projected to be higher throughout much of the tropics under climate change[126–128], particularly impacting Asian countries that contribute the most to mariculture production. Furthermore, the potential area suitable for tropical mariculture is estimated to decline by 3.69% ± 0.59 by the 2090s under RCP 8.5, relative to the 66 million km^2 available in the 2000s[126], limiting the scope for seafood production expansion needed to meet growing demand.

Examples of the expected effects of climate change on fisheries resources and on the socio-economic benefits they provide for communities and economies in PICTs, Brazil and coastal African nations are included in **Box 1, Box 2 and Box 3,** respectively. Fisheries reform has potential to offset the consequences of climate change, however. Indeed, addressing current inefficiencies, adapting to changes in productivity and implementing improvements in institutional management could provide benefits exceeding the adverse effects of climate change and drive net increases in yields and profits[129].

[H1] Tele-coupling of extra-tropical regions

Seafood is the most highly-traded food commodity globally[104,130]. Trade has increased in recent decades due to greater demand and willingness to pay for high-quality produce[131]. Tropical nations often gain considerable benefits from this international trade, especially in exporting countries that have low per capita fish consumption but large offshore fisheries (such as Namibia) or where the rate of production from wild-caught fisheries has increased faster than local demand for fish (such as in Ghana, Thailand and the Philippines)[132]. The partial dependence of developed extratropical countries on tropical fisheries resources exposes them to the consequences of climate change in tropical regions via tele-coupling (**Fig. 1**). For instance, the projected declines in MCP of up to 40% by 2020 for many fish species, combined with increased demand for seafood by many tropical developing countries due to economic growth, could reduce the future supply of seafood to extra-tropical countries[31]. Much of the trade involves high-value species (especially tuna, **Supplementary Table 1** exported from developing tropical countries to developed extratropical nations[130–133131,133] (**Fig. 4**). During 2015–2017, for example, ~46% of fish caught by Caribbean countries was exported to North America, and 20% to the European Union[134].

However, low value, small pelagic fish such as anchovies and sardines also represent a major proportion of fish exports, especially in South America, West Africa[135,136], Thailand and Vietnam[137]. These fish, caught in tropical areas, are often converted to fishmeal, a key component of feeds for the aquaculture of salmon, trout, and shrimp, traded internationally in the extratropics[138,139]. Indeed, in 2016, ~12% of marine fisheries production was used for non-food purposes, of which 74% (~15 million tonnes) was converted to fishmeal and fish oil[104,140140]. Although climate change models predict that marine ecosystems should continue to produce good harvests of small pelagic fish, the sustainability and profitability of the fishmeal trade (and maintenance of its associated economic benefits for fishing communities) will depend on interactions with fisheries management; market stabilization measures; improvements in technology; international cooperation, development of soybean-based fishmeal substitutes[141], and implementation of global rules for seafood markets aimed at improving ecosystem health[142–145].

A potent example of the consequences of tele-coupling on extra-tropical economies and communities is provided by the effects of climate-driven changes in the distribution, catch composition and catch potential of Peruvian anchoveta (a small pelagic fish used to produce fishmeal[139]) on aquaculture operations in northern latitudes. Salmon aquaculture in Norway, Chile, the UK and Canada provides over 85% of global farmed salmon production[146] and, with the exception of Chile, these countries depend heavily on imported fishmeal, including that derived from Peruvian anchoveta[143]. The pronounced effects of ENSO-mediated climatic variability on annual harvests of Peruvian anchoveta led tele-coupled aquaculture industries to develop mechanisms to cope with dramatic variations in the supply of anchoveta. In particular, the wild-fish component in aquaculture feed is being replaced with soybean meal, rendered terrestrial animal products, and seafood or aquaculture processing wastes[142]. These innovations might enable the consumption of farmed fish to increase by 2050 even under RCP 8.5 (Ref [145]), thereby limiting the contribution of climate change to the tele-coupled dependence of salmon farming on Peruvian anchoveta.

Implementation of sustainable fisheries operations by distant water fishing nations in the EEZs of many SIDS and coastal states[159] delivers significant benefits for the well-being of communities and economies in tropical countries[14]. However, it also important for extra-tropical countries. Similarly, fisheries management legislation in extra-tropical countries can affect the socioeconomic benefits derived from fisheries in tele-coupled tropical regions. For example, the Chinese government's decision to reduce fuel subsidies by 60%, and its pending legislation to improve the monitoring of Chinese vessels fishing in the EEZs of other nations, are expected to reduce the high pressure exerted by Chinese vessels on fish stocks in Senegal. These measures should improve the status of marine resources in that country, and the contributions of local fisheries to livelihoods and food security[147,148].

The effects of climate change on tropical fisheries also influence the profitability and employment opportunities of fish-processing industries in extra-tropical regions such as Spain, Italy, France, the USA and Japan. Spain, for example, is the most important producer of canned tuna in Europe (the second largest globally after Thailand)[149], employing more than 18,000 people in 2016 (Refs [15,150]), and responsible for investment of hundreds of millions of Euros in fishing and processing industries in Ecuador, El Salvador, Guatemala and Venezuela – an investment that has provided about 35,000 jobs in these countries[149]. Raw materials for the world's tuna processing industries are often supplied by distant water fleets or imports from SIDS and developing countries in African, Caribbean and Pacific regions. Thus, climate-related changes in the distribution and abundance of tuna – including the poleward shift of albacore, Atlantic bluefin tuna and southern bluefin tuna[151,152] – threaten not only the national plans of SIDS and developing countries to maximize the contributions of their marine fisheries resources for food security, employment and economic development[153], but also investments by distant water fishing nations in tropical developing countries.

[H1] Implications for sustainable development

Tropical marine resources support important aspects of sustainable development, specifically related to the United Nation Sustainable Development Goals on food security (SDG2) and economic development to eliminate poverty (SDG1). It is clear that adaptations that maintain the supply of fish for food security in tropical countries need to address both the effects of climate change on coastal fish habitats and fish stocks as well as the effects of population growth and other socioeconomic factors on the availability of fish per capita. Win-win and 'no-regrets' solutions (**Supplementary Table 2**) (that is, actions that generate net social benefits under all future scenarios and consequences of climate change[154]) are needed[33,122,134]. The Pacific Islands' approach (**Box 1**) demonstrates that adverse effects of climate change on one marine fisheries resource can sometimes be addressed by modifying the way in which another such resource is used. Exemplary management of tuna in the Western and Central Pacific Ocean[155], for example, enables Pacific Island governments to allocate an increased, albeit still minor, proportion of the regional tuna resource to domestic food security[156]. Importantly, climate-driven redistribution of tuna is not expected to affect this capability because ample tuna is still expected to be available for this purpose[122,157].

Two other implications of the Pacific Islands' situation stand out. First, climate justice[158] needs to extend to the fisheries sector because tuna-dependent Pacific Island economies produce a trivial percentage of global greenhouse gas emissions. This fact needs to be recognized and PICTs enabled to retain the important socio-economic benefits they receive from tuna[14], regardless of climate-driven redistribution of tuna resources[123]. Second, the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC) will increasingly need to collaborate as climate change alters the distributions of transboundary tuna stocks. Close collaboration between these two regional fisheries management organizations is expected to reduce the potential for conflict arising from species on the move[159]. Moreover, improved co-ordination of harvest strategies across the jurisdictions of WCPFC and IATTC will help to ensure the sustainability of tropical Pacific fisheries resources.

The wide spectrum of potential climate-related changes influence the services provided by tropical marine ecosystems (including provisioning **[G]**, regulating **[G]**, supporting **[G]** and cultural services **[G]**) in various ways, thereby differentially affecting the abilities of SIDS and other developing countries to achieve their sustainable development goals[160–162]. However, the effects of climate change on the services provided by marine ecosystems often have the largest direct effects on SDG 2 (eliminating hunger)[162] because declines in food production are common when marine species shift their distributions and/or decrease in biomass. However, shifts in the distribution of fish species also hinder progress towards SDG 1 (poverty alleviation) and SDG 8 (economic growth and job creation). Interestingly, although the projected shifts in tuna biomass within the tropical Pacific Ocean[123,157] are expected to make it more difficult for PICTs in the Western and Central Pacific Ocean (which are heavily dependent on marine ecosystems[14,121,163]) to achieve their sustainable development goals, the same shifts are likely to boost the ability of countries in the eastern Pacific to attain theirs[161].

[H1] Adaptation and mitigation measures

Practical and effective adaptations to assist fishers, local communities, industries and governing institutions in SIDS and other tropical developing countries to sustain their fisheries production in the face of climate-related and climate-unrelated stressors[32,121] fall into three broad categories: ecosystem-based solutions, built-environment solutions, and institutional/policy-based solutions. Ecosystem-based adaptations rely on the management, conservation and restoration of fish habitats and fish stocks to provide optimal ecosystem services despite climate change, including sequestration of carbon to mitigate greenhouse gas emissions[164,165]. Built-environment adaptations[166,167] often involve designing coastal infrastructure to cope with sea-level rise in ways that minimize barriers to the landward migration of mangrove and seagrass habitats[33,122]. Institutional or policy-based adaptations[168–170] include practices and policies that support climate-informed, community-based responses to sustain catches within established social governance and economic systems[171]. Additional steps are required to limit greenhouse gas emissions and thereby increase the likelihood that these adaptations will succeed.

[H2] Adaptation of small-scale fisheries

Various practical, cost-effective adaptations could help to maintain the contributions of small-scale fisheries to food security and livelihoods in SIDS and other tropical developing countries[122]. Whenever possible, such adaptations should address present-day factors that affect access to fish for food security as well as the effects of climate change[122,172] (**Supplementary Table 2**). 'Win-win' adaptations and supporting policies revolve around integrated coastal management to safeguard fish habitats, but can also include diversifying fishing methods[125]. One of the examples is to support coastal communities to progressively transfer fishing effort from coral reefs and other threatened coastal habitats to large and small pelagic fish species in near-shore waters to meet shortfalls in fish supply (Supplementary Table 2)[122,173].

Primary fisheries management[174] approaches are also needed to maintain the reproductive potential of fish stocks in data-poor contexts. Improving fisheries management and rebuilding over-exploited or depleted fish stocks can help alleviate climate-induced decrease in potential fisheries production on actual catches[129,175]; however, the effectiveness of such adaptation measures is likely to be lower in many tropical developing countries, and in particularly in small-scale fisheries, where capacity for effective fisheries management is not ideal. As such, enhancing fisheries management capacity, from gathering and utilizing scientific information to fisheries governance, is an important part of the portfolio of adaptation measures for tropical fisheries.

For many small-scale coastal fisheries, community-based fisheries management is an effective method of adaptation to climate change because it is based on iterative cycles of learning from and responding to changing conditions[176]. As evidence of the potential contribution of community-based management of fisheries in vulnerable regions, the government of Solomon Islands has identified community-based resource management as a key tool for building the capacity to adapt to climate change[177]. Similarly, communities in Timor L'este have successfully experimented with small-scale fish aggregating devices[178,179] as a response to changes in species distribution resulting from climate change[180]. Community-based fisheries management requires the participation of communities and resource users in decision-making activities and the incorporation of local institutions, customary practices and knowledge systems into management processes[181].

Community-based management can take many forms, including locally managed marine areas, territorial user rights, customary marine tenure, taboo areas[182] (spatial closures), and periodic harvesting (temporal) closures. These diverse approaches share three characteristics that provide a foundation for effective adaptation[176,183]. First, community-based management is often characterized by experimentation and learning, which are critical components of adaptation solutions in the context of uncertainty and change[32,184]. For example, periodic harvesting closures, a common marine management approach in the western Pacific, involves iterative cycles of experimentation, evaluation, and adjustment[185]. Appropriate spatial and temporal closures can help to maintain fish stocks, fisheries yield, and catch efficiency, thus building ecological resilience and reducing social and ecological vulnerability to climate change[186,187]. Second, community-based fisheries management prioritizes local and indigenous knowledge, which is essential for climate change adaptation[188]. For example, in the Torres Strait Islands, local knowledge about past climactic patterns has been used to design rock walls, wind breaks and the planting of native coastal species to reduce climate vulnerability[189]. Third, the flexibility inherent in many community-based fisheries management approaches supports effective adaptation. For example, changes in permitted equipment or target species enable responses to climate-driven changes arising from shifts in the range of a species or changes in abundance within its range[190,191].

The steps to build climate resilience in tropical fisheries through effective community-based fisheries management might involve promoting trans-disciplinary collaboration, including provision of the necessary expertise to inform stakeholders about climate-driven risks to fish habitats, fish stocks and catches; facilitating the participation of these stakeholders; monitoring the wider fisheries system for the effects of climate change; and allocating resources to enable implementation of an ecosystem approach to fisheries management[171]. The contributions of community-based and ecosystem-based fisheries management to building climate resilience is mediated by how well decision-making institutions fit their social-ecological conditions, effective communication processes among key stakeholders and key leaders, effective cooperation among groups and political management skills as well as global action on climate change[192,193].

[H2] Adaptation of industrial fisheries

The fisheries reform[129] to address current inefficiencies, respond to changes in productivity and improve institutional management, is likely to contribute to reducing the consequences of climate change for industrial fisheries under good national governance. However, climate-driven shifts in distributions of fish species across political boundaries require higher levels of collaboration to avoid disputes that can impair the sustainability of co-managed fisheries[159,194,195]. Some co-operative fisheries management arrangements in the tropics are flexible enough to respond reasonably effectively to transboundary redistribution of biomass[34]. A prime example is the Nauru Agreement (signed by Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu), which addresses the effects of climatic variability and climate change on the distribution of tuna stocks within the combined EEZs of the eight countries[123]. However, projected shifts in tuna from the combined EEZs into international waters[123], and an overall decrease in tuna production across the region in the long term[161], remain key challenges, particularly under RCP 8.5 (**Box 1**).

Ultimately, effective management of transboundary fish stocks in the face of climate change will depend on identifying all self-replenishing populations within the geographical range of the species; modelling the response of each population to climate change; and identifying the stakeholders for each current and redistributed population[123,196,197]. New combinations of stakeholders require the development of co-operative sustainable harvest strategies informed by changing ocean conditions. Effective management of the large transboundary stocks that underpin several tropical industrial fisheries also requires improved monitoring, modelling and decision support frameworks. Built-environment options, such as improved climate forecasting and early warning systems, not only for the extreme events that affect fishing vessel and crew safety at sea, but also for geographical shifts in biomass of target fish species, will also facilitate sustained operation of industrial fisheries, and the equitable sharing of economic benefits derived from them, as the climate continues to change[36].

[H2] Greenhouse gas emission mitigation

Ultimately, the root causes of climate-driven changes in tropical marine fisheries must be addressed[198]. Climate models indicate that mitigating greenhouse gas emissions and keeping global atmospheric warming below 1.5 ^{o}C relative to pre-industrial levels avoids substantial biological and social-economic effects on tropical fisheries[118,199]. Implementation of the Paris Agreement would help to safeguard the annual global catch of high-value fish species and billions of dollars of revenue for fishers and seafood workers[199]. Similar benefits are also expected for tropical developing countries and tele-coupled extra-tropical countries.

Implementation by all countries of the national determined contributions stated in the Paris Accord[200] would help to achieve the necessary mitigation of emissions. Although many tropical developing countries produce very low levels of greenhouse gases compared to developed nations, the tropical marine fisheries sector can still contribute meaningfully to the global mitigation effort. The mangrove, seagrass and saltmarsh habitats that sustain fish stocks and coastal communities throughout much of the tropics are carbon sinks[201–203] that are an important part of the portfolio of mitigation options for many tropical countries[200]. However, damage to these ecosystems due to deforestation and habitat degradation is causing 0.15–1.02 billion tons of CO_2 to be released annually[204]. These emissions are equivalent to 3–19% of those caused by global deforestation, and result in economic damage of $US 6–42 billion annually[204]. Protection of mangrove, seagrass and saltmarsh ecosystems is imperative to maintain their capacity to remove greenhouse gas from the atmosphere[36]. In Columbia, mangroves and seagrasses in marine protected areas account for 49–94% of the nation's annual carbon capture and provide economic benefits totaling €44–295 million per year[205]. Small-scale fishers have potential roles as carbon stewards in projects designed to deliver payments for ecosystem services[206,207], although skeptics suggest that such schemes only facilitate 'ocean grabbing' and effectively cede control of coastal ecosystems to transnational companies seeking to offset their carbon emissions[208]. Thus, although the climate adaptation and mitigation measures taken by the tropical marine fisheries sector offer much potential for success, their effectiveness will depend on strong mitigation of greenhouse gas emissions and socio-economic conditions that support an adequate adaptive capacity[198].

Small-scale fisheries, industrial fisheries and aquaculture operations in tropical countries (and globally) also have a role to play in reducing greenhouse gas emissions. Practical adaptations enabling the sector to do this have been assembled by the United Nations Food and Agriculture Organisation[33]. Fisheries improvement ranging from increasing the efficiency of fishing boats to adjustment or adaptation of fishing methods are also considered as useful mitigation measures for tropical small-scale fisheries. Greenhouse gas emissions from small fishing vessels can be reduced by use of more efficient engines, larger propellers, improved vessel shapes and simply by reducing the mean speed of vessels[33]. Where small-scale tuna fisheries are needed to increase fish supply and ensure food security in SIDS, emissions can be reduced by fishing around fish aggregating devices anchored close to the coast[209].

[H1] Summary and future perspectives

Fisheries have an important role in supporting food security and livelihoods in tropical countries, and in extra-tropical regions through socio-economic tele-coupling (for example, via distant-water fishing and seafood trade). The direct and indirect effects of climate change are projected to impair tropical marine ecosystems and fisheries, reducing their contributions to human well-being in both of these contexts. To reduce the effect of greenhouse gas emissions on both tropical and non-tropical regions, the root causes of problems now evident in the tropics need to be recognized and rectified. Effective climate change adaptation and mitigation solutions require stakeholder commitment and involvement, as well as appropriate supporting policies.

The science linking physical changes (warming, sea level rise) and biogeochemical alterations (acidification, deoxygenation) to the ocean to the physiological and ecological responses of fish species is developing rapidly and giving rise to more robust predictive models. However, there is an urgent need to identify robust, practical adaptations to maintain the vital contributions that tropical fisheries make to communities and economies as the abundance and distribution of fisheries resources are re-arranged by continued greenhouse gas emissions. Until global emissions conform to levels that will limit warming to 1.5 ^{o}C, it is also essential that policy frameworks are developed to support priority adaptations.

These policy frameworks must embrace entire supply chains because even local small-scale fisheries are connected to large marine ecosystems and global trading networks through diverse and multiscale linkages. This complexity poses challenges for the design of science-based adaptations and supporting policies - the responses of fishers and workers in seafood industries to perceived change can be reactive or proactive, autonomous at the individual level or collective, and planned or unplanned[210] but these can be steered effectively by the widely endorsed FAO guidelines for sustaining small-scale fisheries[211].

Understanding the societal impacts of climate change on fisheries and guiding effective adaptive responses requires scientists to step outside their existing interdisciplinary collaborative frame (which is typically limited to Earth and ocean sciences, ecology and economics) to include the study of geopolitical policy, knowledge accrual and communication, human agency, values and behaviour[212,213]. Including these fields in future research will improve the science and policy communities' understanding of the effects of climate change, and improve the knowledge and perception of climate change and fisheries by fishing communities, allowing them to integrate this understanding with their value systems, incentives and capacities to adapt[32]. Explicit consideration of ethical values in the human–Earth relationship are already attracting increased attention in the Earth sciences[214]. Geoethics and human-rights based governance of small-scale fisheries have been compared[215] pointing to a promising convergence of these disparate fields. This enlarged Earth system science, guided by an emergent emphasis on geoethics, may be better placed to serve humanities' transition to sustainability in the anthropocene, including a transition to sustainable and resilient fisheries in a changing climate.

References

1. Dyck, A. J. & Sumaila, U. R. Economic impact of ocean fish populations in the global fishery. *J. Bioecon.* **12**, 227–243 (2010).
2. Golden, C. D. *et al.* Nutrition: Fall in fish catch threatens human health. *Nature* **534**, 317–320 (2016).
3. Teh, L. C. L. & Pauly, D. Who brings in the fish? The relative contribution of small-scale and industrial fisheries to food security in Southeast Asia. *Front. Mar. Sci.* **5**, 44 (2018).
4. Gillet, R. Fisheries in the Economies of Pacific Island Countries and Territories. Noumea, New Caledonia: Pacific Community. (2016).
5. Kawarazuka, N. & Béné, C. Linking small-scale fisheries and aquaculture to household nutritional security: an overview. *Food Secur.* **2**, 343–357 (2010).
6. Sale, P. F. *et al.* Transforming management of tropical coastal seas to cope with challenges of the 21st century. *Mar. Pollut. Bull.* **85**, 8–23 (2014).
7. Bell, J. D. *et al.* Planning the use of fish for food security in the Pacific. *Mar. Policy* **33**, 64–76 (2009).
8. Hicks, C. C. *et al.* Harnessing global fisheries to tackle micronutrient deficiencies. *Nature* **574**, 95–98 (2019).
9. Kennedy, G., Nantel, G. & Shetty, P. The scourge of 'hidden hunger': global dimensions of micronutrient deficiencies. *Food Nutr. Agric.* 8–16 (2003).
10. Teh, L. S. L., Teh, L. C. L. & Sumaila, U. R. Quantifying the overlooked socio-economic contribution of small-scale fisheries in Sabah, Malaysia. *Fish. Res.* **110**, 450–458 (2011).
11. Pauly, D. & Zeller, D. Sea Around Us Concepts, Design and Data. (2015). Available at: http://www.seaaroundus.org.
12. Béné, C. Small-scale fisheries: assessing their contribution to rural livelihoods in developing countries. *FAO Fish. Circ.* **1008**, 46 (2006).
13. Williams, P. & Reid, C. *Overview of Tuna Fisheries in the Western and Central Pacific Ocean, including Economic Conditions-2017. WCPFC Sci. Comm*. (SC14-2018/GN-WP-01 66pp, 2018).
14. FFA. Tuna Development Indicators 2016. *Pacific Islands Forum Fisheries Agency.* (2017). Available at: https://ffa.int/system/files/FFA Tuna Development Indicators

Brochure.pdf.

15. Teh, L. C. L. & Sumaila, U. R. Contribution of marine fisheries to worldwide employment. *Fish Fish.* **14**, 77–88 (2013).

16. Jentoft, S. Life above water—essays on human experiences of small-scale fisheries. *TBTI Glob. B. Ser.* **1**, (2019).

17. Kurien, J. SSF guidelines: The beauty of the small. *Samudra Rep.* 30–36 (2016).

18. Teh, L. S. L., Teh, L. C. L. & Sumaila, U. R. A global estimate of the number of coral reef fishers. *PLoS One* **8**, e65397 (2013).

19. Alberti, M. *et al.* Research on coupled human and natural systems (CHANS): approach, challenges, and strategies. *Bull. Ecol. Soc. Am.* **92**, 218–228 (2011).

20. Liu, J., Hull, V., Luo, J., Yang, W. & Liu, W. Multiple telecouplings and their complex interrelationships. *Ecol. Soc.* **20**, (2015).

21. Cinner, Je. & McClanahan, T. R. Socioeconomic factors that lead to overfishing in small-scale coral reef fisheries of Papua New Guinea. *Environ. Conserv.* **33**, 73–80 (2006).

22. McClanahan, T. R., Hicks, C. C. & Darling, E. S. Malthusian overfishing and efforts to overcome it on Kenyan coral reefs. *Ecol. Appl.* **18**, 1516–1529 (2008).

23. Gardner, T. A., Côté, I. M., Gill, J. A., Grant, A. & Watkinson, A. R. Long-term region-wide declines in Caribbean corals. *Science* **301**, 958–960 (2003).

24. Islam, M. S. & Tanaka, M. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. *Mar. Pollut. Bull.* **48**, 624–649 (2004).

25. Hodgson, G. & Dixon, J. A. Logging versus fisheries and tourism in Palawan: An environmental and economic analysis. (1988).

26. Hodgson, G. & Dixon, J. A. Sedimentation damage to marine resources: Environmental and economic analysis. *Resour. Environ. Asia's Mar. Sect.* 421–426 (1992).

27. Côté, I. M., Green, S. J. & Hixon, M. A. Predatory fish invaders: insights from Indo-Pacific lionfish in the western Atlantic and Caribbean. *Biol. Conserv.* **164**, 50–61 (2013).

28. Lehodey, P., Senina, I., Calmettes, B., Hampton, J. & Nicol, S. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. *Clim. Change* **119**, 95–109 (2013).

29. Asch, R. G., Cheung, W. W. L. & Reygondeau, G. Future marine ecosystem drivers,

biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change. *Mar. Policy* (2017). doi:https://doi.org/10.1016/j.marpol.2017.08.015

30. Jones, M. C. & Cheung, W. W. L. Multi-model ensemble projections of climate change effects on global marine biodiversity. *ICES J. Mar. Sci. J. du Cons.* fsu172 (2014).
31. Lam, V. W. Y., Cheung, W. W. L., Reygondeau, G. & Sumaila, U. R. Projected change in global fisheries revenues under climate change. *Sci. Rep.* **6**, 32607 (2016).
32. Cinner, J. E. *et al.* Building adaptive capacity to climate change in tropical coastal communities. *Nat. Clim. Chang.* 1 (2018).
33. Barange, M. *et al.* Impacts of climate change on fisheries and aquaculture. *Synth. Curr. knowledge, Adapt. Mitig. options. Rome Food Agric. Organ. United Nations* (2018).
34. Pörtner, H. O. *et al.* IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. *IPCC Intergov. Panel Clim. Chang. Geneva, Switz.* (2019).
35. Bindoff, N. L. *et al.* Detection and attribution of climate change: from global to regional. (2013).
36. Bindoff, N. L., Cheung, W. L. & Kairo, J. G. Changing Ocean, Marine Ecosystems, and Dependent Communities. in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds. Pörtner, H.-O. et al.) 198 (IPCC, 2019).
37. Rodgers, K. B., Lin, J. & Frölicher, T. L. Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth system model. *Biogeosciences* **12**, 3301–3320 (2015).
38. Frölicher, T. L., Rodgers, K. B., Stock, C. A. & Cheung, W. W. L. Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. *Global Biogeochem. Cycles* **30**, 1224–1243 (2016).
39. Pörtner, H.-O. *et al.* Ocean systems. *Clim. Chang. 2014 Impacts, Adapt. Vulnerability. Part A Glob. Sect. Asp. Contrib. Work. Gr. II to Fifth Assess. Rep. Intergov. Panel Clim. Chang.* 411–484 (2014).
40. Abram, N. *et al.* Framing and Context of the Report. in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (2019).
41. Cheng, L. *et al.* Record-Setting Ocean Warmth Continued in 2019. (2020).
42. Huang, B. *et al.* Extended reconstructed sea surface temperature version 4 (ERSST. v4).

Part I: Upgrades and intercomparisons. *J. Clim.* **28**, 911–930 (2015).

43. Cheng, L., Abraham, J., Hausfather, Z. & Trenberth, K. E. How fast are the oceans warming. *Science* **363**, 128–129 (2019).

44. IPCC. Summary for Policymakers. in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (ed. H.- O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. W.) (IPCC, 2019).

45. Xie, S.-P. *et al.* Global warming pattern formation: Sea surface temperature and rainfall. *J. Clim.* **23**, 966–986 (2010).

46. Hobday, A. J. *et al.* A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* **141**, 227–238 (2016).

47. Frölicher, T. L. & Laufkötter, C. Emerging risks from marine heat waves. *Nat. Commun.* **9**, 650 (2018).

48. Smale, D. A. *et al.* Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Chang.* **9**, 306–312 (2019).

49. Hughes, T. P. *et al.* Global warming and recurrent mass bleaching of corals. *Nature* **543**, 373–377 (2017).

50. Oliver, E. C. J. *et al.* Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* **9**, 1–12 (2018).

51. Holbrook, N. J. *et al.* Keeping pace with marine heatwaves. *Nat. Rev. Earth Environ.* (2020).

52. Frölicher, T. L., Fischer, E. M. & Gruber, N. Marine heatwaves under global warming. *Nature* **560**, 360 (2018).

53. Collins, M. *et al.* Extremes, Abrupt Changes and Managing Risk. in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* (eds. Pörtner, H.-O. et al.) (2019).

54. Cai, W. *et al.* Increasing frequency of extreme El Niño events due to greenhouse warming. *Nat. Clim. Chang.* **4**, 111–116 (2014).

55. Capotondi, A., Alexander, M. A., Bond, N. A., Curchitser, E. N. & Scott, J. D. Enhanced upper ocean stratification with climate change in the CMIP3 models. *J. Geophys. Res. Ocean.* **117**, (2012).

56. Ganachaud, A. S. *et al.* Observed and expected changes to the tropical Pacific Ocean.

Vulnerability Trop. Pacific Fish. Aquac. to Clim. Chang. Secr. Pacific Community, Noumea, New Caledonia 101–187 (2011).

57. Stramma, L., Johnson, G. C., Sprintall, J. & Mohrholz, V. Expanding oxygen-minimum zones in the tropical oceans. *Science* **320**, 655–658 (2008).
58. Ito, T., Minobe, S., Long, M. C. & Deutsch, C. Upper ocean O_2 trends: 1958–2015. *Geophys. Res. Lett.* **44**, 4214–4223 (2017).
59. Schmidtko, S., Stramma, L. & Visbeck, M. Decline in global oceanic oxygen content during the past five decades. *Nature* **542**, 335–339 (2017).
60. Helm, K. P., Bindoff, N. L. & Church, J. A. Observed decreases in oxygen content of the global ocean. *Geophys. Res. Lett.* **38**, (2011).
61. Bopp, L. *et al.* Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**, 6225–6245 (2013).
62. Cocco, V. *et al.* Oxygen and indicators of stress for marine life in multi-model global warming projections. *Biogeosciences* **10**, 1849–1868 (2013).
63. Doney, S. C., Fabry, V. J., Feely, R. A. & Kleypas, J. A. Ocean acidification: the other CO_2 problem. *Ann. Rev. Mar. Sci.* **1**, 169–192 (2009).
64. Gattuso, J.-P. *et al.* Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science* **349**, aac4722 (2015).
65. Burger, F. A., Frölicher, T. L. & John, J. G. Increase in ocean acidity variability and extremes under increasing atmospheric CO_2. *Biogeosciences Discuss* (2020).
66. Oppenheimer, M. *et al.* Sea level rise and implications for low lying Islands, coasts and communities. (2019).
67. Moon, J., Song, Y. T., Bromirski, P. D. & Miller, A. J. Multidecadal regional sea level shifts in the Pacific over 1958–2008. *J. Geophys. Res. Ocean.* **118**, 7024–7035 (2013).
68. Han, W. *et al.* Intensification of decadal and multi-decadal sea level variability in the western tropical Pacific during recent decades. *Clim. Dyn.* **43**, 1357–1379 (2014).
69. Thompson, P. R. & Mitchum, G. T. Coherent sea level variability on the North Atlantic western boundary. *J. Geophys. Res. Ocean.* **119**, 5676–5689 (2014).
70. England, M. H. *et al.* Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nat. Clim. Chang.* **4**, 222–227 (2014).
71. Hamlington, B. D. *et al.* Uncovering an anthropogenic sea-level rise signal in the Pacific

Ocean. *Nat. Clim. Chang.* **4**, 782–785 (2014).

72. McGregor, S. *et al.* Recent Walker circulation strengthening and Pacific cooling amplified by Atlantic warming. *Nat. Clim. Chang.* **4**, 888–892 (2014).
73. Le Borgne, R. *et al.* Vulnerability of open ocean food webs in the tropical Pacific to climate change. *Vulnerability Trop. Pacific Fish. Aquac. to Clim. Chang.* 189–250 (2011).
74. Steinacher, M. *et al.* Projected 21st century decrease in marine productivity: a multi-model analysis. *Biogeosciences* **7**, (2010).
75. Laufkötter, C. *et al.* Drivers and uncertainties of future global marine primary production in marine ecosystem models. *Biogeosciences* **12**, 6955–6984 (2015).
76. Stock, C. A., Dunne, J. P. & John, J. G. Drivers of trophic amplification of ocean productivity trends in a changing climate. *Biogeosciences* **11**, 7125–7135 (2014).
77. Cheung, W. W. L. & Pauly, D. Impacts and effects of ocean warming on marine fishes. *Di dalam Laffoley D, dan Baxter JM, Ed. Explain. Ocean Warm. Causes, scale, Eff. consequences. Gland IUCN. hlm* 239–253 (2016).
78. Hoegh-Guldberg, O. *et al. The Coral Triangle and climate change: ecosystems, people and societies at risk*. (2009).
79. Hughes, T. P. *et al.* Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* **359**, 80–83 (2018).
80. Hoegh-Guldberg, O. *et al.* Impacts of 1.5 ^{o}C global warming on natural and human systems. (2018).
81. Li, X., Bellerby, R., Craft, C. & Widney, S. E. Coastal wetland loss, consequences, and challenges for restoration. *Anthr. Coasts* **1**, 1–15 (2018).
82. Pörtner, H.-O. *et al.* Climate induced temperature effects on growth performance, fecundity and recruitment in marine fish: developing a hypothesis for cause and effect relationships in Atlantic cod (Gadus morhua) and common eelpout (Zoarces viviparus). *Cont. Shelf Res.* **21**, 1975–1997 (2001).
83. Pörtner, H. O. & Farrell, A. P. Physiology and climate change. *Science* **322**, 690–692 (2008).
84. Pauly, D. & Cheung, W. W. L. Sound physiological knowledge and principles in modeling shrinking of fishes under climate change. *Glob. Chang. Biol.* **24**, e15–e26 (2018).

85. Pinsky, M. L., Worm, B., Fogarty, M. J., Sarmiento, J. L. & Levin, S. A. Marine taxa track local climate velocities. *Science* **341**, 1239–1242 (2013).
86. Poloczanska, E. S. *et al.* Global imprint of climate change on marine life. *Nat. Clim. Chang.* **3**, 919 (2013).
87. Cheung, W. W. L., Dunne, J., Sarmiento, J. L. & Pauly, D. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. *ICES J Mar Sci* (2011). doi:10.1093/icesjms/fsr012
88. Perry, A. L., Low, P. J., Ellis, J. R. & Reynolds, J. D. Climate change and distribution shifts in marine fishes. *Science* **308**, 1912–1915 (2005).
89. Cheung, W. W. L., Lam, V. W. Y. & Pauly, D. Dynamic bioclimate envelope model to predict climate-induced changes in distribution of marine fishes and invertebrates. *Model. Present Clim. Distrib. Mar. fishes Invertebr. Fish. Cent. Res. Reports* **16**, 5–50 (2008).
90. Cheung, W. W. L. *et al.* Projecting global marine biodiversity impacts under climate change scenarios. *Fish Fish* **10**, 235–251 (2009).
91. Mueter, F. J. & Litzow, M. A. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecol. Appl.* **18**, 309–320 (2008).
92. Dulvy, N. K. *et al.* Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *J. Appl. Ecol.* **45**, 1029–1039 (2008).
93. Pörtner, H.-O. Oxygen-and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. *J. Exp. Biol.* **213**, 881–893 (2010).
94. Pauly, D. & Kinne, O. *Gasping fish and panting squids: oxygen, temperature and the growth of water-breathing animals*. **22**, (International Ecology Institute Oldendorf/Luhe, Germany, 2010).
95. Mackenzie, C. L. *et al.* Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. *PLoS One* **9**, (2014).
96. Rosas-Navarro, A., Langer, G. & Ziveri, P. Temperature affects the morphology and calcification of Emiliania huxleyi strains. *Biogeosciences* **13**, 2913–2926 (2016).
97. Pörtner, H.-O., Bock, C. & Mark, F. C. Oxygen-and capacity-limited thermal tolerance: bridging ecology and physiology. *J. Exp. Biol.* **220**, 2685–2696 (2017).
98. Daufresne, M., Lengfellner, K. & Sommer, U. Global warming benefits the small in

aquatic ecosystems. *Proc. Natl. Acad. Sci.* **106**, 12788–12793 (2009).

99. Baudron, A. R., Needle, C. L. & Marshall, C. T. Implications of a warming North Sea for the growth of haddock Melanogrammus aeglefinus. *J. Fish Biol.* **78**, 1874–1889 (2011).
100. Sheridan, J. A. & Bickford, D. Shrinking body size as an ecological response to climate change. *Nat. Clim. Chang.* **1**, 401–406 (2011).
101. Cheung, W. W. L. *et al.* Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. *Nat. Clim. Chang.* **3**, 254–258 (2013).
102. Lotze, H. K. *et al.* Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc. Natl. Acad. Sci.* **116**, 12907–12912 (2019).
103. Cheung, W. W. L. *et al.* Structural uncertainty in projecting global fisheries catches under climate change. *Ecol. Model.* **325**, 57–66 (2016).
104. FAO. The State of World Fisheries and Aquaculture 2018-Meeting the sustainable development goals. (2018).
105. Pauly, D. & Zeller, D. Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. *Nat. Commun.* **7**, (2016).
106. Swartz, W., Sumaila, R. & Watson, R. Global ex-vessel fish price database revisited: A new approach for estimating 'missing' prices. *Environ. Resour. Econ.* 1–14 (2012). doi:10.1007/s10640-012-9611-1
107. Pauly, D., Christensen, V., Dalsgaard, J., Froese, R. & Torres, F. Fishing Down Marine Food Webs. *Science* **279**, 860 LP – 863 (1998).
108. Worm, B. *et al.* Rebuilding global fisheries. *Science* **325**, 578–85 (2009).
109. Costello, C. *et al.* Status and solutions for the world's unassessed fisheries. *Science* **338**, 517–520 (2012).
110. Garcia, S. M. & Rosenberg, A. A. Food security and marine capture fisheries: characteristics, trends, drivers and future perspectives. *Philos. Trans. R. Soc. B Biol. Sci.* **365**, 2869–2880 (2010).
111. Anderson, S. C., Branch, T. A., Ricard, D. & Lotze, H. K. Assessing global marine fishery status with a revised dynamic catch-based method and stock-assessment reference points. *ICES J. Mar. Sci.* **69**, 1491–1500 (2012).
112. Costello, C. *et al.* Global fishery prospects under contrasting management regimes. *Proc. Natl. Acad. Sci.* **113**, 5125–5129 (2016).

113. Thorson, J. T., Branch, T. A. & Jensen, O. P. Using model-based inference to evaluate global fisheries status from landings, location, and life history data. *Can. J. Fish. Aquat. Sci.* **69**, 645–655 (2012).

114. Mcowen, C. J., Cheung, W. W. L., Rykaczewski, R. R., Watson, R. A. & Wood, L. J. Is fisheries production within Large Marine Ecosystems determined by bottom-up or top-down forcing? *Fish Fish.* **16**, 623–632 (2015).

115. Stock, C. A. *et al.* Reconciling fisheries catch and ocean productivity. *Proc. Natl. Acad. Sci.* **114**, E1441–E1449 (2017).

116. Free, C. M. *et al.* Impacts of historical warming on marine fisheries production. *Science* **363**, 979–983 (2019).

117. Cheung, W. W. L., Watson, R. & Pauly, D. Signature of ocean warming in global fisheries catch. *Nature* **497**, 365–368 (2013).

118. Cheung, W. W. L., Reygondeau, G. & Frölicher, T. L. Large benefits to marine fisheries of meeting the 1.5 C global warming target. *Science* **354**, 1591–1594 (2016).

119. Cheung, W. W. L., Jones, M. C., Reygondeau, G. & Frölicher, T. L. Opportunities for climate-risk reduction through effective fisheries management. *Glob. Chang. Biol.* **24**, 5149–5163 (2018).

120. Sumaila, U. R., Cheung, W. W. L., Lam, V. W. Y., Pauly, D. & Herrick, S. Climate change impacts on the biophysics and economics of world fisheries. *Nat. Clim. Chang.* **1**, 449 (2011).

121. Allison, E. H. *et al.* Vulnerability of national economies to the impacts of climate change on fisheries. *Fish Fish* **10**, 173–196 (2009).

122. Bell, J. D. *et al.* Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Mar. Policy* **88**, 303–314 (2018).

123. SPC, P. C. *Implications of climate-driven redistribtuion of tuna for Pacific Island economies*. (2019).

124. Blasiak, R. *et al.* Climate change and marine fisheries: Least developed countries top global index of vulnerability. *PLoS One* **12**, e0179632 (2017).

125. Srinivasan, U., Cheung, W., Watson, R. & Sumaila, U. Food security implications of global marine catch losses due to overfishing. *J. Bioecon.* **12**, 183–200 (2010).

126. Oyinlola, M. A., Reygondeau, G., Wabnitz, C. C. C. & Cheung, W. W. L. Projecting

global mariculture diversity under climate change. *Glob. Chang. Biol.* **n/a**, (2020).

127. Froehlich, H. E., Gentry, R. R. & Halpern, B. S. Global change in marine aquaculture production potential under climate change. *Nat. Ecol. Evol.* **2**, 1745–1750 (2018).
128. Porter, J. R. *et al.* Food security and food production systems. (2017).
129. Gaines, S. D. *et al.* Improved fisheries management could offset many negative effects of climate change. *Sci. Adv.* **4**, eaao1378 (2018).
130. Smith, M. D. *et al.* Sustainability and global seafood. *Science* **327**, 784–786 (2010).
131. Asche, F., Bellemare, M. F., Roheim, C., Smith, M. D. & Tveteras, S. Fair enough? Food security and the international trade of seafood. *World Dev.* **67**, 151–160 (2015).
132. Kurien, J. *Responsible fish trade and food security*. (Food & Agriculture Org., 2005).
133. Watson, R. A., Nichols, R., Lam, V. W. Y. & Sumaila, U. R. Global seafood trade flows and developing economies: Insights from linking trade and production. *Mar. Policy* **82**, 41–49 (2017).
134. Food and Agriculture Organization of the United Nations FAO. FAO yearbook. Fishery and aquaculture statistics. (2017).
135. Gorez, B. West Africa: fishmeal, mealy deal. *Samudra Rep.* 33–35 (2018).
136. Corten, A., Braham, C.-B. & Sadegh, A. S. The development of a fishmeal industry in Mauritania and its impact on the regional stocks of sardinella and other small pelagics in Northwest Africa. *Fish. Res.* **186**, 328–336 (2017).
137. Merino, G., Barange, M., Mullon, C. & Rodwell, L. Impacts of global environmental change and aquaculture expansion on marine ecosystems. *Glob. Environ. Chang.* **20**, 586–596 (2010).
138. Naylor, R. L. *et al.* Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci.* **106**, 15103–15110 (2009).
139. Cashion, T., Le Manach, F., Zeller, D. & Pauly, D. Most fish destined for fishmeal production are food-grade fish. *Fish Fish.* **18**, 837–844 (2017).
140. New, M. B. & Wijkström, U. N. Use of fishmeal and fish oil in aquafeeds: further thoughts on the fishmeal trap. *FAO Fish. Circ.* (2002).
141. Jackson, A. & Shepherd, J. Connections between farmed and wild fish: fishmeal and fish oil as feed ingredients in sustainable aquaculture. (2010).
142. Kristofersson, D. & Anderson, J. L. Is there a relationship between fisheries and farming?

Interdependence of fisheries, animal production and aquaculture. *Mar. Policy* **30**, 721–725 (2006).

143. Deutsch, L. *et al.* Feeding aquaculture growth through globalization: Exploitation of marine ecosystems for fishmeal. *Glob. Environ. Chang.* **17**, 238–249 (2007).
144. Mullon, C. *et al.* Modeling the global fishmeal and fish oil markets. *Nat. Resour. Model.* **22**, 564–609 (2009).
145. Merino, G. *et al.* Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate? *Glob. Environ. Chang.* **22**, 795–806 (2012).
146. Liu, Y. & Sumaila, U. R. Can farmed salmon production keep growing? *Mar. Policy* **32**, 497–501 (2008).
147. Jacobs, A. China's appetite pushes fisheries to the brink. *New York Times* **30**, (2017).
148. Tickler, D., Meeuwig, J. J., Palomares, M.-L., Pauly, D. & Zeller, D. Far from home: Distance patterns of global fishing fleets. *Sci. Adv.* **4**, eaar3279 (2018).
149. Campling, L. Trade politics and the global production of canned tuna . *Marine Policy* **69**, 220–228 (2016).
150. Eurofish. Overview of the Spanish fisheries and aquaculture sector. (2019). Available at: https://www.eurofish.dk/spain.
151. Arrizabalaga, H. *et al.* Global habitat preferences of commercially valuable tuna. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **113**, 102–112 (2015).
152. Erauskin-Extramiana, M. *et al.* Large-scale distribution of tuna species in a warming ocean. *Glob. Chang. Biol.* **25**, 2043–2060 (2019).
153. FFA & SPC. *A Regional Roadmap for Sustainable Pacific Fisheries.* (2015).
154. Heltberg, R., Siegel, P. B. & Jorgensen, S. L. Addressing human vulnerability to climate change: toward a 'no-regrets' approach. *Glob. Environ. Chang.* **19**, 89–99 (2009).
155. Brouwer, S. *et al. The Western and Central Pacific tuna fishery: 2017 overview and status of stocks.* (2019).
156. Bell, J. D. *et al.* Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories. *Mar. Policy* **51**, 584–591 (2015).
157. Senina, I. *et al.* Predicting skipjack tuna dynamics and effects of climate change using SEAPODYM with fishing and tagging data. *12th Regul. Sess. Sci. Comm. West. Cent. Pacific Fish. Comm.* 1–70 (2016). doi:10.1136/bcr-2016-214948

158. Robinson, M. *Climate justice: Hope, resilience, and the fight for a sustainable future*. (Bloomsbury Publishing USA, 2018).

159. Pinsky, M. L. *et al.* Preparing ocean governance for species on the move. *Science* **360**, 1189–1191 (2018).

160. UN. Transforming Our World: The 2030 Agenda for Sustainable Development. *A New Era Glob. Heal.* (2015). doi:10.1891/9780826190123.ap02

161. Pecl, G. T. *et al.* Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science* **355**, eaai9214 (2017).

162. Singh, G. G. *et al.* Climate impacts on the ocean are making the Sustainable Development Goals a moving target travelling away from us. *People Nat.* (2019).

163. Guillaumont, P. Assessing the economic vulnerability of small island developing states and the least developed countries. *J. Dev. Stud.* **46**, 828–854 (2010).

164. Narayan, S. *et al.* The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One* **11**, (2016).

165. Moosavi, S. Ecological coastal protection: Pathways to living shorelines. *Procedia Eng.* **196**, 930–938 (2017).

166. Mutombo, K. & Ölçer, A. A Three-Tier Framework for Port Infrastructure Adaptation to Climate Change: Balancing Breadth and Depth of Knowledge. *Ocean Yearb. Online* **30**, 564–577 (2016).

167. Forzieri, G. *et al.* Escalating impacts of climate extremes on critical infrastructures in Europe. *Glob. Environ. Chang.* **48**, 97–107 (2018).

168. Beiler, M. O., Marroquin, L. & McNeil, S. State-of-the-practice assessment of climate change adaptation practices across metropolitan planning organizations pre-and post-Hurricane Sandy. *Transp. Res. Part A Policy Pract.* **88**, 163–174 (2016).

169. Thorne, J. H. *et al.* The impact of climate change uncertainty on California's vegetation and adaptation management. *Ecosphere* **8**, e02021 (2017).

170. Ziervogel, G. & Ericksen, P. J. Adapting to climate change to sustain food security. *Wiley Interdiscip. Rev. Clim. Chang.* **1**, 525–540 (2010).

171. Heenan, A. *et al.* A climate-informed, ecosystem approach to fisheries management. *Mar. Policy* **57**, 182–192 (2015).

172. Poulain, F., Himes-Cornell, A. & Shelton, C. Methods and tools for climate change

adaptation in fisheries and aquaculture. *Impacts Clim. Chang. Fish. Aquac. Synth. Curr. knowledge, Adapt. Mitig. options. FAO Fish. Aquac. Tech. Pap. 627.* **627**, 535–566 (2018).

173. Bell, J. *et al.* Impacts and effects of ocean warming on the contributions of fisheries and aquaculture to food security. *IUCN* (2016).

174. Cochrane, K. L., Andrew, N. L. & Parma, A. M. Primary fisheries management: a minimum requirement for provision of sustainable human benefits in small-scale fisheries. *Fish Fish.* **12**, 275–288 (2011).

175. Free, C. M. *et al.* Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. *PLoS One* **15**, e0224347 (2020).

176. Armitage, D. Adaptive capacity and community-based natural resource management. *Environ. Manage.* **35**, 703–715 (2005).

177. MECM/MFMR. *Solomon Islands Coral Triangle Initiative National Plan of Action. Honiara: Solomon Islands Government.* (2010).

178. Bell, J. D. *et al.* Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands. *Mar. Policy* **56**, 98–105 (2015).

179. Tilley, A. *et al.* Nearshore fish aggregating devices show positive outcomes for sustainable fisheries development in Timor-Leste. *Front. Mar. Sci.* **6**, 487 (2019).

180. Mills, D. J. *et al.* Developing Timor-Leste's coastal economy: assessing potential climate change impacts and adaptation options. *Final Rep. to Aust. Gov. Coral Triangle Initiat. Coral Reefs, Fish. Food Secur. Natl. Initiat. WorldFish, Penang, Malaysia* (2013).

181. Pomeroy, R. S. Community-based and co-management institutions for sustainable coastal fisheries management in Southeast Asia. *Ocean Coast. Manag.* **27**, 143–162 (1995).

182. Foale, S., Cohen, P., Januchowski-Hartley, S., Wenger, A. & Macintyre, M. Tenure and taboos: origins and implications for fisheries in the Pacific. *Fish Fish.* **12**, 357–369 (2011).

183. Tompkins, E. & Adger, W. N. Does adaptive management of natural resources enhance resilience to climate change? *Ecol. Soc.* **9**, (2004).

184. Biggs, R. *et al.* Toward principles for enhancing the resilience of ecosystem services. *Annu. Rev. Environ. Resour.* **37**, 421–448 (2012).

185. Cohen, P. J. & Foale, S. J. Sustaining small-scale fisheries with periodically harvested

marine reserves. *Mar. Policy* **37**, 278–287 (2013).

186. Carvalho, P. G. *et al.* Optimized fishing through periodically harvested closures. *J. Appl. Ecol.* (2019).

187. Cinner, J. E. *et al.* Evaluating social and ecological vulnerability of coral reef fisheries to climate change. *PLoS One* **8**, e74321 (2013).

188. Ford, J. D. *et al.* Including indigenous knowledge and experience in IPCC assessment reports. *Nat. Clim. Chang.* **6**, 349 (2016).

189. McNamara, K. E. & Westoby, R. Local knowledge and climate change adaptation on Erub Island, Torres Strait. *Local Environ.* **16**, 887–901 (2011).

190. Miller, D. D., Ota, Y., Sumaila, U. R., Cisneros-Montemayor, A. M. & Cheung, W. W. L. Adaptation strategies to climate change in marine systems. *Glob. Chang. Biol.* **24**, e1–e14 (2018).

191. Weeks, R. & Jupiter, S. D. Adaptive comanagement of a marine protected area network in Fiji. *Conserv. Biol.* **27**, 1234–1244 (2013).

192. Ogier, E. M. *et al.* Fisheries management approaches as platforms for climate change adaptation: Comparing theory and practice in Australian fisheries. *Mar. Policy* **71**, 82–93 (2016).

193. Bruno, J. F., Côté, I. M. & Toth, L. T. Climate change, coral loss, and the curious case of the parrotfish paradigm: Why don't marine protected areas improve reef resilience? *Ann. Rev. Mar. Sci.* **11**, 307–334 (2019).

194. Oremus, K. L. *et al.* Governance challenges for tropical nations losing fish species due to climate change. *Nat. Sustain.* **3**, 277–280 (2020).

195. Mendenhall, E. *et al.* Climate change increases the risk of fisheries conflict. *Mar. Policy* **117**, 103954 (2020).

196. Moore, B. R. *et al.* Defining the stock structures of key commercial tunas in the Pacific Ocean I: Current knowledge and main uncertainties. *Fish. Res.* 105525 (2020).

197. Moore, B. R. *et al.* Defining the stock structures of key commercial tunas in the Pacific Ocean II: Sampling considerations and future directions. *Fish. Res.* 105524 (2020).

198. Gattuso, J.-P. *et al.* Ocean solutions to address climate change and its effects on marine ecosystems. *Front. Mar. Sci.* **5**, 337 (2018).

199. Sumaila, U. R. *et al.* Benefits of the Paris Agreement to ocean life, economies, and people.

Sci. Adv. **5**, eaau3855 (2019).

200. Gallo, N. D., Victor, D. G. & Levin, L. A. Ocean commitments under the Paris Agreement. *Nat. Clim. Chang.* **7**, 833 (2017).

201. Mcleod, E. *et al.* A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Front. Ecol. Environ.* **9**, 552–560 (2011).

202. Herr, D. & Landis, E. Coastal blue carbon ecosystems. Opportunities for Nationally Determined Contributions. Policy Brief. *Gland. Switz. IUCN. Washington, DC TNC* (2016).

203. Goldstein, A. *et al.* Protecting irrecoverable carbon in Earth's ecosystems. *Nat. Clim. Chang.* 1–9 (2020).

204. Pendleton, L. *et al.* Estimating Global "Blue Carbon" Emissions from Conversion and Degradation of Vegetated Coastal Ecosystems. *PLoS One* **7**, e43542 (2012).

205. Zarate-Barrera, T. G. & Maldonado, J. H. Valuing blue carbon: carbon sequestration benefits provided by the marine protected areas in Colombia. *PLoS One* **10**, e0126627 (2015).

206. Wylie, L., Sutton-Grier, A. E. & Moore, A. Keys to successful blue carbon projects: lessons learned from global case studies. *Mar. Policy* **65**, 76–84 (2016).

207. Locatelli, T. *et al.* Turning the tide: how blue carbon and payments for ecosystem services (PES) might help save mangrove forests. *Ambio* **43**, 981–995 (2014).

208. Barbesgaard, M. Blue Carbon: Ocean Grabbing in Disguise? *Policy* (2016).

209. Sharp, M. The benefits of fish aggregating devices in the Pacific. *SPC Fish. Newsl.* **135**, 28–36 (2011).

210. Grafton, R. Q. Adaptation to climate change in marine capture fisheries. *Mar. Policy* **34**, 606–615 (2010).

211. Kurien, J. Voluntary guidelines for securing sustainable small-scale fisheries in the context of food security and poverty eradication: summary. (2015).

212. Castree, N. *et al.* Changing the intellectual climate. *Nat. Clim. Chang.* **4**, 763–768 (2014).

213. Allison, E. H. & Bassett, H. R. Climate change in the oceans: Human impacts and responses. *Science* **350**, 778–782 (2015).

214. Bobrowsky, P., Cronin, V. S., Di Capua, G., Kieffer, S. W. & Peppoloni, S. 11. THE

EMERGING FIELD OF GEOETHICS. *Sci. Integr. ethics Geosci.* **73**, 175 (2017).
215. Bohle, M. One Realm: Thinking Geoethically and Guiding Small-Scale Fisheries? *Eur. J. Dev. Res.* **31**, 253–270 (2019).
216. UNEP-WCMC, WorldFish, WRI & TNC. Global distribution of warm-water coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. Version 4.0. Includes contributions from IMaRS-USF and IRD (2005), IMaRS-USF (2005) and Spalding et al. (2001). Cambridge (U. (2018).
217. UNEP-WCMC & Short, F. Global distribution of seagrasses (version 5.0). Fourth update to the data layer used in Green and Short (2003). Cambridge (UK): UNEP World Conservation Monitoring Centre. (2017).
218. Giri, C. *et al.* Status and distribution of mangrove forests of the world using earth observation satellite data (version 1.3, updated by UNEP-WCMC). *Glob. Ecol. Biogeogr.* **20**, 154-159. (2011).
219. Mcowen, C. J. *et al.* A global map of saltmarshes. *Biodivers. Data J.* **5**, (2017).
220. Lehodey, P. *et al.* Vulnerability of oceanic fisheries in the tropical Pacific to climate change. *Vulnerability Trop. Pacific Fish. Aquac. to Clim. Chang.* 433–492 (2011).
221. Lehodey, P. *et al.* Modelling the impact of climate change including ocean acidification on Pacific yellowfin tuna. *13th Regul. Sess. Sci. Comm. West. Cent. Pacific Fish. Comm.* (2017).
222. Senina, I. *et al. Impact of climate change on tropical Pacific tuna and their fisheries in Pacific Islands waters and high seas areas*. *14th Regular Session of the Scientific Committee of the Western and Central Pacific Fisheries Commission* (2018).
223. Bell, J. D. *et al.* Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nat. Clim. Chang.* **3**, 591–599 (2013).
224. Bell, J. D. *et al.* Implications of climate change for contributions by fisheries and aquaculture to Pacific Island economies and communities. *Vulnerability Trop. Pacific Fish. Aquac. to Clim. Chang.* 733–801 (2011).
225. Bell, J. D. *et al.* Climate change impacts, vulnerabilities and adaptations: Western and Central Pacific Ocean marine fisheries. *Impacts Clim. Chang. Fish. Aquac.* 305 (2018).
226. Scott, F., Scott, R., Yao, N., Pilling, G. M. & Hampton, J. Considering uncertainty when testing and monitoring WCPFC harvest strategies. *15th Regul. Sess. Sci. Comm. West.*

Cent. Pacific Fish. Comm. (2019).

227. Pratchett, M. S. *et al.* Vulnerability of coastal fisheries in the tropical Pacific to climate change. *Vulnerability Trop. Pacific Fish. Aquac. to Clim. Chang.* 167–185 (2011).
228. Gasalla, M. A., Abdallah, P. R. & Lemos, D. Potential impacts of climate change in Brazilian marine fisheries and aquaculture. *Clim. Chang. Impacts Fish. Aquac. A Glob. Anal.* **1**, 455 (2017).
229. Popova, E. *et al.* From global to regional and back again: common climate stressors of marine ecosystems relevant for adaptation across five ocean warming hotspots. *Glob. Chang. Biol.* **22**, 2038–2053 (2016).
230. Schulz, C. *et al.* Physical, ecological and human dimensions of environmental change in Brazil's Pantanal wetland: Synthesis and research agenda. *Sci. Total Environ.* (2019).
231. Barros, D. F. & Albernaz, A. L. M. Possible impacts of climate change on wetlands and its biota in the Brazilian Amazon. *Brazilian J. Biol.* **74**, 810–820 (2014).
232. Johnson, J. E. *et al.* Climate change adaptation: vulnerability and challenges facing small-scale fisheries on small islands. *COMING SOON* 65 (2019).
233. Martins, I. M. & Gasalla, M. A. Perceptions of climate and ocean change impacting the resources and livelihood of small-scale fishers in the South Brazil Bight. *Clim. Change* **147**, 441–456 (2018).
234. Martins, I. M., Gammage, L. C., Jarre, A. & Gasalla, M. A. Different but Similar? Exploring Vulnerability to Climate Change in Brazilian and South African Small-Scale Fishing Communities. *Hum. Ecol.* **47**, 515–526 (2019).
235. Gasalla, M. A. Six decades of change in the South Brazil Bight Ecosystem. in *3rd GLOBEC Open Science Meeting: From ecosystem function to Ecosystem Prediction* (2008).
236. Dahlet, L. I., Downey-Breedt, N., Arce, G., Sauer, W. H. H. & Gasalla, M. A. Comparative study of skipjack tuna Katsuwonus pelamis (Scombridae) fishery stocks from the South Atlantic and western Indian oceans. *Sci. Mar.* **83**, 19–30 (2019).
237. Araújo, F. G., Teixeira, T. P., Guedes, A. P. P., de Azevedo, M. C. C. & Pessanha, A. L. M. Shifts in the abundance and distribution of shallow water fish fauna on the southeastern Brazilian coast: a response to climate change. *Hydrobiologia* **814**, 205–218 (2018).

238. Gasalla, M. A. An overview of climate change effects in South Brazil Bight fisheries. in *6th World Fisheries Congress* (2012).
239. Santos, L. C. M., Gasalla, M. A., Dahdouh-Guebas, F. & Bitencourt, M. D. Socio-ecological assessment for environmental planning in coastal fishery areas: a case study in Brazilian mangroves. *Ocean Coast. Manag.* **138**, 60–69 (2017).
240. Zou, D. & Gao, K. Physiological responses of seaweeds to elevated atmospheric CO 2 concentrations. in *Seaweeds and their role in globally changing environments* 115–126 (Springer, 2010).
241. Ramaglia, A. C., de Castro, L. M. & Augusto, A. Effects of ocean acidification and salinity variations on the physiology of osmoregulating and osmoconforming crustaceans. *J. Comp. Physiol. B* **188**, 729–738 (2018).
242. Freduah, G., Fidelman, P. & Smith, T. F. The impacts of environmental and socio-economic stressors on small scale fisheries and livelihoods of fishers in Ghana. *Appl. Geogr.* **89**, 1–11 (2017).
243. Bunce, M., Rosendo, S. & Brown, K. Perceptions of climate change, multiple stressors and livelihoods on marginal African coasts. *Environ. Dev. Sustain.* **12**, 407–440 (2010).
244. Burke, L. *et al.* Coastal Capital: Jamaica–The economic contribution of Jamaica's coral reefs. *World Resour. Inst.* (2011).
245. Roberts, C. M. *et al.* Marine biodiversity hotspots and conservation priorities for tropical reefs. *Science* **295**, 1280–1284 (2002).
246. Lam, V. W. Y., Cheung, W. W. L., Swartz, W. & Sumaila, U. R. Climate Change Impacts on Fisheries in West Africa: Implications for Economic, Food and Nutritional Security. *African J. Mar. Sci.* **34**, 103–117 (2012).
247. Barange, M. *et al.* Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nat. Clim. Chang.* **4**, 211–216 (2014).
248. Blanchard, J. L. *et al.* Potential consequences of climate change for primary production and fish production in large marine ecosystems. *Philos. Trans. R. Soc. B Biol. Sci.* **367**, 2979–2989 (2012).
249. Belhabib, D., Lam, V. W. Y. & Cheung, W. W. L. Overview of West African fisheries under climate change: Impacts, vulnerabilities and adaptive responses of the artisanal and industrial sectors. *Mar. Policy* **71**, 15–28 (2016).

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Author contributions

All authors contributed to writing the article. In addition, V.W.Y.L. and J.D.B. researched data for the article, V.W.Y.L., E.H.A., J.D.B. and W.C., contributed to discussions of its content, and V.W.Y.L., E.H.A., J.D.B., J.B., W.C., T.H.L., M.A.G. and U.R.S. participated in review or editing of the manuscript before submission.

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Online ToC

Stressors arising from anthropogenic climate change threaten tropical fisheries, and in turn, those extratropical nations reliant on them. This Review, discusses the impact of climate change on tropical fish stocks and catch potential, the corresponding telecoupling, and subsequent adaptation measures.

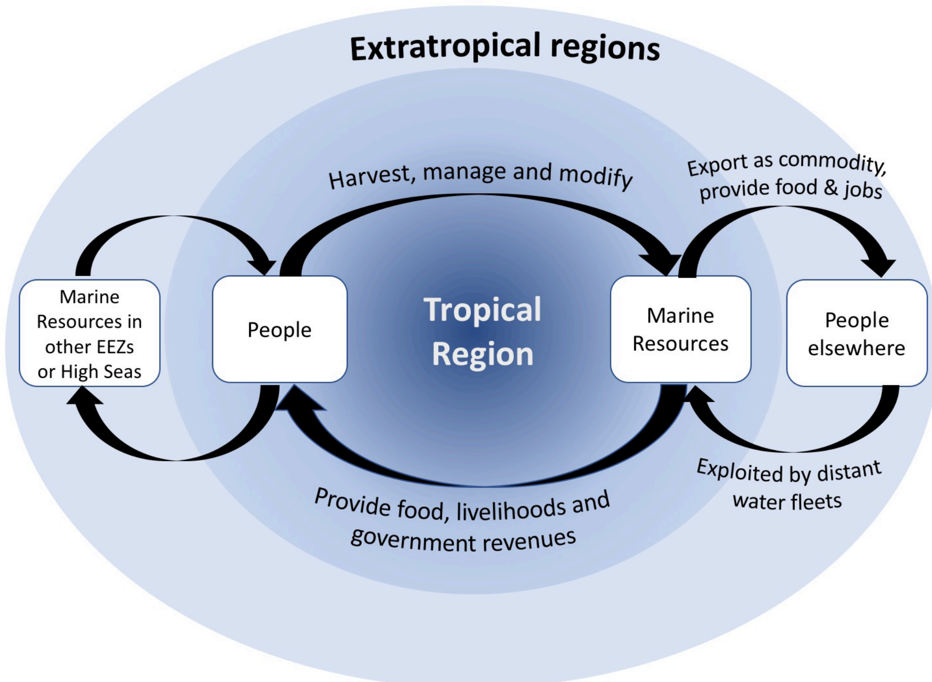
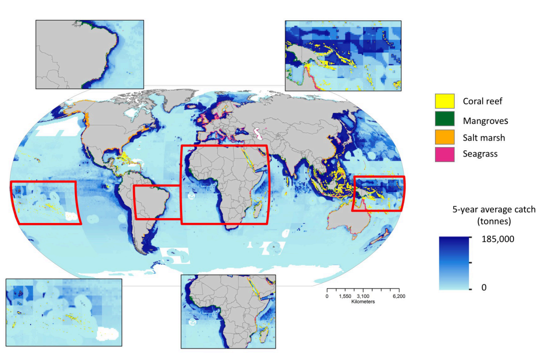


Figure 1. Tele-coupling linkages between tropical marine fisheries and extra-tropical regions. These linkages enable the flow of benefits, including food, livelihoods and government revenue from tropical fisheries to extra-tropical locations. Fish from the tropics sold in temperate-zone markets provides jobs and revenue to tropical nations. That flow of benefits is threatened by the larger impact and lower adaptive capacity of climate change on tropical fishery systems.



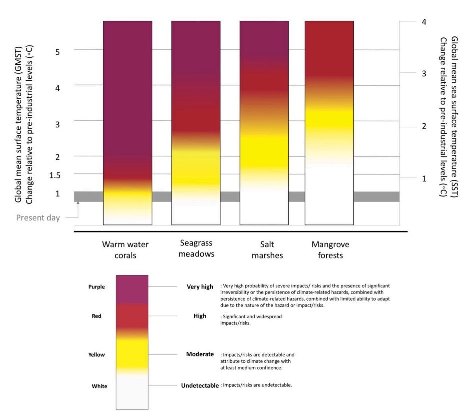


Figure 2. Climate change impacts on fish habitats and coastal fisheries. a| Spatial distribution of warm water corals, seagrass, salt marshes and mangrove forests[216–219], and 5-year annual average catch of marine species[105] ; **b|** level of risk posed by climate change to the four coastal ecosystems, as derived from expert judgement (**Supplementary Table 3**). The four major coastal habitats are highly vulnerable to climate change. These habitats have been already affected by warming and are projected to continue to be reduced in area under projected increase in temperature, with impacts on the marine ecosystems supporting fisheries. In panel **b,** "undetectable" represents impacts/risks are undetectable; "moderate" represents impacts/risks are detectable and attribute to climate change with at least medium confidence; "high" represents significant and widespread impacts/risks; and "very high" represents very high probability of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts and risks. Figure adapted, with permission, from Ref [44].

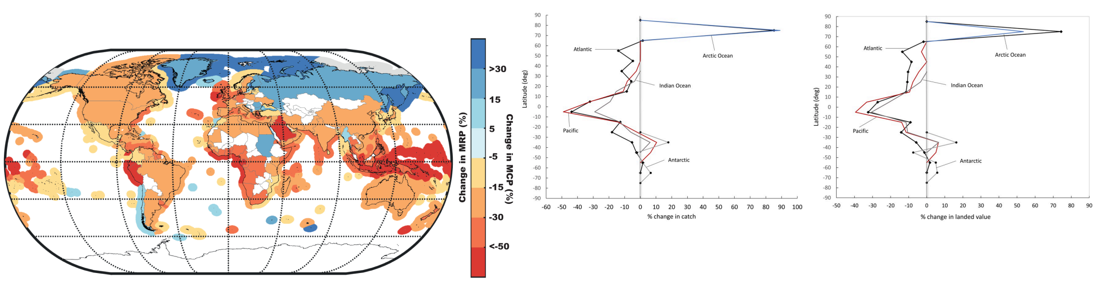


Figure 3. Climate change impacts on maximum catch potential and maximum revenue potential. a| mean percentage change in maximum catch potential (MCP) and maximum revenue potential (MRP) for 2041–2060 relative to 1991–2010 under RCP8.5. **b|** zonally averaged projected changes in MCP based on data in **a** for the major ocean basins**. c|** zonally averaged projected changes in MRP based on data in **a** for the major ocean basins**.** The greatest declines in MCP and MRP are found in tropical regions of the Pacific, Atlantic and Indian Oceans. Figure adapted, with permission, from Ref [31].

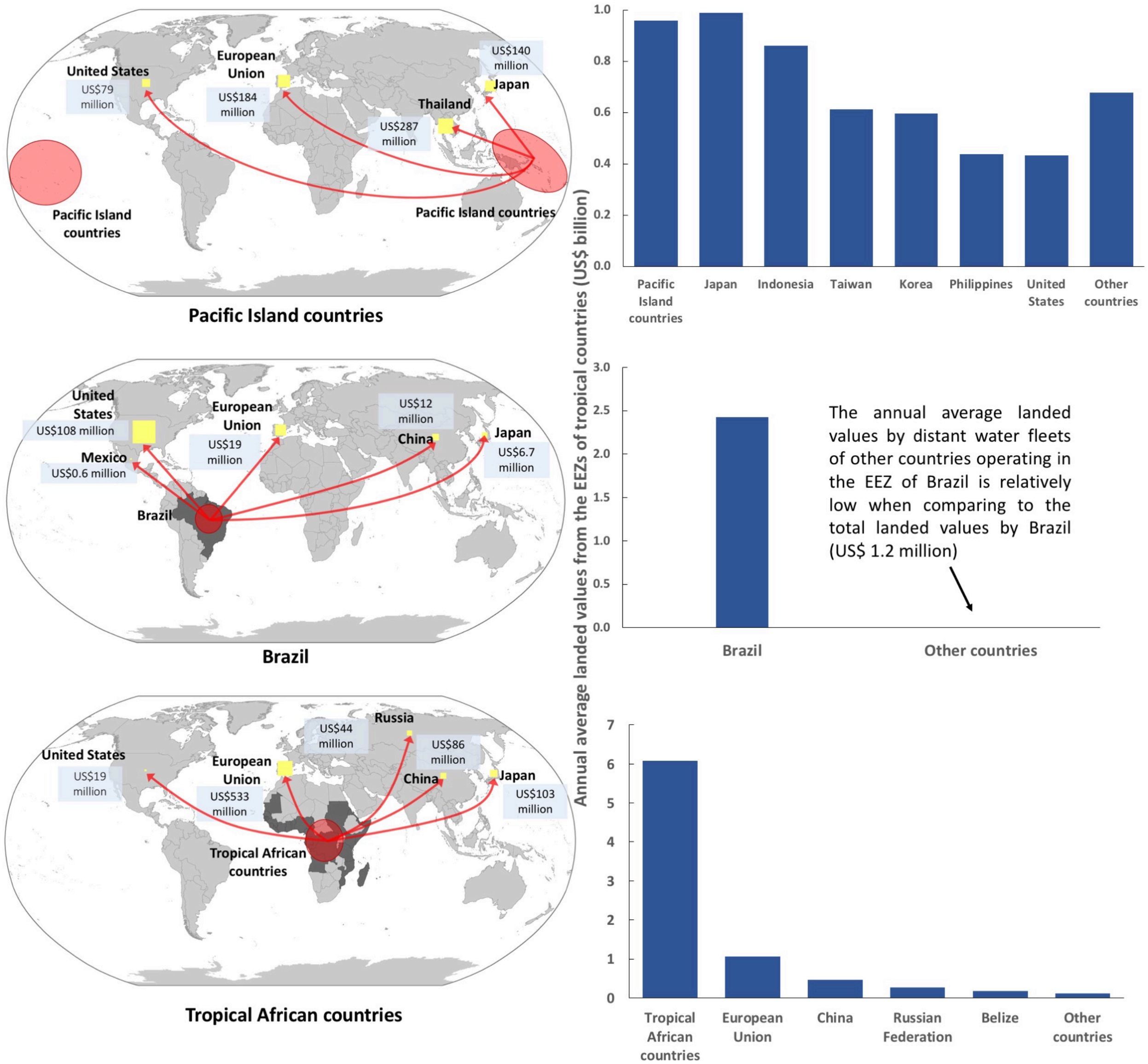


Figure 4. Economic tele-coupling of tropical fisheries. Annual mean value (US$ million) of fish exports from Pacific Island countries and territories (PICTs) (panel **a**), Brazil (panel **b**) and Africa (panel **c**) to their main trading partners for 2014-2018 (left), and the landed values (US$ billions) of fish caught in the three corresponding groups of exclusive economic zones (EEZs) by the countries/territories in those regions and by distant water fishing nations between 2007 and 2016 (right). There are close linkages between the tropical countries/regions with the extra-tropical nations through trade and distant water fishing. This implies that any climate-related changes to tropical fishers thus have socio-economic implications for many extratropical nations.

Note that values from the Pacific Islands region are for tuna only, and the catch values refer to tuna caught from the Western and Central Pacific Fisheries Convention Area, which is larger than the combined EEZs of PICTs. See **Supplementary Tables 1;4-8**.

Box 1. Fisheries in the Pacific Islands region

Across the 22 Pacific Island countries and territories (PICTs), models predict an eastern redistribution in the biomass of skipjack and yellowfin tuna – the primary exported fish – by 2050 (Refs [28,157,220–222]). Under representative concentration pathway (RCP) 8.5, for example, the combined catch of both tuna species is projected to decrease by ~10–40% by 2050 in the exclusive economic zones (EEZs) of Federated States of Micronesia, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, Tokelau and Tuvalu)[123,222]. However, given the eastern redistribution, tuna catch is anticipated to increase in the EEZs of Kiribati and Cook Islands by 15–20% (Ref [123,222]).

As several PICTs are tuna-dependent economies[123], the impact of climate change on tuna fisheries increases the vulnerability of these small island developing states (SIDS)[223,224,124]. For instance, shifts in tuna distribution, and resulting increases in catches from international waters[222], are expected to cause proportional changes in government revenue received by SIDS from fishing licence fees[123,224]. These changes need to be considered by the Western and Central Pacific Fisheries Commission when governing the sustainable use of the region's tuna resources[159,225], developing harvest strategies[226] , and allocating fishing rights to minimise the implications of tuna redistribution for island economies.

The projected 20–50% decrease in productivity of coral reef fish in the Pacific Island region by 2050 under RCP 8.5 (Refs [29,227]) is expected to influence the contributions of small-scale fisheries to food security in most PICTs[7,224]. However, rapid population growth in several PICTs is expected to have a greater influence than declining reef fish production on future availability of fish per capita[223,224]. The rich tuna resources of the Pacific Island region can be used to fill the widening gap between the total amount of fish that can be harvested sustainably from coral reefs and other coastal habitats, and that required for good nutrition[122,156].

Box 2. Fisheries in Brazil

The south-western Atlantic Ocean is a hotspot of climate change[228], with increased sea surface temperature the most prominent climate risk to marine resources, followed by changes in ocean circulation and stratification. These physical climatic changes are anticipated to influence primary production, reducing productivity for fisheries in Brazil [228,229]. In saline and freshwater wetlands, climate change modified hydrological regimes, which can cause intense droughts or inundation, are expected to reduce habitat area and the abundance of fish in confined refugia[230]. Increase in temperature on floodplains are expected to increase the frequency and duration of hypoxic or anoxic episodes, leading to a reduction in growth rates and a mismatch in reproductive success of many species[231].

In fact, Brazilian fishers have already seen changes in fish distribution, influencing livelihoods[228,232–234]. Climate-related shift in spatial distribution of marine species has been recorded in both coastal and offshore waters[235–237]; some species (such as the Brazilian sardine) are moving to cooler and deeper waters, whereas others (squid) have migrated to areas with warmer winter temperatures[238]. Rising sea levels and hydroclimatic variability, for example, have resulted in loss of mangrove and wetland habitats [239], including in the Amazon and Pantanal floodplains[230], and this is expected to have knock-on effects of the production of fisheries associated with these habitats. Ocean acidification has also inhibited coastal seaweed photosynthetic pigments[240] and the osmoregulation capacity of crustaceans such as crabs[241].

Given the large internal market for fish in Brazil, as well as increasing per capita fish consumption, these changes will have corresponding economic impacts[228]. El Niño events, for example, have been attributed to economic losses of US$9 million per year in the shrimp and mullet fisheries of South Brazil[228]. Moreover, climate-induced distribution shifts of some transboundary fish species may lead to conflicts between countries in the region and negatively affect international relations.

Box 3. Fisheries in African nations

Already affected by pollution, overfishing, and weak enforcement of fishing regulations[242,243], marine ecosystems in Africa are now also threatened by various physical and biogeochemical anthropogenic stressors. While many African marine fish are more resilient to warming than species elsewhere, unprecedented coral bleaching and extensive coral mortality across most of the western Indian Ocean has decreased fisheries production and their associated benefits for communities in east Africa[244,245]. Model simulations also predict that marine fish catches in most West African countries will decrease by >50% by 2050 under RCP 8.5, with the largest reductions in countries nearest the equator[246]. Projections are, however, model dependent; for example, some predict the fish landing with a decline of 8 – 26% (Ref [246]), whereas others project a 23.9% increase in the Gulf of Guinea by 2050 (Refs [247,248]). Nevertheless, all models suggest that fisheries in the tropical African countries are highly vulnerable to climate change[121,124].

These climate-related changes are anticipated to decrease the value of landed catch by ~20% by 2050, as well as reduce fisheries-related jobs by ~50% (Ref [246]). These impacts will not only affect food security in tropical African countries, but also influence other economies reliant on African fish imports. However, the consequences for local fishing communities depend strongly on their adaptive capacity[247,249].

Glossary

Landed Value

The value of marine fish catches when removed from vessels in domestic or foreign ports

Exclusive Economic Zones (EEZs)

A sea zone prescribed by the 1982 United Nations Convention on the Law of the Sea over which a country has the sovereign right to explore and exploit, conserve and manage living and non-living resources in the water column and on the seafloor, as defined by Part V of the Law of the Sea. It stretches from the baseline out to 200 nautical miles (nmi) from its coast.

Maximum Sustainable Yield (MSY)

The highest possible annual catch that can be removed from a population, by keeping the population at the level producing maximum growth, over a long period of time. The MSY refers to hypothetical equilibrium state between the exploited population and the fishing activity.

Maximum Catch Potential (MCP)

MCP is the potential of the fish stocks to provide long-term fish catches; it is considered a proxy of maximum sustainable yield (MSY).

Human development Index

A summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and a decent standard of living.

Species Turnover

The number of species locally extinct and newly established at a particular area, and is used to represent the extent of changes in species assemblage.

Maximum Revenue Potential (MRP)

Landed values at maximum catch potential.

Provisioning services

Include tangible products from ecosystems that humans make use of, such as fish and seafood, agricultural crops, timber or fresh water.

Regulating services

The benefits people obtain due to the regulation of natural processes such as carbon sequestration and storage, erosion prevention, waste-water treatment, and moderation of extreme events.

Supporting services

Life-cycle maintenance for both fauna and local, element and nutrient cycling.

Culture services

Tourism, recreational, aesthetic, and spiritual benefits

Representative concentration pathways

RCPs. Four climate change scenarios included in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Only scenarios with the highest and lowest radiative forcing are mentioned in this Review.

RCP 8.5

No CO_2 mitigation leads to total radiative forcing of 8.5 Wm^{-2} by 2100 (relative to 1750), increases global mean surface air temperature by 4.0–6.1 °C, an outcome resembling A1F1, A2 and A1B scenarios included in previous IPCC reports.

RPC 2.6

Strong CO_2 emission mitigation results in falling greenhouse gas concentrations and total radiative forcing of 2.6 Wm^{-2} by 2100, leading to global increases in mean surface air temperature of 1.3–1.9 °C

Supplementary information

Supplementary Table 1. Value (in US$ million) of tuna products exported by Pacific Island countries to the four main importing countries/regions for the period 2014–2018.

Exporting country	**Importing country/region**							
	Thailand		**USA**		**European Union**		**Japan**	
	Average	SD	**Average**	SD	**Average**	SD	**Average**	SD
Cook Islands	0.78	1.13	0	0	0	0	1.41	1.62
Fiji	5.82	1.98	70.64	6.24	3.98	1.84	20.24	6.22
FSM	41.00	30.21	0.00	0.00	0	0	7.79	6.18
Kiribati	82.86	25.41	1.44	0.74	0	0	8.94	2.12
Marshall Islands	29.28	6.46	5.35	2.29	0	0	12.66	9.60
Nauru	0	0	0	0	0	0	0	0
Niue	0.50	1.11	0	0	0	0	0	0
Papua New Guinea	93.61	49.62	0.04	0.09	132.87	43.83	9.61	4.88
Palau	0	0	0.11	0.10	0	0	15.06	4.78
Samoa	0.15	0.33	0.46	0.28	0	0	0.33	0.33
Solomon Islands	14.17	9.05	0.73	1.35	46.72	8.27	3.05	1.80
Tonga	0.34	0.76	0.16	0.13	0	0	1.01	0.20
Tuvalu	6.71	5.97	0.0	0.0	0	0	2.17	0.30
Vanuatu	11.35	4.76	0.19	0.15	0	0	57.74	9.11
Total	**286.57**	102.99	**79.14**	5.51	**183.56**	50.00	**140.01**	10.38

Values are based on estimated prices received for products upon entry to the country/region in which they are sold (source: Pacific Islands Forum Fisheries Agency). FSM, Federated States of Micronesia; SD, standard deviation.

Supplementary Table 2. Examples of priority adaptations and supporting policies to assist Pacific Island countries and territories in capitalizing on the opportunities and reducing the threats posed by climate change to the contributions of small-scale fisheries to food security.

<table>
<tr><th>Adaptation options</th><th>Classification</th><th>Supporting policies</th></tr>
<tr><td>Manage catchment vegetation to reduce transfer of sediments and nutrients to rivers and coasts to reduce damage to freshwater fish habitats, and coral reefs, mangroves and seagrasses supporting coastal fisheries</td><td>Win-win</td><td rowspan="8">● Strengthen governance for sustainable use of coastal fish habitats by: building national capacity to understand the threats of climate change; empowering communities to manage fish habitats; and changing agriculture, forestry and mining practices to prevent sedimentation and pollution
● Minimise barriers to landward migration of coastal habitats in adaptation plans for infrastructure
● Promote primary fisheries management for stocks of coastal fish and shellfish to maintain their potential for replenishment
● Allocate the necessary quantities of tuna from total national catches to increase access to fish for both urban and coastal populations
● Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security
● Include inshore FADs as part of national infrastructure for food security, and undertake regular maintenance and replacement of FADs</td></tr>
<tr><td>Foster the care of coral reefs, mangroves and seagrasses by preventing pollution, managing waste and eliminating direct damage to these coastal fish habitats</td><td>Win-win</td></tr>
<tr><td>Provide for landward migration of fish habitats by prohibiting construction adjacent to areas of mangroves and seagrasses, and installing culverts beneath roads to help plants colonise low-lying areas as sea level rises</td><td>Lose-win</td></tr>
<tr><td>Limit and diversify catches of coral reef fish to maintain the replenishment potential of all stocks</td><td>Lose-win</td></tr>
<tr><td>Increase access to small tuna and bycatch caught by industrial fleets through storing and selling these fish at major ports to provide inexpensive fish for rapidly growing urban populations</td><td>Win-win</td></tr>
<tr><td>Install FADs close to the coast to improve access to tuna and other large pelagic fish for rural communities as human populations increase and coral reef fish decline</td><td>Win-win</td></tr>
<tr><td>Develop coastal fisheries for small pelagic fish species such as mackerel, anchovies, pilchards, sardines and scads</td><td>Win-win*</td></tr>
<tr><td>Improve simple post-harvest methods, such as traditional smoking, salting and drying, to extend the shelf life of fish when good catches are made</td><td>Win-win</td></tr>
</table>

Measures classified as ‘win-win’ adaptations address other drivers of the sector in the short term and address climate change in the long term. The benefits of measures classified as ‘lose-win’ are exceeded by costs in the short term but accrue under long-term climate change (source: Bell, J. D. et al. *Nat. Clim. Chang.* 3, 591–599; 2013). *Small pelagic fish are expected to be favoured by climate change only where changes to currents and eddies deliver more nutrients to surface waters. FAD, fish aggregating device.

Supplementary Table 3.
The global mean sea surface temperatures at which transitions in the level of risk occur for coastal ecosystems in response to climate-related hazards.

Ecosystems	**Risk level**	**SST (GMST) °C**		**Confidence***
		Transition begins	**Transition ends**	
Salt marshes	White to yellow	0.7 (1.0)	1.2 (1.7)	High
	Yellow to red	1.8 (2.6)	2.7 (3.9)	Moderate
	Red to purple	3.0 (4.3)	3.4 (4.9)	Moderate
Mangrove forests	White to yellow	1.2 (1.7)	2.0 (2.9)	Moderate
	Yellow to red	2.3 (3.3)	3.0 (4.3)	Moderate
	Red to purple	NA	NA	NA
Seagrass meadows	White to yellow	0.5 (0.7)	0.8 (1.2)	Very high
	Yellow to red	1.5 (2.2)	1.8 (2.6)	High
	Red to purple	2.2 (3.2)	3.0 (4.3)	High
Warm water corals	White to yellow	0.2 (0.3)	0.4 (0.6)	High
	Yellow to red	0.4 (0.6)	0.6 (0.9)	Very high
	Red to purple	0.6 (0.9)	1.2 (1.7)	Very high

*Source: Summary for Policymakers, in IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (eds H.- O. Pörtner et al.). Data derived from expert judgement and updated literature since publication of the IPCC 5th Assessment Report (AR5) and the IPCC Special Report on the impacts of global warming of 1.5°C (SR1.5). The corresponding global mean surface temperature (GMST) is calculated by multiplying a scaling factor of 1.44 based on changes in an ensemble of representative concentration pathway (RCP)8.5 simulations; uncertainty of ~4% in this scaling factor is based on differences between the RCP2.6 and RCP8.5 scenarios. Levels of risk posed by climate-related hazards: white, no detectable risk; yellow, moderate risk; red, high risk; purple, very high risk. IPCC, Intergovernmental Panel on Climate Change; NA, not applicable; SST, sea surface temperature.

Supplementary Table 4.
Value (in US$ million) of the fish commodity exported by Brazil to the five main importing countries/regions for the period 2014–2018.

Exporting Country	Importing country/region									
	China		Japan		Mexico		Russian Federation		USA	
	Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Brazil	11.71	7.01	6.68	1.09	0.57	0.00	0.01	0.00	108.40	18.72

Data from the UN Commodity Trade Statistics database. The fish commodity includes fish, crustaceans, molluscs and other aquatic invertebrates. The annual average export value data are shown in Figure 5 in the main text. SD, standard deviation.

Supplementary Table 5.
Value (in US$ million) of fish commodity exported by 21 tropical African countries to the four main importing countries/regions for the period 2014–2018.

Exporting country	Importing country/region							
	China		Japan		Russian Federation		USA	
	Average	SD	Average	SD	Average	SD	Average	SD
Angola	18.28	3.50	12.33	2.23	0	0	0	0
Benin	0.03	0.01	0	0	0	0	0.02	0.002
Cote d'Ivoire	16.12	2.82	0.0016	0	0.000004	0	0.34	0.08
Cabo Verde	0.61	0.23	0	0	0	0	0.01	0
Cameroon	0.09	0	0	0	0	0	0.01	0.003
Congo	5.99	4.21	0	0	0	0	0	0
Democratic Republic of Congo	0	0	0	0	0	0	0	0
Gambia	0	0	0	0	0	0	0.16	0.02
Ghana	29.01	5.39	9.30	2.65	0	0	0.19	0.06
Kenya	3.19	0.81	0.43	0.19	0.01	0.00	0.27	0.09
Madagascar	83.00	7.46	14.18	0.60	0	0	0.99	0.27
Mauritania	74.98	4.97	306.21	14.98	216.81	20.78	0.72	0.20
Mauritius	44.16	4.15	123.85	4.51	0.10	0	60.62	14.38
Mozambique	42.18	2.97	2.96	0.38	0.11	0	1.42	0.49
Nigeria	3.41	1.13	0.10	0	0	0	17.21	0.97
Sao Tome and Principe	0.01	0	0.02	0	0	0	0	0
Senegal	52.17	4.36	27.62	2.01	0.15	0	7.88	0.65
Seychelles	1.46	0.21	2.37	0.68	0.97	0.28	0.95	0.27
Sierra Leone	25.77	16.71	0	0	0	0	1.28	0.43
Sudan	0.72	0.51	0	0	0	0	0	0
United Rep. of Tanzania	29.38	5.34	17.64	2.13	0.04	0.02	1.36	0.24
Total	**430.57**	**7.67**	**517.02**	**26.29**	**218.19**	**30.89**	**93.43**	**5.06**

Data i from the UN Commodity Trade Statistics database. The fish commodity includes fish, crustaceans, molluscs and other aquatic invertebrates. The annual average export value data are shown in Figure 5 in the main text. SD, standard deviation.

Supplementary Table 6. Estimated value (in US$ million) of tuna catches made by fishing fleets operating in the Western and Central Pacific Fisheries Convention Area for the period 2007–2016.

Fishing fleets	**Year**										**Average value**	**SD**
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**		
Pacific Island countries*	695	717	614	738	953	1360	1082	1171	1095	1166	959	253
Japan	922	1098	917	1123	1229	1257	974	870	740	756	989	183
Indonesia	566	731	672	659	951	1157	1274	981	708	906	861	232
Taiwan	555	629	538	621	695	774	721	580	461	544	612	96
Korea	474	628	552	577	634	859	628	578	470	560	596	109
Philippines	469	638	405	389	363	518	495	454	331	322	438	97
US	187	426	387	383	436	651	598	531	359	367	432	133
Other countries**	497	671	613	566	762	901	925	684	582	577	678	144

Data source: Pacific Islands Forum Fisheries Agency. *Includes tuna fishing vessels flagged within the 14 Pacific Island countries that are members of the Pacific Islands Forum Fisheries Agency: Cook Islands, Fiji, Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Niue, Papua New Guinea, Palau, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu. **Dominated by China and Vietnam, with average catch values of US$ 280 million and US$ 205 million, respectively. SD, standard deviation.

Supplementary Table 7.
Estimated value (in US$ million) of catches made by fishing fleets operating in the exclusive economic zones of Brazil for the period 2007–2016.

Fishing fleets	Year										Average value	SD
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016		
Brazil	2,113	1,737	2,071	2,428	2,795	2,772	2,534	2,785	2,485	2,517	2,424	351
Unknown	0.72	1.68	ND	ND	ND	ND	ND	ND	ND	ND	1.20	0.68

Source: Sea Around Us catch database. ND, no data; SD, standard deviation.

Supplementary Table 8.
Estimated value (in US$ million) of catches made by fishing fleets operating in the exclusive economic zones of tropical African countries for the period 2007–2016.

Fishing fleets	Year										Average value	SD
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016		
Tropical African countries*	6,267	6,929	5,704	5,839	5,762	6,082	5,969	6,150	6,143	6,029	6,087	346
EU	1,594	1,403	2,523	2,168	930	744	155	279	376	395	1,057	832
China	357	407	501	633	440	438	447	477	456	430	459	73
Russian Federation	646	323	436	478	215	193	53	61	80	117	260	204
Belize	151	160	280	214	190	110	119	274	175	82	175	66
Unknown	181	222	248	191	57	60	52	55	46	58	117	82

Source: Sea Around Us catch database. *Includes fishing vessels of 21 tropical African countries: Angola, Benin, Cote d'Ivoire, Cape Verde, Cameroon, Congo, Democratic Republic of Congo, Gambia, Ghana, Kenya, Madagascar, Mauritania, Mauritius, Mozambique, Nigeria, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Sudan, Tanzania and Togo. SD, standard deviation.