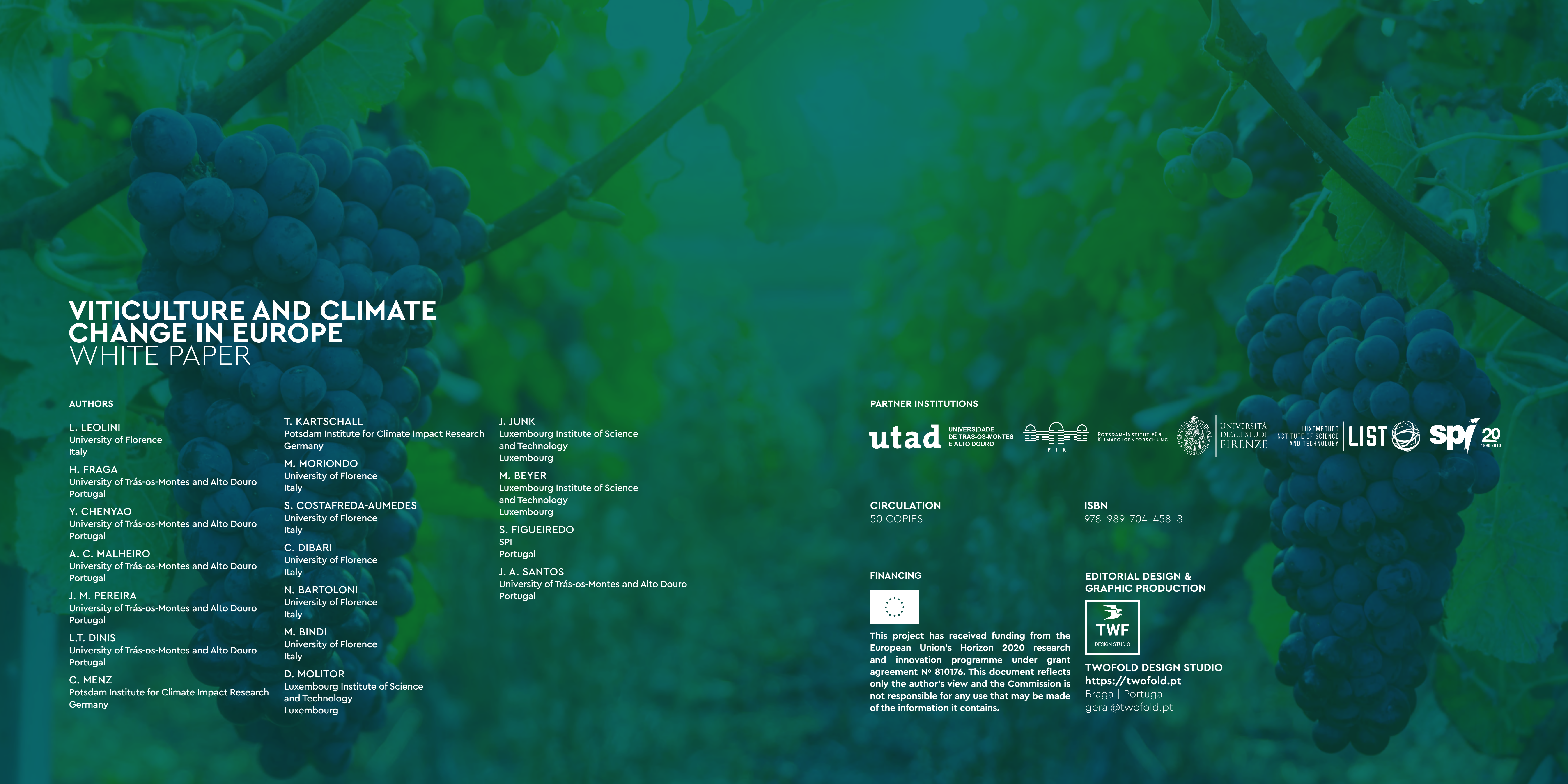
VITICULTURE AND CLIMATE CHANGE IN EUROPE
WHITE PAPER

Clim4Vitis

Climate change impact mitigation
for European viticulture



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EXECUTIVE SUMMARY

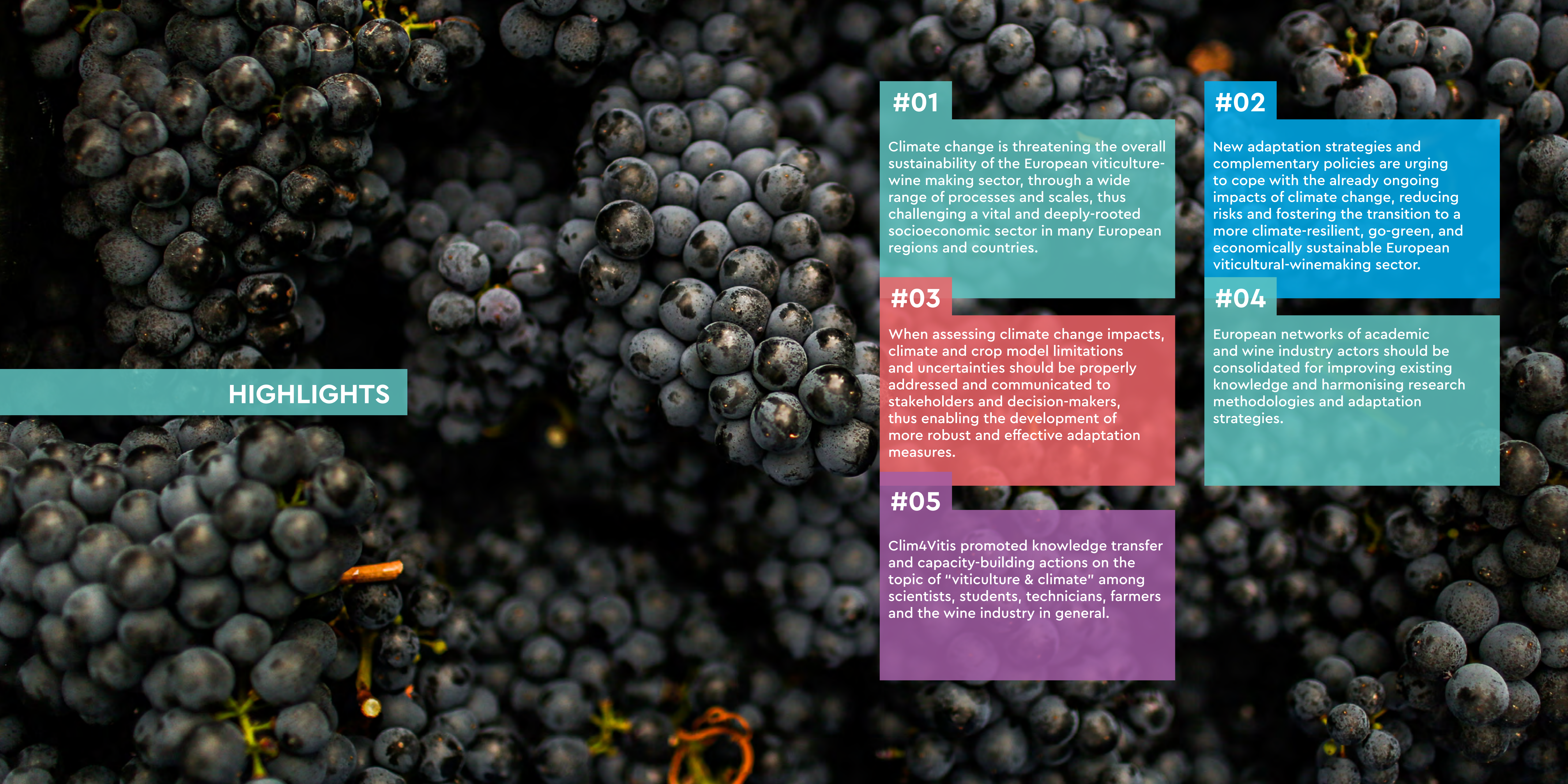
In Europe, viticulture is a prominent activity sector, providing important income and contributing to the improvement of social and environmental conditions in many regions. The leadership of the European Community in world wine production and export hints at the key role played by the wine industry in the agricultural sector and the European economy as a whole. The impact of global climate change and extreme events is, nonetheless, affecting this sector. Ongoing changes in current climatic conditions are threatening the European wine regions, including the most traditional and world-renowned. The anomalously high temperatures during the last decades have already favoured a northward shift of the main wine regions in Europe. In particular, higher temperatures and variations in the precipitation regimes, as well as the occurrence of weather extremes, such as severe droughts or major heatwaves, determined by the gradual increase in greenhouse gas concentrations (especially CO2), are jointly affecting vine photosynthetic activity, biomass accumulation and growth, phenological development, berry development and, eventually, yields and wine organoleptic properties, attributes and typicity.

In this context, the scientific community is focusing on the assessment of the climate change impacts on viticulture, under current conditions and future climate change scenarios, through combined applications of climate and crop models. The evaluation of climate change impacts is critical for developing new ad-hoc adaptation strategies for helping winegrowers to mitigate the impact of climate change in the viticulture and wine-making sector. These strategies should reduce vulnerability and exposure risks, while fostering cost-effective and go-green practices, warranting the future sustainability, vitality, and competitiveness of the European winemaking sector.

"Climate change impact mitigation for European viticulture: knowledge transfer for an integrated approach (Clim4Vitis)" was a European Commission-funded Twinning action that aimed to promote knowledge and skill transfer on the general topic of "climate & viticulture" among European scientists and wine industry, as well as it aimed to grow awareness on climate change impacts on viticulture. The main objective of the action was to enhance the science and technology (S&T) capacity of the Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB)'s research group at the Universidade de Trás-os-Montes e Alto Douro (UTAD; project coordinator) concerning climate change and viticulture issues.

The Clim4Vitis activities were mostly devoted to knowledge transfer and expertise-sharing on tools for assessing climate change impacts on European viticulture, namely through the application of both climate and grapevine models. The exploitation and dissemination of the main outcomes were also carried out through capacity-building actions. The organization of the Clim4Vitis events (e.g. workshops, short courses, staff exchange, visits, among others) were the privileged meeting point between researchers and stakeholders, either encouraging or deploying new science-industry collaborations. The Clim4Vitis action also allowed to lay the foundations for long-term sustainability among Clim4Vitis partners, which will be consolidated through future collaborative research and projects within similar fields of research, also enlarging the consortium to other European R&D units and further engaging the industry.

Clim4Vitis envisages contributing to the development of new European Commission policies (e.g. the "Green Deal") towards a more sustainable and resilient Europe. Clim4Vitis also contributed to the United Nations Sustainable Development Goals, particularly in the following: "Climate Action" and "Partnerships for the Goals"



HIGHLIGHTS

#01

Climate change is threatening the overall sustainability of the European viticulture-wine making sector, through a wide range of processes and scales, thus challenging a vital and deeply-rooted socioeconomic sector in many European regions and countries.

#02

New adaptation strategies and complementary policies are urging to cope with the already ongoing impacts of climate change, reducing risks and fostering the transition to a more climate-resilient, go-green, and economically sustainable European viticultural-winemaking sector.

#03

When assessing climate change impacts, climate and crop model limitations and uncertainties should be properly addressed and communicated to stakeholders and decision-makers, thus enabling the development of more robust and effective adaptation measures.

#04

European networks of academic and wine industry actors should be consolidated for improving existing knowledge and harmonising research methodologies and adaptation strategies.

#05

Clim4Vitis promoted knowledge transfer and capacity-building actions on the topic of "viticulture & climate" among scientists, students, technicians, farmers and the wine industry in general.

CHAPTER 1

THE VITICULTURAL SECTOR IN EUROPE

Grapevine (Vitis vinifera L.) is a valuable perennial crop cultivated between 30° and 50° parallels in the Northern Hemisphere (Amerine et al., 1980). In this area, the most traditional wine regions are favoured by optimal temperature conditions (from 12–13°C to 22–24°C on average in the growing season; Schultz and Jones, 2008; Schultz and Jones, 2010) that allow the production of high-quality wines. In Europe, where the wine regions producing renowned wines are strictly regulated and delimited (e.g. denomination of origin), viticulture and wine-making sectors play a relevant role in their contribution to the local economy and the improvement of the landscape ecosystem services (Fig. 1).

The global importance of European viticulture is evidenced by the amount and the worth of the vineyard area, wine production, and exports of the main producer countries. According to the International Organisation of Vine and Wine (OIV), three main European countries, i.e., Spain (13%), France (11%) Italy (9%), and a non-European country (China, 12%) hold the majority of the world vineyard area. However, while that area tends to increase in some extra-EU countries (e.g. China and India), the percentage of vineyard area in Europe remained relatively stable during the last years (-1%, 0%, +2% of the total vineyard area 2014–2018 in Spain, France, and Italy, respectively). By contrast to other extra-EU countries (e.g. China, India, Egypt), most of the grapes harvested in Europe are devoted to wine-making (the 86.5% and 96% of the grapes produced in Italy and Spain in 2018 were used for wine production; OIV, 2019), making of Europe the major wine producer at global scale. Indeed, European countries contribute more than 50% to global wine production. In 2019, Italy, France and Spain (i.e. the most world wine producer countries) reached 48, 42, and 34 millions of hectolitres (mhl) of wine production followed by Germany (8.2 mhl) and Portugal (6.5 mhl; OIV, 2020). An important part of this European wine production is exported towards extra-EU countries (71 mhl), especially the United Kingdom and the United States. In this context, Italy, France, and Spain contributed to 34%, 25%, and 22% of the extra EU wine export. Regarding the wine imports (48 mhl in 2019), Germany, Netherlands and Denmark represented the main European wine importer countries with 2.3, 1.1, and 0.7 mhl, respectively (Eurostat, https://ec.europa.eu/).

In this regard, the consumer appreciation for wines produced in traditional and renowned wine regions may offer additional advantages for the EU compared to other countries or regions as demonstrated by the high demand for European wines outside Europe. However, despite the highly-valued European wines, climate change impacts on viticulture are changing world wine region distribution. In fact, the growing suitability of environmental conditions in new viticultural areas, coupled with the improvement of the wine-making techniques, are leading to a reshaping of the global wine production and trade.

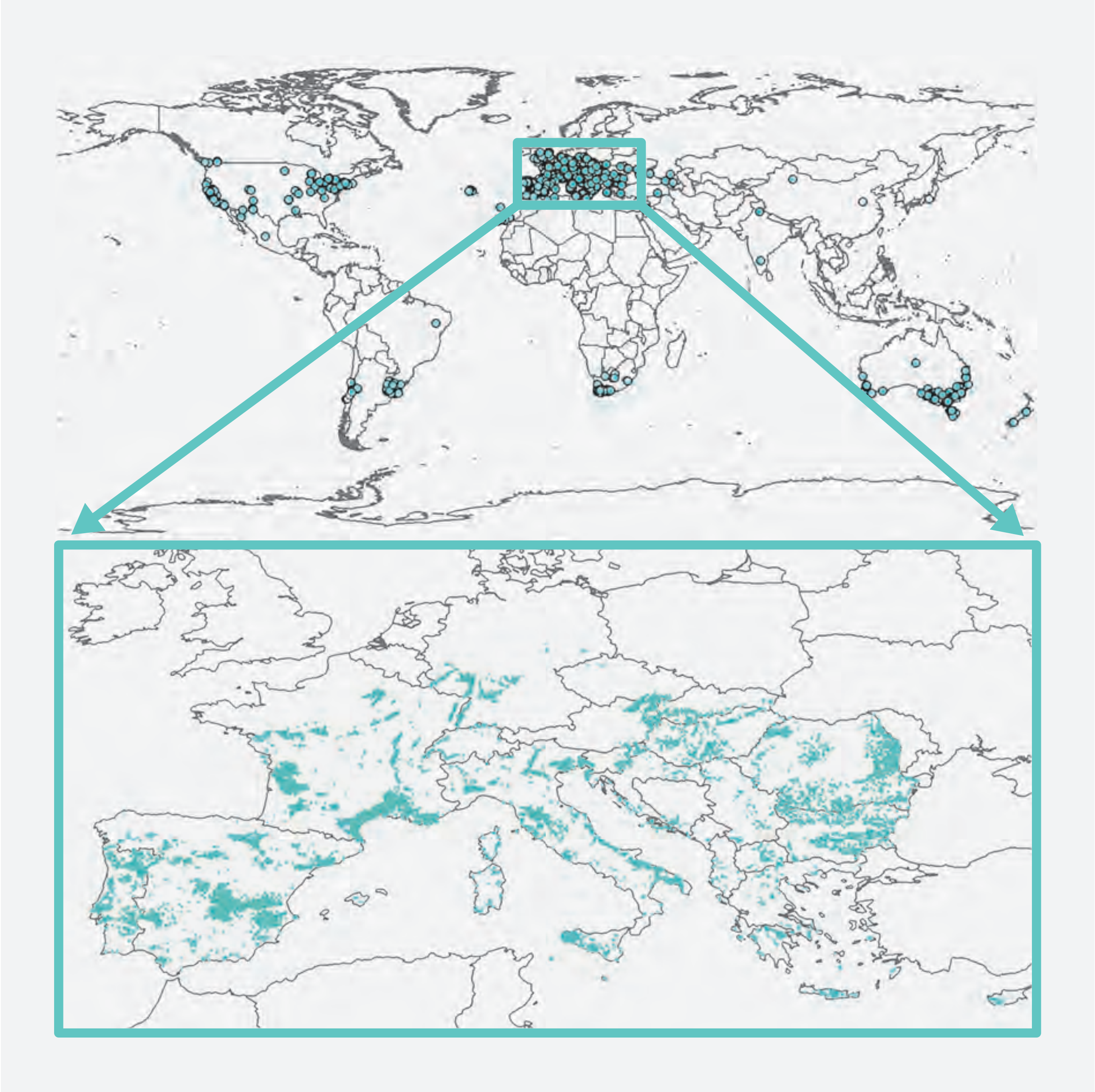


Figure 1 – (Top panel)

Distribution of the main wine regions in the world. (Bottom panel) Current vineyard land cover area in Europe

CHAPTER 2

CLIMATE CHANGE IMPACT ON VITICULTURE AND WINEMAKING

The most high-rated European wine regions are located in narrow geographical areas, characterized by environmental conditions well suited to viticulture. In these areas, the interactions among climate, soil, cultivar and human factors (Terroir) influence the wine style and attributes, contributing to the achievement of the high-quality standards and consumer-recognized typicity of the final product. Nevertheless, over the last years, climate change is threatening the viticultural suitability of these regions, with negative impacts on the main grapevine physiological processes, final grape yield, and wine quality. Considering that several studies predict that these changes in climate conditions will worsen in the future, a comprehensive analysis of the main climate change impacts on grapevine development, growth, and production (Fig. 2) is needed for better understanding their likely role on the future European viticulture, as well as for identifying effective adaptation strategies to new climate conditions.

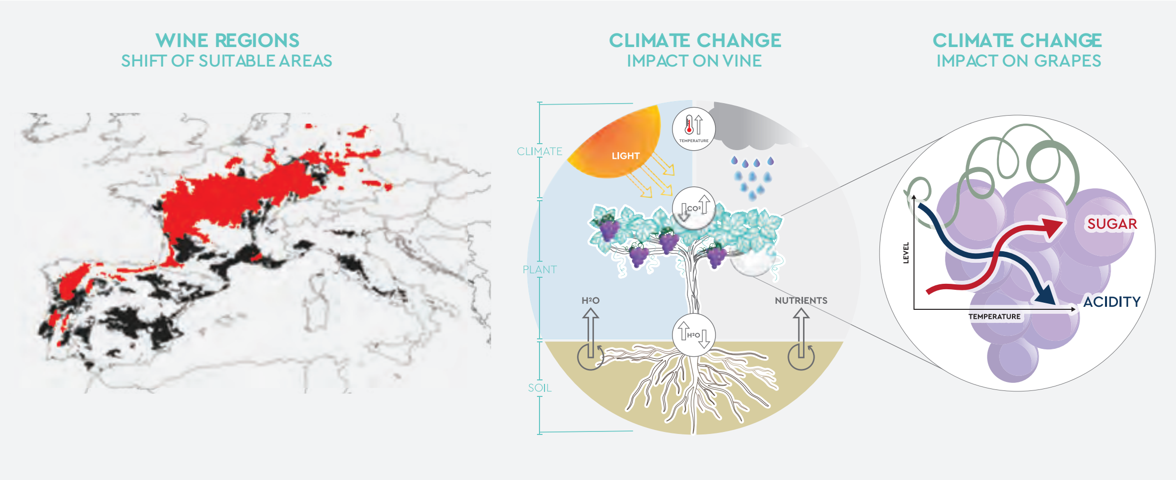


Figure 2

Impact of climate change on viticulture. First panel: adapted from Moriondo et al. (2013).

2.1. Phenological development

Climate change impacts on grapevine phenology are largely evident in many European wine regions (Jones and Davis, 2000; Bock et al. 2011; Tomasi et al. 2011), where the warmer temperatures of the last decades are leading to a general earlier occurrence and shortening of the main phenological stages (e.g. budbreak, flowering, veraison, and maturity), with important effects on the final grape production and wine quality. Due to this warming, most traditional wine regions in Europe are adapting by following a latitudinal (from southern to northern Europe) and an altitudinal (from low to high altitudes) shift towards more suitable environmental conditions (Caffarra and Eccel, 2011; Moriondo et al. 2013; Leolini et al. 2018). In warmer areas, indeed, the influences of climate change on phenology (e.g. the shift of the developmental stages) may alter grapevine growth and reduce yield. For instance, a delayed or uneven budbreak occurrence may lead to detrimental effects on crop growth (i.e. limited shoot growth and plant vigour; Wicks et al., 1984; Dokoozlian, 1999). These effects on budbreak date are often determined by temperature change, which is the main driver of phenology, during the dormancy period. Warmer temperatures limit the accumulation of chilling units in the first sub-period of dormancy (first part of the winter; endo-dormancy), delaying the achievement of the chilling requirement. Concurrently, the milder temperatures during late winter may shorten the second sub-period of dormancy (eco-dormancy), producing an early occurrence of budbreak.

As a response to the impact of warmer temperature on phenology, several studies have also evidenced the consequences of a shifted budbreak on the subsequent phenological phases in the present and future climates (Fila et al., 2014; Leolini et al., 2018). Indeed, high temperatures around budbreak may reduce the number of flowers per inflorescence and increase flower size (Keller et al., 2010), while the occurrence of suboptimal temperatures around flowering and heat stress events negatively influence flower fertility and reduce fruit-set (Kliewer, 1977). The overall increase of temperature coupled with heat stress events has also relevant impacts on the veraison-maturity period of grapevine, by influencing the sugar and acid accumulation (Jones and Davis, 2000), by one side, and the aromatic composition of the berries, by the other side (e.g. anthocyanins; Yan et al., 2020). This dual effect is determined by the decoupling of the technological and phenolic maturity, which modifies the final grape quality, particularly in those wine regions where ripening typically occurs under hot and dry conditions (Petrie and Sadras, 2008; Sadras and Moran 2012; Arrizabalaga et al. 2018).

2.2. Photosynthesis and gas exchange

Climate change affects grapevine growth through modification in photosynthesis activity, gas exchange, and the light-, water- and nutrient- use efficiency (Schultz et al., 2000; Bindi et al.

2001a,b). In C3 plants as grapevine, the net photosynthesis rate and the water use efficiency (ratio between photosynthesis and transpiration) increase in CO2 enriched environments while no significant effects are evidence for the transpiration rate (Bowes, 1991; Schultz, 2000; Moutinho-pereira et al. 2009). Differently, transpiration rate evidenced an increasing trend under elevated temperatures (Schultz, 2000; Moriondo et al., 2015). Moreover, despite the positive effect of CO2 on grapevine growth, heat events, high radiation, and water stress conditions can decrease CO2 assimilation and photosynthesis activity due to a strong reduction of stomatal conductance (Flexas et al., 1998; Medrano et al., 2003; Bertamini et al., 2006; Greer and Weedon, 2013). This implies that, while an increase of leaf area and photosynthesis activity is possible under elevated CO2 concentrations (Bindi et al., 1996, 2001a,b), prolonged and severe drought periods negatively influence grapevine vegetative growth (Flexas et al., 2002). However, some grapevine varieties developed different stomatal behavior (anisohydric vs isohydric) which has an important role for their adaptive mechanisms to water stress conditions (Schultz, 1995, 2003).

2.3. Biomass accumulation and yield

Biomass accumulation and final yield are mainly affected by elevated CO2 concentration, drought, and high temperatures. Indeed, the increase of photosynthesis activity, caused by elevated CO2 concentration, determines an increase of biomass accumulation rate that is partitioned among the different plant organs (Bindi et al., 1996). In 550 and 700 µmol mol-1 CO2 enriched experiment, the increase of the total plant and fruit biomass was found 40–45% and 45–50% higher than in CO2 ambient conditions (Bindi et al., 2001a,b). This positive effect of CO2 can, in some cases, offset the negative impacts of water stress, which determine a reduction in the leaf area growth and fruit dry matter production (Kizildeniz et al., 2015). While the impact of warming on grapevine yield showed an asymmetric effect in some regions (from 46% reduction to 177% increase, as shown by Sadras and Moran, 2013), it is evidence-based that prolonged drought periods, especially at specific plant development stages, strongly reduce final grape production. Some authors showed that severe water stress conditions in the pre-veraison stage may lead to a significant reduction of berry growth and berries per cluster, unlike when the water stress occurs (or it is applied) in the post-veraison stage (Poni et al. 1993; Wenter et al., 2018). However, the impact of water stress seems to be reduced by the adoption of appropriate deficit irrigation strategies, which limit the effects on final yield and grape quality (Chaves et al., 2010; Mirás-Avalos et al., 2017; Wenter et al., 2018).

2.4. Pests and diseases

Climate change influences the development cycle and the distribution of grapevine pests and diseases. It was observed how warmer temperatures, determining anticipation of the phenological stages, caused an earlier occurrence of the grapevine pest cycle in some regions (e.g. Lobesia botrana in Spain), with positive effects also on their voltinism (i.e. the number of insect generation per year; Tobin et al., 2008; Martín-Vertedor et al., 2010). Although the early occurrence of the maturity phase and harvest date is expected to limit the detrimental effects of some pests in the future (Caffarra et al., 2012), mild temperatures (especially in winter) may favour the presence of invasive species at northern latitudes, as expected for Drosophila suzukii, a native pest of Southeast Asia (Langille et al., 2017). A warmer climate is expected to impact not only the distribution pattern of pests and vectors, migrating from the tropical environments towards temperate regions, but also the distribution and expansion of their parasitoids and predators, as well as on the trophic interactions in the vineyard (Reineke and Thiery, 2016). Concerning grapevine diseases, a decreasing pressure of some diseases (i.e. evaluated in terms of the number of treatments for mildews) due to changing climate conditions is projected in some European regions (Zito et al., 2018). However, the interactions between climate change, pests and diseases, and vines should be further investigated also considering the impact of other climate change drivers (e.g. CO2 and water stress), which directly affect plant growth and development (Section 2.3).

2.5. Quality

The combination of the climate change factors, such as elevated CO2 concentrations in the atmosphere, high temperature, and water stress, influences not only vine yield but also grape quality. For instance, elevated CO2 levels coupled to high temperatures and partial irrigation treatments were found increase the tonality index (Sudraud, 1958) and pH of cv. Tempranillo grapes at ripeness (20–23° Brix; Salazar-Parra et al., 2010). Moreover, a decreasing concentration of malic acid was found under elevated CO2 and high temperatures in well-watered plants (Salazar-Parra et al., 2010; Kizildeniz et al., 2015). Regarding anthocyanin content, Sadras and Moran (2012) evidenced a decoupling trend of these components with sugar content (delayed onset) under elevated temperatures in Shiraz and Cabernet Franc berries (Sadras and Moran, 2012). This effect influences the colour and alcohol balance in red wines and it can partially be limited by the application of deficit irrigation strategies. Indeed, an increase of phenolic concentrations and sugar content was evidenced using some regulated deficit irrigation strategies in the pre-veraison stage (Intrigliolo et al., 2012; Casassa et al., 2015), while sugar content accumulation can be limited by the impact of water stress on leaf photosynthesis in the post-veraison phase (Intrigliolo et al., 2012). The effect of high temperatures on sugar contents in grapes can also determine a consequent increase of the potential alcohol in wine (Jones and Davis, 2000; Teslić et al., 2018). This trend, as well as a decrease in acidity level, is expected to increase in future with the impact of global warming (Leolini et al., 2019). Finally, positive effects on chemical compound synthesis have been evidenced under high sunlight exposure (UV-B radiation), which induces the production of some photo-protectors (phenols in berry skin; Berli et al., 2008) and overall improves grape quality (Martínez-Lüscher et al., 2014).

2.6. Winemaking

Climate change may cause detrimental effects on wine production and quality, not only during grapevine growth but also during the winemaking process. More specifically, warmer temperatures, determining increases of sugar concentration in grapes at the ripening stage, may lead to osmotic issues in yeasts (Saccharomyces cerevisiae), with consequent limitations in the fermentation process of the grapes (Bely et al., 2005). This implies that, in some cases, yeast strains of Saccharomyces cerevisiae may be replaced by other yeast strains (Saccharomyces bayanus), generally used for high sugar concentration (Lafon-Lafourcade et al., 1979). The dual effect of warmer temperatures determines an increase of sugar content and a decrease of acidity over the veraison-maturity phase, with a consequent pH increase in the subsequent malolactic fermentation, which in turn will negatively influence wine quality (Lonvaud-Funel, 2001; Massera et al., 2009). The increase of sugar content in grapes and, consequently, of the potential alcohol in wine may alter wine sensory perception (Ferrer-Gallego et al., 2014; Jordão et al., 2015). An increase of by-products production, due to the high content of residual sugars during fermentation, leads to higher volatile acidity levels, with detrimental effects on wine quality (Boulton et al., 1996; Vilela-Moura et al. 2011). Additionally, high-temperature influences yeast assimilation of the assimilable nitrogen. Indeed, the yeast request for assimilable nitrogen may increase in response to the high must sugar content driven by warmer temperatures. In this case, a low initial concentration of assimilable nitrogen leads to a reduction of yeast population, with consequent reduction and/or stuck of the fermentation process (Bely et al., 1990).

CHAPTER 3

FUTURE CLIMATE SCENARIOS: UNCERTAINTIES OF THE CLIMATE AND CROP MODELS PROJECTIONS

The risk assessment by modelling climate change impacts on cropping systems provides crucial information to policymakers and farmers (Fig. 3). However, there are inherent uncertainties in such modelling exercises. Firstly, extensive uncertainties exist in how mankind will choose to co-develop with the society and environment, which are often being explored and characterized by a range of plausible emission scenarios. Simulating the response of the climate system to anthropogenic emissions using General Circulation Models (GCMs), or more advanced Earth System Models (ESMs), and the downscaling of these simulations to higher spatial resolutions are both introducing additional uncertainty, as they represent only abstractions and approximations of the physical climate system. Furthermore, simulating the climate impacts on crop growth and productivity are subject to a wide range of crop model uncertainties, arising from different model structures, input data availabilities, and adopted calibration approaches. Therefore, uncertainty estimation, providing likelihood analysis and boundary information on potential risks, is essential to complement the impact results and to promote better communication with the general public.

3.1. Uncertainties deriving from climate projections

3.1.1. Natural climate variability

Natural (internal) climate variability results from the non-deterministic physical processes of the climate system and non-linear interactions among its components. It represents an intrinsic limitation to long-term climate projections, and its temporal evolution is found to be associated with the initialization status of the climate model component (Deser et al., 2012). To account for natural variability, multiple model-initialization ensembles should be used in climate.

3.1.2. Anthropogenic and emission scenario uncertainties

GCMs and ESMs are the most relevant tools to estimate future climate change at a global scale. They require input information on the possible evolution of the composition of atmospheric gases like Greenhouse Gases (GHG). However, the trajectory of GHG emissions is difficult to project, as they are influenced by various aspects of anthropogenic activities, such as social-economic development, technological advancement, as well as land use, and environmental changes. Emission scenarios that provide plausible descriptions of future pathways of these key sectors have thus been utilized to estimate the resulting changes in the atmospheric concentrations of

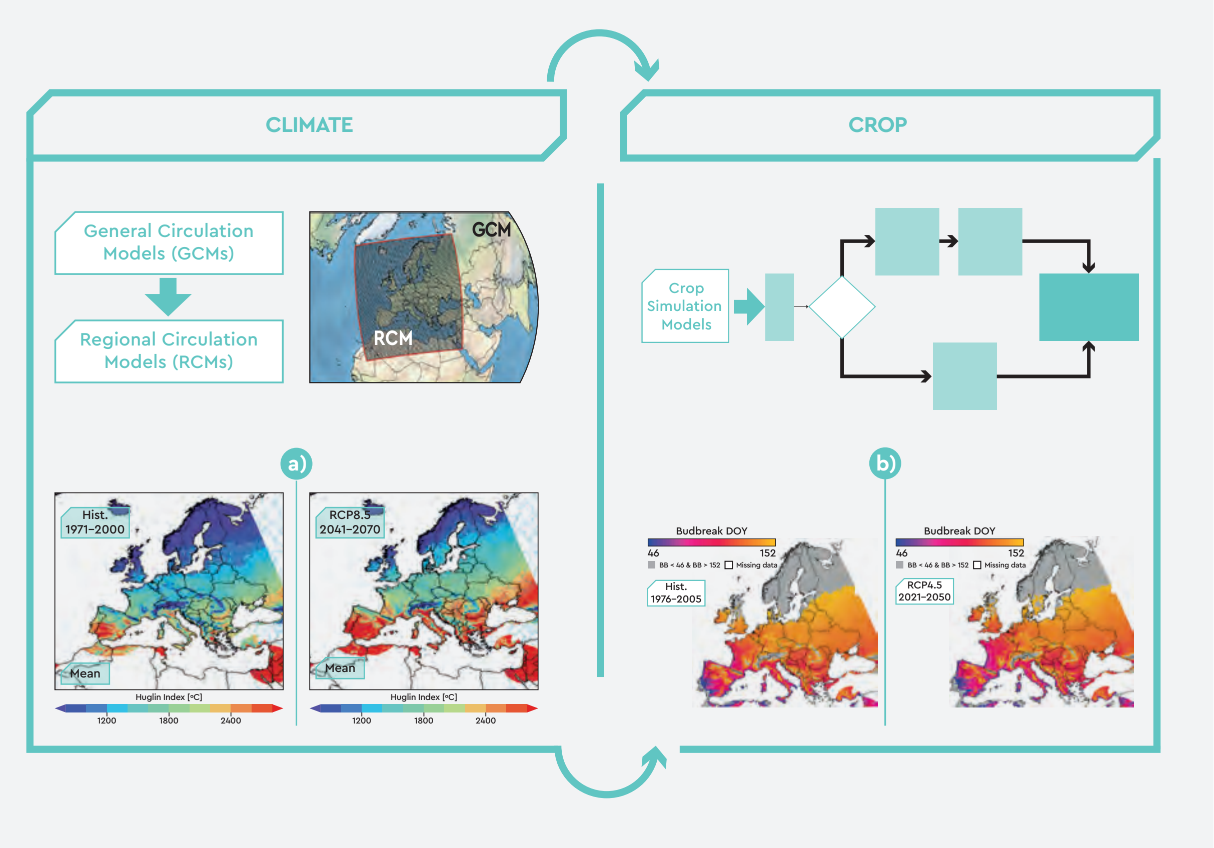


Figure 3

Application of climate and crop models in Europe. a) Huglin Index (°C) estimation for historical (1971–2000; top panel) and future (RCP 8.5: 2041–2070; bottom panel) scenarios. b) Phenological model application for budbreak occurrence (DOY), under historical (1976–2005; top panel) and future (RCP 4.5: 2021–2050; bottom panel)

GHG and other substances (e.g. aerosols). These concentrations are used to drive the GCMs/ESMs. To account for the different socio-economic pathways and land-use changes different Representative Concentration Pathways (RCPs) are used.

3.1.3. Climate model uncertainties

GCMs and ESMs are developed to describe the various physical processes and their complex interactions governing the Earth's climate system, but they are limited by their coarse horizontal resolutions (~50–300 km) and the approximations to represent small-scale physical processes. These limitations also affect the simulated climate change signal of those models. Different GCMs/ESMs differ for example in their horizontal resolution, the bio-geophysical processes considered, and the parameterization schemes used to represent those processes. Consequently, different models simulate different climate change signals. To account for this difference (structural uncertainty) in terms of future climate change uncertainty a multi-model ensemble of different GCMs/ESMs should be used.

Due to their coarse horizontal resolution, GCMs/ESMs cannot be used in regional climate impact studies. Therefore, Regional Climate Models (RCMs) are employed to dynamically downscale the GCMs outputs to a higher spatial resolution. The advantages of RCMs are a better representation of local geographic features and a more detailed description of physical processes with sub-grid parameterization schemes. Nevertheless, similar to GCMs/ESMs results from RCMs also show structural uncertainty. Furthermore, uncertainties and errors in the GCM simulation can propagate into the RCM. Hence, to account for the structural uncertainty in the driving GCM/ESM and the RCM itself and considering the uncertainty propagation of a GCM/ESM-RCM, a modelling matrix with multiple global and regional models should be used.

3.1.4. Bias adjustment

Climate model uncertainties can partly be related to systematic biases. The systematic biases of climate models can be quantified by a systematic deviation between the observed and the modelled value of any measurable quantity of the climate system (e.g. daily average temperature or precipitation). For example, GCMs can overestimate precipitation in certain regions by one order of magnitude. The uncertainty related to systematic biases can be reduced by applying appropriate bias adjustment to the simulated time series.

Depending on the variable and bias type, various bias adjustment methods can be applied. All of these methods are intended to adjust specific statistical properties of the modelled time series towards observations. Hence, the quality of the adjustment and the degree of bias reduction depends on the method applied and observation dataset utilized. Furthermore, while reducing the bias in one statistical property the adjustment can also introduce errors into another property or distorting the physical consistencies between variables.

3.2. Uncertainties deriving from crop model simulations

3.2.1. Crop model structural uncertainties

The process-based crop models are useful tools to estimate climate change impacts on crop productions, by taking into account the complex interactions among genotype × management × environment. These models are typically composed of various mathematical equations to describe crop development and growth in a systematic manner, which is derived from experimental observations and empirical evidence (or assumptions). However, those mathematic equations cannot include all explanatory variables to fully capture the source of variability (Seidel et al., 2018; Wallach et al., 2019). Furthermore, different models commonly adopt different function forms and parameterization approaches, resulting in considerable prediction uncertainties when a single model is used.

Many studies have consistently reported that uncertainties in climate impact projections are larger due to variations among crop models than from variations among climate models (Rötter et al., 2011; Asseng et al., 2013; Tao et al., 2020). A strategy to address this issue is to apply the crop multi-model ensembles (MMEs) to quantify, manage and consequently reduce the uncertainties (Rosenzweig et al., 2013; Ewert et al., 2015). It is recognized that MMEs median or mean should be used, as they provided more robust and reliable predictions than any individual model (Rötter et al., 2018; Wallach et al., 2018; Tao et al., 2020). Yet, the better representation of observations by ensemble median or mean can be the fortuitous result of error compensation among models, which highlights the need to optimize the ensemble size and composition under a certain environment (Rötter et al., 2011; Asseng et al., 2013; Ewert et al., 2015). Reducing the source of model structural uncertainties can be carried out through target experimentations to gain insights into specific biophysical processes, e.g. how a given crop responds to increasing CO2, with interactions of water, nutrient and heat stresses (Asseng et al., 2015; Rötter et al., 2018).

3.2.2. Input data uncertainties

Integrated modelling and assessment require the availability of high-quality observational data as inputs to test, evaluate and improve crop model simulations as a basis for policy and management decisions (Rötter et al., 2011; Kersebaum et al., 2015; Seidel et al., 2018). However, the quality of these input data is often inadequate for many reasons. Firstly, it is naturally variable in the actual field conditions, e.g. the soil chemical properties can vary substantially within a very small distance of a few centimetres (Hartemink et al., 2020). Such small-scale variability of observations has frequently led to sampling errors when the measurements are taken at several spatial points to be representative of the whole field. Accordingly, high spatial and temporal resolutions of measurements, together with enough sample size and sufficient details of records, are essential to improve the accuracy and quality of field measurements (Boote et al., 2016; Seidel et al., 2018). Moreover, there are increasing needs for model applications to test and examine the sensitivity of model response to the underlying spatial variability within the field (Kersebaum et al., 2015). For example, to test the secondary soil properties beyond the dominant unit at a specific site.

The second important source of input uncertainties derives from the fact that it is extremely difficult to compile consistent and balanced datasets, which include multiple observed variables to test all the processes and assumptions of a given crop model (Rosenzweig et al., 2013; Kersebaum et al., 2015). For instance, sometimes we can adjust model parameters to fit simulations to annual yield data, but simultaneously resulting in poor simulations of phenology and other state variables (e.g. soil water dynamics), due to limited data availability (Yang et al., 2020).

Thirdly, there are uncertainties in the experimental data regarding whether they can adequately cover a wide range of local conditions, e.g. from very dry to very wet seasons. A reliable model calibration should use site-specific and more comprehensive data to ensure the delivery of robust information (Wallach et al., 2019).

Lastly, glasshouse and pot experimental data should be avoided for model calibration and validation, as they are often not suitable to mimic crop temperature response under field conditions (e.g. root heating is exaggerated in pots; Asseng et al., 2015).

3.2.3. Calibration and parameters estimation uncertainties

Application or adaptation of crop models to a new environment often involves calibration (adjustment) of some parameters to reflect local conditions. The calibration/parameter estimation practice often uses a small portion of available field data, which are normally independent of those used for model evaluation. Several studies suggest that calibration can compensate to some extent for the difference of model structure, thanks to the use of the same calibration data, which in turn affects subsequent model simulation performance (e.g. variability between multi-model simulations are reduced; Asseng et al., 2013; Wallach et al., 2019).

The employed calibration methodology may not be the one to give the best parameter values that minimize model prediction errors. This is because there are different calibration approaches available, each of which has its basic statistical assumptions, calibration steps, and, hence, calibration results (Wallach et al., 2017; Wallach et al., 2019). For instance, the frequentist approach to calibration focuses on the underlying distribution of simulation errors, whereas the Bayesian method seeks to determine the probability distribution of each calibrated parameter (Wallach et al., 2017; Wallach and Thorburn, 2017). Therefore, the choice of the calibration approach that largely determines the model predictability will depend on whether the objective function is explicitly defined, e.g. to minimize the sum of squared errors or maximize the concentrated likelihood (Wallach et al., 2019).

In practice, calibration has been frequently undertaken using ad hoc or trial and error approaches, which provide little information on the parameter uncertainties (Seidel et al., 2018). As a result, there is currently no standard calibration protocol established and recommendations might be better derived for each model separately (Seidel et al., 2018; Wallach et al., 2019). Additionally, uncertainties in calibration may be caused by difficulties to choose the correct estimation parameters. One can choose to estimate one or several parameters simultaneously to fit the calibration data. The general criteria for the choice of calibrating parameters should consider its relevance to the observed variables and prioritize the choice for local (cultivar & management) parameters to preserve the potential robustness of the model (Seidel et al., 2018; Wallach et al., 2019).

Overall, studies devoted to modelling climate change impacts should give particular attention to how the model is calibrated, where sufficient methodology details would facilitate the development of common calibration guidelines and deploy tools for the crop modelling community.

CHAPTER 4

ADAPTATION STRATEGIES: GUIDELINES FOR WINEGROWERS

Adaptation to climate change will be needed at the level of the winegrowers to maintain the typicity of their wines as far as possible, as well as the economic sustainability of the viticultural sector in the regions concerned. Adaptation strategies can be grouped into combinations of short-term measures, adopted during the annual grapevine cycle, and long-term measures, adopted beyond a given vineyard lifetime (Santos et al., 2021a,b; Fig. 4).

4.1. Short-term adaptation strategies

Short-term adaptation measures can be considered as a primary protection strategy against climate change impacts. They are commonly applied to trigger plant reactions on specific climatic conditions/threats during the growing season and they consist of specific agronomic practices (Santos et al. 2021b).

4.1.1. Crop canopy management

Crop canopy management includes some short-term agricultural practices and techniques that allow to re-modulate and adapt canopy shape to face the impact of climate change. Considering the effect of warmer temperatures on phenology, some changes in canopy structure can be adopted, for example, delaying the ripening phase into cooler periods. The reduction of leaf area to fruit weight ratio and photosynthesis activity allows to minimize the crop water consumption and to delay maturation, thus limiting the impact of above-optimal temperatures or heat stress during this stage. Similarly, late winter pruning can delay the onset of budbreak. As a consequence of the budbreak shift, the ripening phase may also be delayed into a later cooler period (Neethling et al. 2016).

4.1.2. Protection against extreme heat and sunburns

The negative impacts of extreme heat (Fraga et al., 2020), water scarcity, and high irradiance in vineyards urge short-term adaptation strategies, such as the application of exogenous compounds (e.g. as calcium carbonate ($CaCO3$), kaolin ($Al2Si2O5(OH)4$) and potassium silicate ($K2SiO3$; Santos et al. 2020). In this context, the application of a chemically inert clay, such as kaolin, allows reducing the impact of sunburns on leaves under heat stress (Dinis et al. 2016). Likewise, the use of shade nets enables to maintain, or even improve, plant growth and development, offering protection against environmental stresses.

Figure 4

Short- and Long-term adaptation strategies for reducing the impact of climate change on viticulture.

4.1.3. Irrigation

Despite irrigation is not a common practice in EU wine regions, the application of this short-term adaptation strategy in dry seasons has rapidly increased, especially in the Mediterranean countries. Supplemental irrigation is used to improve and standardize crop yield and quality, whenever rainfall is too low (~ 250 mm) to meet grapevine water requirements (Neethling et al. 2016). However, this practice reveals some constraints concerning additional financial costs, water use regulations for maintaining wine typicity, and water resource scarcity. Water availability, indeed, is expected to become a major limiting factor for vineyard irrigation, mainly in Southern Europe, where water availability is projected to decrease in the future. For this reason, supplemental irrigation should be carefully applied only during the most sensitive phenological stages and optimized for minimizing water wastes (Duchêne et al. 2014). Drip irrigation is generally implemented as the most efficient water-saving method, although sprinkler and furrow irrigation systems are still being used. The main recommendation is to adopt drip irrigation complemented with plant water status indicators (e.g. stem/leaf water potential, trunk diameter, or sap flow measurements), which enables optimized scheduling of water applications. For instance, Pisciotta et al. (2018) demonstrated that grapevine yield can be increased by the application of subsurface drip irrigation with −0.4 and −0.6 MPa leaf water potential thresholds before and after veraison, respectively. Despite these findings, further research is needed to duly assess the strengths and weaknesses of this strategy, envisioning the optimization of irrigation under future climates.

4.1.4. Pest and disease control

Under future climate conditions, grape-growing regions may struggle with increased risks of invasive pests and diseases or the spreading of already established ones. This might result in higher demands for more intense plant protection measures, particularly when the use of pesticides is increasingly questioned and supposed to be reduced. Some practices, such as irrigation, may limit the outbreaks of the leafhopper population and, thus, can be included as a short-term adaptation strategy for monitoring these pests in the vineyard (Reineke and Thiery, 2016). However, efforts to guarantee constant monitoring of pests and diseases, the application of innovative technologies, and adaptation measures should be further promoted and sustained. Most likely, forecast and decision support systems will gain more importance in the future. Adaptation can also take place through technology transfer from regions where a specific pest is already successfully controlled.

4.1.5. Soil management

Soil management should be adopted as an effective strategy for reducing soil erosion, improving plant vigor, and manage water supply (Santos et al. 2020). Soil erosion needs to be avoided as much as possible, since eroded soils have low fertility and low-water holding capacity, thereby limiting water use efficiency. Thus, practices such as soil tillage, which promotes soil erosion, should be avoided. Conversely, vineyard inter-row spaces should be covered by vegetation (either spontaneous or cultivated herbaceous cover crops). In case of water scarcity, cover crops such as self-reseeding annual legumes guarantee a low competition for water with the main plant, while they contribute to improving the soil fertility conditions. On the contrary, in high rainfall environments, the use of cover crops enhances soil bearing capacity. Finally, the use of composts obtained from different materials can be an option to improve soil fertility. However, when applying composts, the nutrient input into the vineyard has to be deeply analyzed. Furthermore, the use of synthetic (e.g. black polyethylene and geotextile) and organic mulches, including compost, bark, or straw, may bring positive effects on soil water content, mostly in environments characterized by high soil evaporation and runoff.

4.2. Long-term adaptation strategies

Long-term adaptation strategies are measures, employed by growers, to adapt grapevine cultivation to climate change before the planting of a vineyard. Long-term adaptation strategies must be carefully considered since incorrect decisions at this early stage can either be ineffective or their refinements can be extremely costly (Santos et al. 2021a).

4.2.1. Changes in training systems

The increase of temperature associated with prolonged drought periods in the Mediterranean regions will require new training systems for reducing crop water demand. The Gobelet training system was widely used in the Mediterranean basin for limiting the crop photosynthesis and transpiration demand, though this practice was recently abandoned because of its unsuitability for mechanical harvesting. Currently, the changes in training systems should aim to achieve the following objectives: (i) Delay the maturation period. To avoid that grapes are ripening under high-temperature conditions, training systems that delay ripening may have beneficial effects under future climate conditions. Minimal pruning systems in their various forms (i.e. semi-minimal pruned hedge) might represent an interesting option in cooler and warmer regions (Molitor et al., 2019). (ii) Reduce sugar accumulation. To achieve reduced sugar content of grapes and thus reduced alcohol content, the leaf area to fruit weight ratio can be reduced by adopting specific training systems that lower the leaf area per hectare. (iii) Lowering radiation and temperature in the cluster zone. Modifications of crop management, such as row orientation, will influence exposure to light and wind speed in the canopy, and may also provide high adaptive potential. For example, higher canopies, as well as closer distances between rows, may increase shadowing. Moreover, the increase of trunk height allows for reducing high temperatures in the cluster area, especially in dry and stony soils.

4.2.2. Varietal, scion-rootstock clonal selection

Varietal selection may represent a useful practice for coping with the impact of climate change. Indeed, since the suitability for the successful cultivation of different varieties is largely dependent upon air temperature, long-term adaptation strategies may encompass changes in the varietal spectrum. One of the most largely adopted strategies is the introduction of grapevine varieties with a late-ripening phase, thus counteracting the overall trend for earlier phenology. With this regard, Duchêne et al. (2014) investigated a range of phenological phases in the progeny of Riesling x Gewurztraminer cross. However, replacing grapevine varieties in a given location may change the quality of the final product, which may have important consequences on the local economy and consumer appreciation, thus requiring a gradual adaptation of the sector and consumer education to the new wine styles. In this context, the exploitation of the wide variability of the scion-rootstock clones to take advantage of their maturation timing differences (e.g. 8–10 days) has a large adaptation potential. Clones characterized by a late-ripening phase and grafted onto the same variety can indeed be adopted for delaying maturation, but without considerably changing wine typicity.

The varietal/clonal variability should also be considered to increase the pest and disease resistance, as well as to select more heat and drought-tolerant grapevines. In the first case, the use of interspecific crossings, with reducing susceptibility towards fungal diseases (the so-called "Piwis") has increased in recent years. This plant material is considered to be particularly resistant to fungal diseases and severe climate conditions and might represent an interesting adaptation strategy. In the second case, after choosing rootstocks 140 Ruggeri and 110 Ritcher, Corso et al. (2016) selected a new rootstock (M4) to improve plant resistance to water stress. The selection of water stress-tolerant plant material is of foremost pertinence, particularly in Southern Europe. Furthermore, while cooler northern European winemaking regions may benefit from a wide range of varieties from southern Europe, the latter region will be limited to varieties well adapted to very dry and warm climates, which can be found in other continents and latitudes. Although some water stress tolerant rootstocks have already been proposed, the high variability of plant responses under dry conditions does require further research on the selection of both variety and scion-rootstock material.

4.2.3. Vineyard relocation

Shifts of wine regions, towards higher latitudes and altitudes, coastal zones, or areas with overall lower solar radiation (for reducing the excessive exposure to UV-B radiation), is a long-term measure that may also be considered when choosing new vineyard sites, particularly in regions where climate change will bring more dramatic changes and where viticulture may become economically and environmentally unsustainable (Santos et al., 2020). In some mountainous wine regions, the strong temperature variability between the hilltop and lower areas frequently leads to wide ranges of microclimates, enabling the winegrowers to adapt their management strategies to the different local vineyard conditions. However, this drastic long-term measure should be carefully evaluated taking into account the actual conditions of the new implantation areas (e.g. spatial variability of local climate, slope, and economic suitability), which can affect the wine production and composition.

CHAPTER 5

CLIM4VITIS ACTION OVERVIEW

The impact of climate change on viticulture is a relevant issue that drew the attention of the European Commission. Over the last years, some European projects were funded in order to raise awareness among stakeholders about the effects of climate change on future viticulture sustainability. In particular, the "Climate change impact mitigation for European viticulture: knowledge transfer for an integrated approach (Clim4Vitis)" twinning action aimed to enhance the knowledge and skill transfer between and towards scientific actors and stakeholders regarding the evolution of the climate change impacts in viticulture. For reaching this objective, the Clim4Vitis action was focused on enhancing the visibility of UTAD – and its research group Centre for the Research and Technology of Agro-Environmental and Biological Sciences (CITAB) – in terms of grapevine modelling and of the identification of methods and tools for assessing the impacts of such climate change on grapevine productivity, quality attributes and risk of diseases and pests in European vineyards. In this context, the expertise of each Clim4Vitis partner (i.e. Universidade de Trás-os-Montes e Alto Douro, UTAD; Potsdam Institut für Klimafolgenforschung, PIK; Università degli Studi di Firenze, UNIFI; Luxembourg Institute of Science and Technology, LIST and the Sociedade Portuguesa de Inovação, SPI) was useful for raising the science and technology (S&T) capacity of UTAD and the entire consortium on this relevant topic.

The project activities were organized in six work-packages, which included the synchronization of a common database and a standardized model family (WP1), the implementations and evaluation of the capacity building actions (WP2–3), the foundations of the long-term sustainability of the project (WP4), the dissemination of the results (WP5) and the project coordination and management (WP6; Fig. 5).

The scientific results of the Clim4Vitis action derived by the application of climate and crop growth models and were published in an open access repository (Zenodo) and scientific journals, laying foundations for mutual collaboration between partners in future research. The Clim4Vitis outputs were also disseminated to stakeholders through the promotion of twinning actions (e.g. thematic workshops, short courses, and staff exchange). This allowed the consolidation of transnational networks (ranging from stakeholders to academic/scientific and industrial actors) to the adoption of top-quality approaches for assessing and facing the impact of climate change in viticulture (Fig. 5). The activities and results obtained during Clim4Vitis, besides the reinforcement of UTAD and CITAB´s S&T&I performances, contributed to improving collaboration among project partners and stakeholders, as well as to increase the attractiveness towards the climate change and viticulture topic.

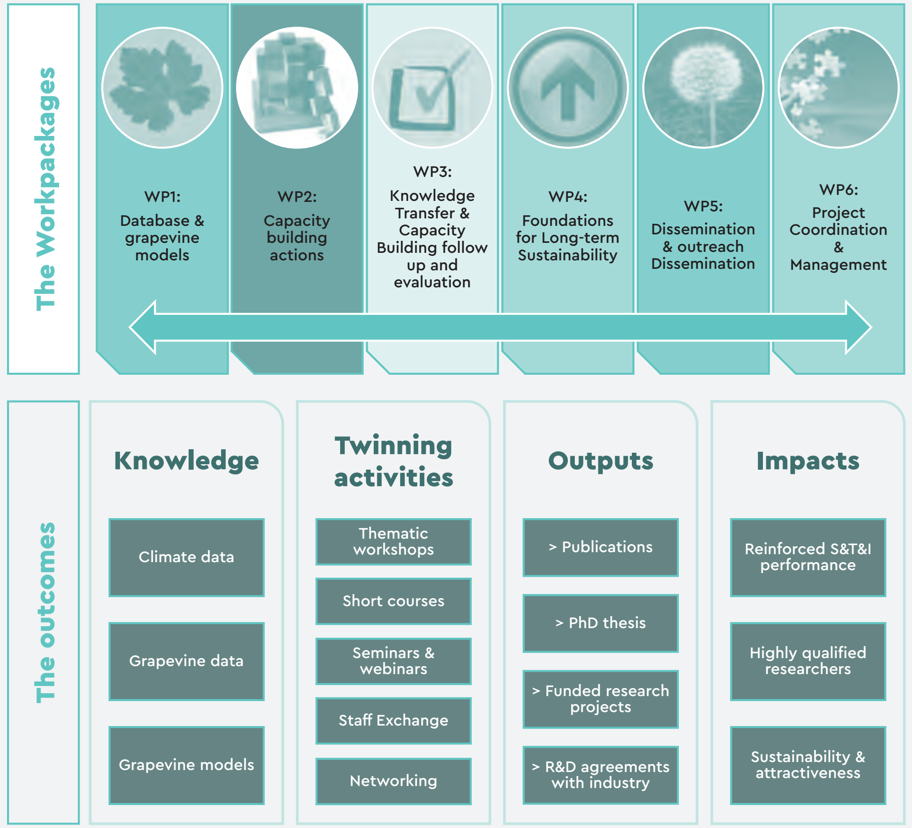


Figure 5

Clim4Vitis project work-packages and outcomes

5.1. Clim4Vitis activities and dissemination results

Clim4Vitis consortium disseminated scientific project results and promoted knowledge transfer in order to increase awareness on the "viticulture & climate change" topic, among stakeholders and the general public. The purpose of Clim4Vitis was also to create trans-national networks for future collaborations and innovative projects among different institutions and stakeholders.

5.1.1. Clim4Vitis events: thematic workshop, short courses and staff exchange

The results of Clim4Vitis project were disseminated at four main Clim4Vitis events organized by project partners (UTAD, UNIFI, LIST, and PIK) in the respective countries. The first Clim4Vitis event, organized by UTAD, was held at Vila Real (Portugal) on the 18th-21st February 2019 and it included the Clim4Vitis launch event, thematic workshop "An overview of different approaches for modelling grapevines", the "Viticulture & Climate change" short courses and the visit at a renowned farm of the Douro valley. The second Clim4Vitis event, organized by UNIFI, was held in Florence (Italy) on the 09th-12th July 2019 where was hosted the "Methodologies for assessing climate change impacts: Technical Aspects" thematic workshop, the staff exchange, and the farm visit in the Chianti region. The third Clim4Vitis event, organized by LIST, on the 17th-20th February and it included the "Modelling pest and disease in vineyard" thematic workshop, the advisory board meeting, the staff exchange, and the farm visit at the Moselle valley. The fourth Clim4Vitis event, organized by PIK in collaboration with the Hochschule Geisenheim University (HGU), was held remotely on the 1st-2nd December 2020 because of the COVID-19 pandemic emergency. The event included the "Global change impacts on viticulture" thematic workshop and the staff exchange among PIK, HGU, and Clim4Vitis partners. The last Workshop was held at UTAD, in November 2021, within the Clim4Vitis Open Day, which was also the project closure event. At all Clim4Vitis events, several researchers, students, and winegrowers participated giving room to an interesting discussion on the viticulture and climate change issue.

5.1.2. Stakeholder meetings

Meetings with stakeholders were organized by the Clim4Vitis partners in the respective countries. The objective of these events was to address the relevant topic of climate change and viticulture with the target audience of some main wine regions (e.g. winegrowers, winegrowers associations and cooperatives, wine industry, etc.) in order to find common solutions and to increase future viticulture sustainability. These events were fully appreciated and contributed to creating opportunities for future collaborations.

5.1.3. Scientific results dissemination

Scientific results (i.e. papers, presentations, short communications, etc.) of Clim4Vitis project were disseminated in different scientific journals, as well as on an open-source web repository (Zenodo).

5.1.4. Other sources of communication and dissemination

Clim4Vitis results and events were also communicated and disseminated through periodic newsletters, project website (https://clim4vitis.eu), target journals, and through other sources of dissemination materials (e.g. flyers, brochures).

CHAPTER 6

KNOWLEDGE GAPS AND FUTURE CHALLENGES FOR VITICULTURE IN EUROPE

The Clim4Vitis project produced several encouraging outcomes regarding the involvement of the target audience (from researchers to stakeholders) on the role of viticulture in European society and economy, as well as the potential impacts of climate change on the whole value chain. For this reason, new projects and research that will contribute to improving the sustainability of future wine production and promoting the application of mitigation and adaptation strategies in European viticulture should be strongly encouraged.

Some knowledge gaps still arise regarding grapevine and climate modelling, as well as the most appropriate adaptation options to follow in the context of climate change (Fig. 6). During the Clim4Vitis action, we identified the most relevant gaps, which should be taken into account in forthcoming research for better understanding the climate change impact on grapevines:

1. The evaluation of climate change impacts on grapevine cultivation is strongly correlated to the uncertainties of the future climate projections. Climate projections are affected by intrinsic climate uncertainties dependent on the interactions between the physical factors in the climate system and the evolution of anthropogenic GHG emissions (Chapter 3). These uncertainties should be considered when climate projections are generated in order to avoid the under- or over-estimation of the future climate change signal. On this basis, the use of probabilistic distributions for climate projections, built on a multi-model ensemble approach (Fronzek et al., 2010) and based on the probabilistic estimates of a certain future event, are generally more informative for end-users compared to the deterministic projections, which provide quantitative estimates of the expected climate variables. However, new research is needed to improve the accuracy of climate projections, including the effect of climate seasonality, which most of the existing climate models do not yet skilfully account for.

2. Growth models represent useful tools for reproducing plant growth and their interactions in the soil–plant–atmosphere continuum at different detail levels. One important issue related to these models is the type of physiological processes implemented for describing grapevine growth. Despite process-based models are used for describing the main dynamics of crop growth, not all physiological processes and interactions of the plant with the environment are taken into account in grapevine simulation models. However, some physiological processes appear essential for improving the estimation of vine development, production, and quality. In this last case, for example, the modelling of berry sugar and acid content (or other phenolic compounds) is not included in most grapevine simulation models. The implementation of these specific processes in crop growth models may provide important information about grape quality during the growing season to winegrowers and consumers. Besides this aspect, also the poor quality and, sometimes, the high request of input data for describing a particular process limit the implementation of the grapevine growth models. Likewise, a scarce model calibration under present climate conditions and the lacking of a comprehensive dataset of observations may lead to an erratic description of the behaviour of a specific grapevine variety, magnifying this uncertainty when simulation models are applied under future climate scenarios.

3. Growth simulation models, coupled with climate projections, are currently the sole tools able to predict future grapevine behaviour. However, those models need additional implementations for improving their reliability to estimate vine development and production under future climates. In some cases, ad hoc experiments are needed for improving knowledge about the impact of changing climate conditions on vine physiology (e.g. temperature and CO2 increase or reduced water availability), which may be used for implementing simulation models so as to estimate future yield and quality variability. In this regard, some authors have already evidenced the influence of weather variables on grapevine phenology, production, and quality in experiments under controlled or semi-controlled environments (Kizildeniz et al., 2015; Martínez-Lüscher et al., 2016). Currently, one of the most useful systems for describing plants' behaviour in changing climates is FACE (Free Air CO2 Enrichment). The FACE experiments allow simulating the effect of different CO2 concentrations on crops under open field conditions (Bindi et al. 1996; Bindi et al., 2001a,b). Although FACE and current experiments in semi-controlled conditions represent a good proxy for evaluating the responses of crops to future climates, further studies are still required for evaluating the role of the long-term exposure and the combined effect of different climatic factors on plant growth (e.g. CO2 and temperature on radiation and water use efficiency; Moriondo et al., 2015).

4. The application of crop growth models provides useful information on the trend of grapevine growth and production under present and future climates. However, these tools are sometimes not able to detect the within-field crop variability, especially in a complex environment such as a vineyard. For this reason, the assimilation of data derived by remote sensing systems (e.g. Unmanned Aerial Vehicles, satellites)

in crop growth models may allow the spatial analysis of vineyard conditions at high resolution. The implementation of new decision support tools (e.g. web platform or apps) have been already proposed for monitoring crop development and production, also supporting stakeholder's decisions for the application of appropriate management practices (e.g. pesticide distribution) and to reduce farm costs, However, this holistic approach is still poorly represented in viticulture. In this perspective, the combining of grapevine simulation models with precision remote systems and seasonal forecasts should be promoted to provide seasonal predictions (yield, phenological timing, etc.) and technical solutions to winegrowers for improving final production. Thus, the meeting point between current research in viticulture and the stakeholder's requests should be focused on the implementation of these strategic solutions to face the current and future challenges of this sector. New dedicated events with stakeholders should be organized for promoting scientific results and technologies, as well as to discuss the main monitoring and adaptation strategies to climate change.

5. Clim4Vitis project laid the foundations for long-term collaboration between partners to find new opportunities for joint participation in research projects. In particular, the collaboration between research institutions by one side, and the establishment of transnational networks among researchers and stakeholders, by the other side, is expected to improve the quality of research in viticulture and the sharing of information with stakeholders that have direct experience in the field. In this regard, innovation projects should take into account the development of new tools for adaptation strategies adopted to support the stakeholder's decision-making, creating a link between research and farmers' request. In this regard, more applicative measures might be related to the establishment of the European Operational Groups and networks (comprised of farmers, wine industries, retailers, among others). These initiatives, together with research projects or actions such as Clim4Vitis, will be critical for increasing awareness of target stakeholders and find solutions to cope with climate change. Finally, considering the relevant role played by viticulture in the European economy, European policies (e.g. PAC incentives) should favour the increase of winegrowers' incomes, supporting them in the application of timely, suitable, and cost-effective adaptation strategies for improving viticulture sustainability and climate-resilience.

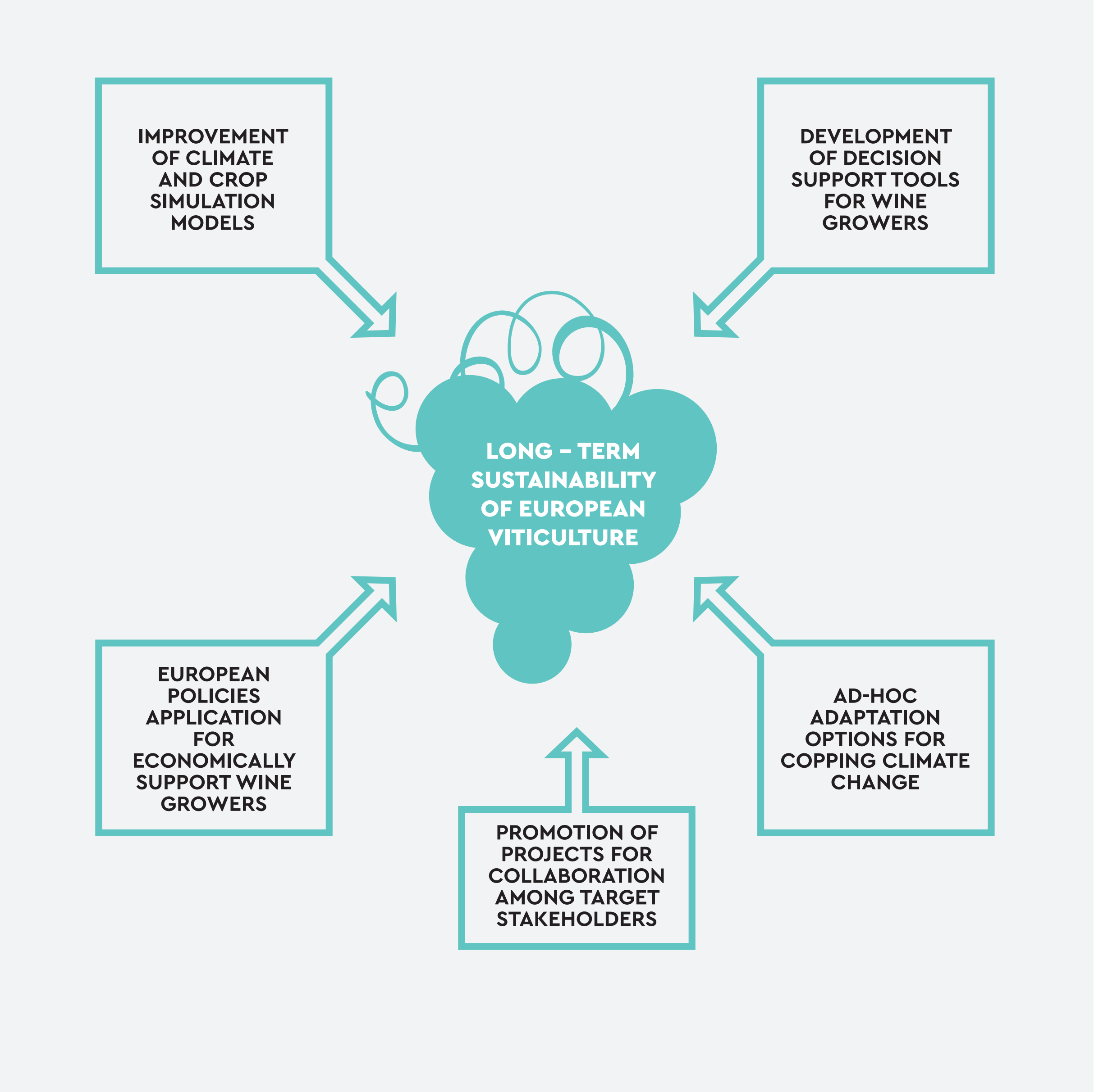


Figure 6

Knowledge gaps and research needs for increasing long-term sustainability of future European viticulture

CHAPTER 7

CONCLUSIONS

The impact of climate change in viticulture became a relevant issue for winegrowers during the last years, mostly because of the detrimental consequences that warmer temperatures, prolonged drought periods, and other adverse climate conditions, showed on grape production and wine quality. In Europe, where the viticultural and winemaking sector has important economic, societal and environmental implications for the community, the increasing pressure and the market demand for high-quality wines stimulated the scientific community to deeply investigate the causes and the effects of climate change on viticulture.

In this regard, the Clim4Vitis horizon 2020 twinning action faced up one of the most important issues of the European agricultural scenario: the impact of climate change on viticulture. The results derived by the application of climate and crop models highlighted that climate change is threatening the sustainability of viticulture in the European traditional wine regions and new adaptation strategies are needed for maintaining high-quality wine production. These findings were published in scientific journals (Fraga et al., 2020; Leolini et al., 2020; Molitor et al., 2020; Santos et al., 2020) and web platforms (e.g. Research Gate and Zenodo), and disseminated during the Clim4Vitis Days events in all partner's countries. The dissemination and communication of results during the Clim4Vitis events promoted the knowledge transfer between scientific and industrial actors on this important topic.

In order to improve dissemination, the Clim4Vitis action organized, in addition to the thematic workshops already foreseen in the project proposal, local meetings strictly dedicated to winegrowers to raise awareness in this stakeholder category that is expected to be vulnerable to climate change were organized. The number and active participation of stakeholders at all these Clim4Vitis events, properly documented and monitored by project partners, demonstrated the great interest around these activities and allowed to open interesting debates between researchers, winegrowers, students, and other stakeholders about climate change and viticulture issues, as well as to allow us to create synergies between project partners and stakeholders for future collaborations in a common framework.

As described in this document, the Clim4Vitis consortium has already created a strong partnership and we have identified major lines of research that can be the basis for future research and innovation carried out by the Clim4Vitis team.

GLOSSARY AND REFERENCES

Glossary

ADAPTATION STRATEGIES | A set of measures used to reduce and prevent (in long- or short-term) the negative impact of climate change on agricultural systems.

CAPACITY-BUILDING ACTIONS | Educational, training, and mentoring actions to enhance the science and technology capacity of a specific subject and to promote the technology transfer.

CLIMATE MODEL | A set of mathematical equations used for simulating, identifying, and quantifying the physical and chemical processes of the climate system.

COMMUNICATION | Strategic and targeted measures for promoting the action itself and its results to a multitude of audiences.

CROP SIMULATION MODEL | Simplified description of a real system able to reproduce the behaviour of a plant and its interactions with the environment through the implementation of mathematical equations.

DISSEMINATION | A process of public disclosure, promotion, and awareness-raising of the project results.

EXPLOITATION | Use and benefiting of the project results for different purposes.

GLOBAL CLIMATE CHANGE: long-term alteration of the average climate conditions (e.g. temperature and rainfall) of the earth.

Knowledge transfer: a set of activities dedicated to share and disseminate knowledge that is available to the community.

Stakeholder: any person or group directly or not directly involved in a specific activity that can influence or can be influenced by its results.

Viticulture sustainability: a global approach to viticulture that adopts economically feasible and viable farming management, prevents environmental risks, and values cultural and social aspects.

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