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Review

A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture

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Abstract: Viticulture and winemaking are important socioeconomic sectors in many European regions. Climate plays a vital role in the terroir of a given wine region, as it strongly controls canopy microclimate, vine growth, vine physiology, yield, and berry composition, which together determine wine attributes and typicity. New challenges are, however, predicted to arise from climate change, as grapevine cultivation is deeply dependent on weather and climate conditions. Changes in viticultural suitability over the last decades, for viticulture in general or the use of specific varieties, have already been reported for many wine regions. Despite spatially heterogeneous impacts, climate change is anticipated to exacerbate these recent trends on suitability for wine production. These shifts may reshape the geographical distribution of wine regions, while wine typicity may also be threatened in most cases. Changing climates will thereby urge for the implementation of timely, suitable, and cost-effective adaptation strategies, which should also be thoroughly planned and tuned to local conditions for an effective risk reduction. Although the potential of the different adaptation options is not yet fully investigated, deserving further research activities, their adoption will be of utmost relevance to maintain the socioeconomic and environmental sustainability of the highly valued viticulture and winemaking sector in Europe.

Keywords: viticulture; wine production; climate change; adaptation; risk reduction

1. Introduction

A brief characterization of the global viticulture and winemaking sector is provided upfront to better understand its relevance in the world economy. As detailed in the latest report of the International Organization of Vine and Wine (OIV) [1], it is estimated that the world vineyards cover an area of approximately 7.449 million ha (2018). In this same year, Spain encompassed 13% of the world vineyard area, closely followed by China (12%), France (11%), Italy (9%), and Turkey (6%). These five countries represent approximately one half of the global vineyard area. From the same report, it can be concluded that the time evolution of the world vineyard area underwent an overall downward trend over the last two decades, particularly in the period from 2003 to 2011. The weak recovery from 2012 to 2014 was then followed by a new decline thereafter. Stabilization of the vineyard area, or a slightly decreasing trend, is observed during the last five years in most of the countries where viticulture is a relevant sector, apart from the robust declines in Turkey and Iran. Nonetheless, some countries show a clear growth of the vineyard area, mainly China and India [1].

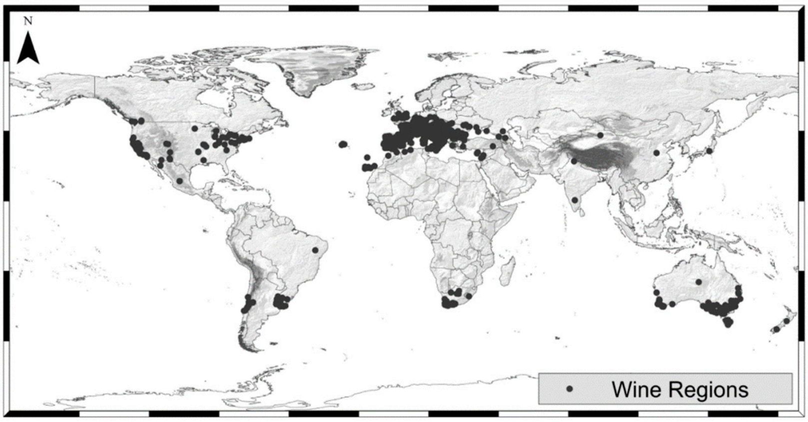
Following the same OIV report [1], and on the contrary to the world vineyard area, the global grape production experienced a noticeable upward trend over the last two decades, highlighting productivity gains. As also reported by the OIV [1], the estimated production quantity was of roughly 77.8 million tons (10^3 kg) in 2018, a record-breaking value, against 60–65 million tons at the beginning of the 21st century. Generally, grapes are produced in the form of wine grapes (57% of all grapes), table grapes (36%), or dried grapes (7%). The production of both table and dried grapes is prevalent in some countries that have no tradition in wine production, such as China (89.7% of all grape production), Turkey (96.8%), India (98.5%), Iran (100%), Uzbekistan (96.3%), Egypt (99.5%), and Brazil (53.5%). Conversely, the production of wine grapes is associated with countries where viticulture is largely devoted to wine production, such as Italy (86.5%), Spain (96%), France (99.6%), Argentina (93.7%), Australia (90.9%), Germany (99.6%), or Romania (93.1%), ranked in descending order in terms of production volume. The evolution of global table grape production, mostly generated by China, Turkey, India, Iran, Uzbekistan, Italy, and the USA (all of them with production over 1 million tons in 2018), has shown a consistent increase, whereas wine grape production has remained relatively stable [1]. No significant changes occurred for dried grapes. Hence, wine grapes are becoming gradually less prominent in the viticultural sector in terms of volume, but still represent the majority [1].

Concerning the winemaking sector, global wine production was 292 million hl in 2018, remaining relatively stable over the last two decades [1]. The four most important wine producers, ranked by their production in volume, are Italy (54.8 million hl), France (48.6), Spain (44.4), and the USA (23.9), with the first three being the most important global exporters. Wine consumption increased from 2000 to 2007, but remained nearly constant thereafter, with a current value of 246 million hl [1]. The five major wine consumers are the USA (13% of world wine consumption), France (11%), Italy (9%), Germany (8%), and China (8%) [1]. Although wine trade, in volume, has been stable since 2011, wine trade in monetary value has been growing continuously to reach a record-breaking value of approximately EUR 30,000 million in 2018 [1].

Geographically, grapevines are historically cultivated on six out of seven continents, between latitudes 4° and 51° in the Northern Hemisphere (NH) and between 6° and 45° in the Southern Hemisphere (SH), and across a large diversity of climates (oceanic, warm oceanic, transition temperate, continental, cold continental, Mediterranean, subtropical, attenuated tropical, arid, and hyperarid climates), but with the majority occurring in temperate climate regions [2]. The most important viticultural regions in the world are shown in Figure 1a, whereas the vineyard land cover in Europe is displayed in Figure 1b. Large areas in Europe, equatorward of the 51° N parallel, are devoted to viticulture. Many viticultural regions also underlay strict regulations concerning typicity and quality of the product, sometimes several centuries old [3], also, in some cases, with wine region delimitation systems (e.g., denominations or appellations of origin, among many others).

Along the previous lines, it is clear that viticulture is a key socioeconomic and cultural sector in many countries and regions worldwide, with a high economic impact in the network of all relevant industry branches of the supply and distribution chains. Besides the direct income from wine sales, which benefit the whole production chain (wine and subsidiary companies, their employees, viticulturists, and property owners), there are other indirect benefits provided, spreading from landscape and ecosystem services to tourism. Therefore, an assessment of the sustainability of viticulture under future conditions, both environmentally and economically, is of utmost importance.

This paper will treat the subject in seven sections. First, a brief description of the *terroir* concept, which is the interplay between soil, climate, and human activity, in many ways fundamental to wine production (Section 2), and the interplay between weather/climate and grapevines (Section 3) will be given. Second, the potential climate change impacts (Section 4) and the adaptation options (Section 5) on these interrelationships will be discussed on the basis of state-of-the-art scientific knowledge. Finally, some existing knowledge gaps and research challenges will be explored (Section 6), followed by the conclusions (Section 7).



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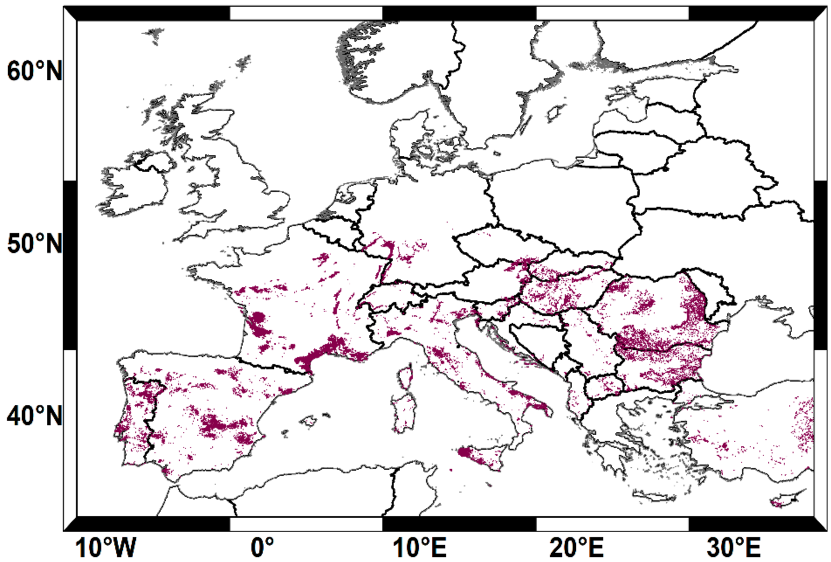

(**b**)

Figure 1. (**a**) World distribution of the viticultural regions (black circles) [4]. (**b**) Political map of Europe with the vineyard land cover (shading). Source: Copernicus CORINE Land Cover (CLC) 2018 (https://land.copernicus.eu/).

Taking into account the wide-ranging scope of the present review, an exhaustive compilation of all previous studies in the field is not feasible, not even of the most recent studies. The main goal is to provide an updated overview of this topic on the basis of the results of relevant and illustrative research, which may be useful not only for researchers and academics, but also for stakeholders and decision-makers. Although the focus is largely on European viticulture, most of the discussion can be easily extrapolated to other wine regions outside Europe that share similar environmental conditions.

2. Viticultural *Terroir*

Winemaking regions are characterised by their particular natural environment, such as climate, soil properties, and a human factor, deciding on the use of grapevine cultivars and viticultural practices. According to Carbonneau [5], the climatic characteristics of a given viticultural region are key factors in understanding its varietal suitability and wine types, as will be further discussed in Section 3. The soil properties of a given region or site also play a central role in viticulture, whereas soils are also prone to changes induced by climate evolution (see Section 4). Grapevine varieties and scion/rootstock combinations have different soil preferences that eventually determine the characteristics of the produced wine. In fact, soil physical and chemical properties heavily influence grapevine development and grape berry composition [6]. The importance of these local-scale pedoclimatic characteristics has been recognized in all winemaking regions, sometimes over centuries, as vine growers have continuously adapted local viticultural practices, to some extent empirically, to best suit their surrounding environmental conditions [7]. The soil–plant–atmosphere continuum largely determines the outcomes from a vineyard. Besides pedoclimatic conditions, biotic factors, such as the influence of pests and diseases; the role of functional biodiversity in the vineyard; and agro-management practices, namely, scion and rootstock choice, pruning, pinching, girdling, topping, or thinning, play a key role in grapevine growth, development, and berry quality [8].

On the basis of the aforesaid interactions, the concept of *terroir* has been widely adopted [3]. According to OIV (Resolution OIV/VITI 333/2010), "Terroir is a concept which refers to an area in which collective knowledge of the interactions between the identifiable physical and biological environment and applied viticultural and oenological practices develops, providing distinctive characteristics for the products originating from this area. Terroir includes specific soil, topography, climate, landscape characteristics and biodiversity features". As such, the terroir significantly affects grapevine development and berry composition and has been accepted as a key aspect in determining wine quality and typicity of a given region [9].

3. Atmospheric Influence on Grapevine Development

3.1. Grapevine Cycles Versus Weather and Climate

Grapevine development is associated with several stages of its vegetative and reproductive cycles. Under the conditions of many traditional viticultural regions (i.e., extratropical viticulture), the grapevine vegetative cycle extends over one full year, whereas its reproductive cycle lasts for two years. The reproductive cycle governs several important qualitative and quantitative properties, such as the number of grape clusters in the following year. The vegetative cycle encompasses two main sequential periods: dormancy period and growing season. The grapevine phenological development comprises several stages or phenophases (Figure 2). These stages of grapevine vegetative and reproductive cycles are largely controlled by atmospheric conditions [10].

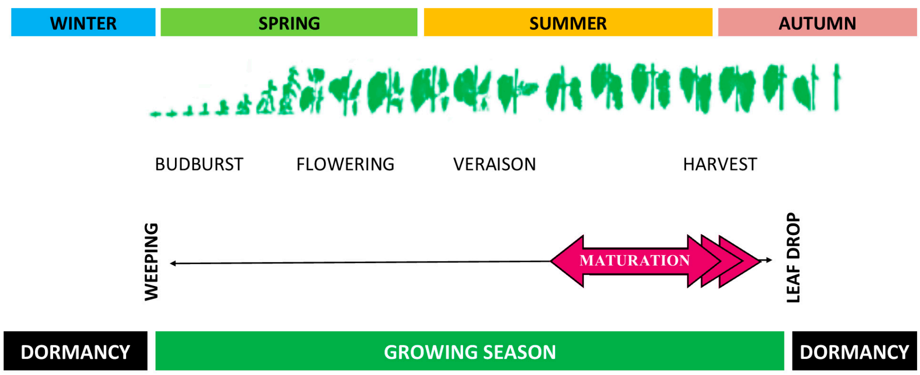

Figure 2. Vegetative cycle and main vine phenological stages.

The impact of atmospheric forcing on grapevine can be divided into two different time scales. On the long-term, climate, which corresponds to the statistical distribution of the different atmospheric variables over long-term periods (decades) at a given location [11], determines the bioclimatic envelope of that location and its viticultural suitability [3,12]. Macroclimates are determinant of the wine geography and the distribution of grapevine varieties, whereas mesoclimates and microclimates promote different terroir units, with diverse wine identity and diversity [13]. The wide range of climate-driven scales, as well as the spatial complexity and temporal dynamics in viticulture, have already been documented [14]. On the short-term, weather considerably governs the whole grapevine development process, as it requires suitable temperatures, radiation intensities, and duration, as well as specific levels of water availability throughout its growth cycle, ultimately influencing yield, biomass production, berry attributes, and wine structure and flavour [15,16]. Effectively, the evolution of weather conditions in a given location can be used to predict local/regional grapevine parameters, such as yield [17] or phenology [18].

3.2. The Role of Temperature

Among all atmospheric elements, air temperature is considered the most important in driving the growth and development of grapevines [19], in cases where water, radiation, and nutrient requirements of the plant are fulfilled [20,21]. From the climatological viewpoint, the distribution of traditional viticultural regions worldwide is mainly confined within a belt defined by the isotherms of average growing season temperatures (April–October, NH; October–April, SH) of 12–13 °C and 22–24 °C [12], underlining the key role played by temperature on viticultural suitability. Growing season temperatures below 12–13 °C commonly occur in regions with growing seasons too short for proper vine development, with typically low solar radiation levels and insufficient heat accumulation. On the other hand, growing season temperatures above 22–24 °C often lead to excessive heat stress on vines, which is also frequently associated with either severe water stress, in dry climates, or strong pest and disease pressures, in humid climates. These areas may also have difficulty in meeting the chilling requirements for the dormancy period, with resulting erratic bud break [12].

For the meteorological timescales, temperature conditions strongly control both grapevine physiology and berry composition during the preceding and the current growing season [22,23]. The inflorescence primordia differentiation starts around the bloom stage of the preceding year [24,25]. Warm and sunny conditions during this period promote the formation of inflorescence primordia, whereas cool and cloudy weather promotes the formation of tendrils [26,27]. Hence, the environmental conditions in the preceding year have a direct influence on the yield of the following season [28].

From leaf fall to the beginning of spring, grapevines are dormant and consist entirely of woody tissue, with little physiological activity [3]. This period encompasses two sub-periods that are controlled by endogenous and exogenous thermal factors needed for dormancy release. The first sub-period (endo-dormancy) is triggered by chilling accumulation (chill units) during autumn/winter, whereas the second sub-period (eco-dormancy) is driven by heat accumulation until bud break. Therefore, the winter chill is an important condition for grapevine growth development, as cold promotes bud dormancy [29,30], besides other processes such as day length shortening and ageing of the photosynthetic active parts of the plants. From late winter to early spring, the accumulation of daily mean temperatures above 7 to 10 °C generally promote dormancy break and the onset of the grapevine growing cycle [31].

During the growing season, grapevines undergo constant changes in terms of morphology and physiology. The length of the growing season for each variety is directly related to the growing season mean air temperature [32], though it may be additionally linked to soil moisture and crop management practices [33]. The length of the different phenological stages significantly differs not only according to each variety, but also to the thermal conditions in a given region for each specific year [34,35]. Despite relatively high resilience to abiotic stresses, extremely low temperatures during winter [36], negative temperatures (Celsius scale) around/after budburst [37–40], and hail events may severely damage the developing buds, leaves, and inflorescences [41,42]. Cool conditions [38] or extreme heat [28,43,44] may also affect vine physiology and yield, though some grapevine varieties are more tolerant to extreme temperatures than others. Grapevines under severe heat stress may undergo a significant decrease in photosynthetic productivity, as well as suffer injures in other biochemical processes [45]. Extreme events during the veraison–maturity period, such as heatwaves, can significantly influence sugar accumulation [46] and may lead to a decrease in anthocyanin biosynthesis and content [47]. Secondary metabolites, more specifically phenolics, due to their contribution to colour, flavour, aroma, texture, astringency, and stabilization of wine, as well as antioxidant properties [48], are extremely important for fruit quality and wine production [49]. High temperatures may also lead to important losses, as they also influence the synthesis of volatile compounds, which strongly contribute to the sensory character of wines [50]. In autumn, the gradual shortening of the day length and decreasing of temperatures promote acclimation to freezing temperatures in winter. During this phase, the translocation of carbohydrates, amino acids, organic acids, and some minerals from leaves to perennial organs (trunk and roots) reaches its maximum [51]. This period, considered as a survival strategy, ordinarily coincides with the generalized leaf senescence, followed by leaf fall and the subsequent dormancy period.

3.3. The Role of Water

Precipitation is another key atmospheric variable in viticulture, as it has a large footprint on soil water balance, determining soil water availability for the plant and its corresponding water status. Water stress leads to a wide range of effects that are also dependent on the grapevine development stage [52]. For instance, moderate-to-high soil moisture during budburst and shoot/inflorescence development is critical for vine growth [53]. Water stress at this stage may lead to stunted shoot growth, as well as poor flower-clustering development and berry set [54]. However, excessive humidity during early development stages may also overstimulate growth, which may lead to excessively vigorous and dense canopies, thereby potentiating the risks of diseases. From flowering to berry ripening, severe water stress may lead to reduced leaf area, thus limiting photosynthesis, as well as promoting flower abortion and cluster abscission [55]. Nevertheless, dry weather during ripening is generally favourable to high-quality wine production [56–58]. Slower leaf development also promotes higher water use efficiency [59]. Conversely, excessive precipitation is commonly unfavourable to maturation [2], for instance due to sugar dilution [60] or to bunch rot [61]. Recent studies indicated that water deficit affects grape and wine composition [62,63]. Regulated deficit irrigation has been used to improve berry and wine quality [64], increasing the concentration of terpenes by modulating structural and regulatory genes involved in volatile organic compounds biosynthesis [62]. Water deficit early in the season, before veraison, also stimulated increased anthocyanins and phenolic concentrations [65]. Furthermore, the timing and intensity of water deficits influence the extent of changes in berry metabolism and in wine colour, aroma, and flavour by modifying berry size and/or the synthesis of berry compounds, with a positive contribution to the fruit and wine organoleptic properties. Indeed, a water-deficit treatment typically increases the skin to pulp ratio in the berries, when compared with well-watered grapevines [66], increasing the amount of skin tannins and anthocyanins. Colour differences may result from increased anthocyanin synthesis caused by water deficit during the fruit development [67].

3.4. The Role of Radiation

Solar radiation is also a crucial factor in viticulture. The synthesis and accumulation of sugar, phenolic, and many aromatic compounds during maturation are indeed favoured by high solar radiation levels [68]. Regions with relatively low solar radiation normally adjust the training systems and canopy density to maximize the sun-exposed leaf area. Although more exposed leaves generally favour photosynthesis and stomatal conductance, water demand also increases [69], and other problems may also arise, such as leaf and cluster sunburn. On the contrary, less exposed clusters result in lower berry temperatures, generally leading to lower sugar contents and lower anthocyanin concentrations [70].

Additionally, shading due to high canopy density may significantly decrease bud fertility [71], thus negatively affecting the yield potential in the subsequent season.

In the Mediterranean-type climatic regions, such as in Southern Europe, vineyards are already typically exposed to high radiation levels, high air temperatures, and soil water deficits, which can impact grapevine productivity. Under these circumstances, grapevine leaves often show temporary photoinhibition, chlorosis, and necrosis, thus leading to low intrinsic water use efficiency and excessive exposure of grape clusters [72]. Hence, low vigour tends to be connected to reduced berry weight, sugar content, and yields. Still, other organoleptic properties of berries, such as flavour and aroma attributes, are frequently inhibited by excessive solar radiance and severe dryness or, as in the case of tannins, may be exacerbated in concentration and/or altered in molecular structure. These conditions may lead to unbalanced wines, with undesirable high alcoholic content and low acidity [73], with low commercial value. However, other studies [74–76] showed that vineyards exposed to relatively high levels of sunlight, including UV-B radiation, produce berries of high quality for winemaking by inducing synthesis of polyphenols and monoterpenes as photo-protectors.

3.5. Agro-Climatic Indices and Viticultural Zoning

The aforementioned effects of climate and weather on grapevines have been described by several agro-climatic indices. They commonly provide closer relationships between the grapevine development and atmospheric conditions than individual atmospheric variables, such as monthly mean temperatures, radiation, or precipitation. These indices were developed to integrate the plant–atmosphere interactions, thus following the plant physiological development more closely. Further, they can be used to assess the suitability of a given region or site for viticulture, in general, or a specific variety in particular. Due to the strong link between temperature and grapevine development, the agro-climatic indices are frequently based on temperature, such as indices using simple growing degree-day concepts (temperature integration). As a classical example, Amerine and Winkler [31] developed the Winkler growing degree-day scale for a base temperature of 10 °C. Following a similar concept, after some modifications in the temperature summation during the growing season and including a coefficient for day length, the Huglin index [77] was later developed. Molitor et al. [78] applied a trapezoidal model approach to simulate grapevine phenology (UniPhen), on the basis of cumulative degree-days, using three threshold temperatures (10 °C—lower threshold; 20 °C—upper threshold; 30 °C—heat threshold). Other indices based on hourly temperature accumulation were more recently applied [30]. To put more emphasis on the temperature conditions during the ripening period, which may ultimately influence the wine style, the cool night index [2,79], based on the mean minimum temperature in September (NH), was proposed. The dryness index is another very common index in viticultural zoning [68,79], which is based on an estimation of the potential soil water balance. Hence, viticultural zoning using agro-climatic indices is common to assess the suitability of a given region for viticulture and wine production for specific grapevine varieties.

4. Potential Climate Change Impacts

4.1. Ongoing Climate Change

The above-mentioned close relationships between grapevine development and weather/climate make viticulture particularly vulnerable to climate change and susceptible to its detrimental impacts. Through the combination of (i) generally increasing air temperatures and (ii) shift of the ripening period toward earlier (usually warmer parts of the season), climate change has a two-fold impact from the recent-past warming, especially clear during the ripening period [80].

Historical temperature trends for the main viticultural regions worldwide show that the growing season mean temperatures increased by 1.3 °C between 1950–1999 and 1.7 °C from 1950 to 2004 [81]. Associated with increasing temperatures over the last few decades, alterations in the grapevine growth and physiological development have been documented [56,57,82–84]. Changing climates are thereby influencing grapevine yield, as well as berry and wine quality [81,85]. In this regard, it was found that higher temperatures during the growing season promoted a decrease in the grape berry total acidity content [12,86], upward trends in sugar content or probable alcohol [87], and a decoupling between technological and phenolic maturity [83]. Earlier phenological timings and growing season shortening were observed in many viticultural regions [88–92]. These earlier phenological timings may lead to ripening during excessively warm conditions [93], with increased alcohol content, decreased acidity, and modifications in wine sensory profiles [94,95]. The 2019 ProWein Business Report (available at https://www.prowein.de/) presented the results of an industry survey, with the participation of more than 1700 enterprises, stating that the sensory profiles of wines have changed over the past decades. As such, climate change is also potentially threatening the wine typicity of traditional winemaking regions [80].

4.2. Climate Change Projections and Impacts on Grapevines

Climate change projections for the 21st century, based on global and regional climate models, are in general agreement with the observed trends over the past decades [96], leading to important impacts on viticulture. In some regions, climate change is supposed to be beneficial for viticulture, for instance due to higher fruit maturity and opening new areas for cultivation, whereas the impact might be detrimental in other regions by challenging the ability for adequate grape cultivation and wine production [12]. Alterations in the spatial patterns and temporal regimes of temperature and precipitation [97] may significantly modify current viticultural bioclimatic zones in Europe [98]. Climate change studies for Italy [99–102], France [82,103,104], Spain [105], Portugal [18,30,106], Germany [37,107,108], Greece [109], and Luxembourg [80,110,111], among others, hint at an increase in the growing season mean temperature.

In future scenarios, the current winemaking regions in southern Europe may undergo a decline in their viticultural suitability [112–115], mainly due to severe dryness [112]. These regions may indeed become excessively dry for high-quality winemaking [85] and, in some most extreme cases, will require intensive irrigation [112,116]. Regions such as Andalucía, La Mancha (Spain), Alentejo (Portugal), Sicily, Puglia, and Campania (Italy) will very likely suffer from severe water deficits [98]. It was also shown that increased summer dryness in southern Europe will lead to yield reduction, mostly due to the synergistic effect of warming and drying [98].

For some southern European winemaking regions, increased inter-annual variability and more frequent extremes are expected to intensify the irregularity of yields, with harmful impacts on the whole winemaking sector. Winemaking regions under extremely high temperatures may experience an increase in the risk of organoleptic degradation [94], excessively high alcohol contents [117], an acceleration in the degradation of organic acids [84], and an inhibition in the synthesis of anthocyanin [118], thus affecting grape colour and aroma [119–122]. In particular, the fruitiness, aroma [84], acidity, and relatively low alcohol content, characteristics of white wines in (former) cool climate wine regions, is expected to be negatively affected by high ripening temperatures [80]. Moreover, such high ripening temperatures are supposed to lead to higher concentrations of some specific phenols and an astringent wine taste [123]. Projected future increases in minimum temperatures during ripening, for example on the Iberian Peninsula [98], may also result in a decrease in wine quality. Higher respiratory rates at night associated with higher temperatures will consume more sugar, which is a key precursor for the biosynthesis of vital flavour compounds.

Future warmer climates may also have positive impacts for several traditional wine regions in Western and Central Europe, such as Burgundy, Champagne, Alsace, Loire Valley, Rheingau, and Mosel [95,114], as well as for potential new areas north- and eastwards of these traditional regions, although there are still many uncertainties owed to the complex interplay of different factors. As an example, a doubling of the areas suitable for viticulture in Austria by 2050s was projected on the basis of temperature evolution [124]. Hungarian southern winemaking regions are also expected to expand [125]. Furthermore, the expected warming in Central and Northern Europe will lead to longer growing seasons and frost-free periods [126], which will reduce fall frost damage and favour potential wine quality [127].

The impact of climate change on spring frost risk has been discussed controversially in the scientific literature in recent years. Generally, spring frost occurs when budburst precedes the date of the last frost event in the spring of a given year. Under future climate conditions, both events are projected to occur earlier. Although some studies suggest that the last frost events will move to earlier dates at a faster rate than budburst and, hence, reduce spring frost risk in the future [39], other studies were inconsistent or predicted increased risks for spring frost damage [37,38,40,128,129], indicating a high degree of uncertainty [80].

Although winter, spring, and fall frosts may threaten the economic sustainability of viticulture in a specific region/location and, hence, warming is considered as mostly positive, the production of ice wines is jeopardized. Ice wines are traditional premium wines of many cool climate regions that are produced when grape berries are exposed in fall or early winter to a frost event of −7 °C, or below, and are pressed in the frozen status. In this case, water in the berries is in the form of ice crystals and the juice is then concentrated, leading to the production of these unique dessert wines. However, these conditions are expected to become increasingly rare in the future. This is mostly due to the combination of two effects: higher temperatures leading to earlier maturity, and the date of first relevant frost events (minimum temperature of −7 °C or below) being delayed, or such events not even occurring in the future. Hence, ripe grapes have to sustain a much longer period until the freezing event occurs and the risk of severe berry decay and complete yield loss will thus increase [130].

In a comprehensive modelling effort, where a process-based crop model was coupled with climate, soil, and terrain databases, taking into account physiological effects of water supply and CO_2 concentration, European grapevine yields, phenology, water, and nitrogen stresses, both for present (1980–2005) and future (2041–2070) climate scenarios (Representative Concentration Pathway (RCP), RCP4.5 and RCP8.5), were analysed [98]. For current climates, the simulated components (e.g., yield and phenology) were validated against multi-site observations. For the future climates, the projected changes suggested an extension of the climatic suitability for grapevine cultivation up north to the 55° N parallel, thus creating the necessary conditions for the emergence of new winemaking regions at higher latitudes in Europe. The main phenological stages (budburst, flowering, veraison, and maturation) are projected to undergo significant advancements (> 2 weeks earlier), with implications for phenophase lengths between these stages [98]. Increased dryness throughout Europe was also projected, but with severe water stress over several regions in southern Europe (e.g., southern Spain, Portugal, and Italy), locally reduced yield and leaf area. Future biomass changes may lead to modifications in nitrogen (N) demands. Under future climate conditions, vineyards in Southern Europe may experience a reduction in biomass growth, owing to severe water stress. This will result in a high propensity of N deficit in Northern/Central Europe, under warmer and moist conditions [98]. In this context, increased atmospheric CO_2 may partially offset the dryness effects, promoting yield and leaf area index increases in Central/Northern Europe.

The higher concentrations of CO_2 in the future are expected to have positive impacts on the grapevine development cycle and yield attributes [131–136], although many uncertainties remain. Experiments conducted in free air carbon dioxide enrichment (FACE) systems have shown significant impacts of elevated CO_2 on, for instance, several vegetative growth parameters, primary productivity, grapevine bud fertility, and yield potential [135,136]. Higher CO_2 concentrations may contribute to a decrease in plant transpiration rates, which may tend to compensate for increased soil evaporation [137], thus mitigating the evapotranspiration increase under future conditions [138].

Changes in UV-B radiation have been of concern in the past, due to alterations of the protective ozone layer. UV-B radiation has an impact on grape composition, with modifications in secondary metabolites, such as flavonoids, amino acids, and carotenoids [134]. Irrespective of a further future increase in UV-B radiation, the combination of high radiation levels and high temperatures, particularly under severe water stress, is often responsible for sunburn damages in both leaves and berries [139,140], conditions that are anticipated to become more frequent in Southern Europe.

Crop protection may be another critical aspect of changing climates. It faces mostly two challenges: (i) pests and diseases from warmer regions may increasingly survive during warmer winters and (ii) the spectrum of existing pests and diseases may change. An example of a new challenge posed by an invasive species in viticulture is the spotted wing drosophila, a fruit fly that is native to Southeast Asia, but has been spreading to the USA and Europe since 2008. Whereas the spreading is a result of increasing globalization and not climate change, the survival and continuous spread into new areas of this species is due to increasingly mild winters [141]. Data from three decades on selected grape pests point to changes in the phenology of grape berry moths, shifts in distribution ranges of leafhoppers as vectors of grapevine diseases, and range expansion of grapevine mealybugs [142]. On the one hand, temperature increases resulting from climate change are likely to allow for more pest generations per growing season, however, at the same time, fruit maturity and thus harvest dates are expected earlier, limiting damage from late-season pest generations [143]. Climate change may also result in decreasing disease pressure and, consequently, a reduced necessity for the use of pesticides, as was demonstrated for powdery and downy mildew in the region of Burgundy [144]. However, at the global level, mildews are likely to remain the major phytosanitary threat [145].

Modifications in interannual variability and extremes of the meteorological conditions are showing a profound influence in the year-to-year variations in yields and wine quality [56,94]. Extreme weather events, such as heatwaves, extreme precipitation, droughts, hailstorms, and windstorms, among others, are more likely to occur in the future [146] and, as a result, may also have an important impact on future viticulture. Overall, climate change is expected to significantly change grapevine growth, development and yield, grape berry attributes, wine style and typicity, and, hence, the perception of the terroir of many traditional viticultural regions [2,80,147], thus requiring adaptation to warrant future sustainable viticulture. Despite the genetic diversity amongst grapevine varieties and clones within varieties, as well as the resulting plasticity in their adaptation to a wide range of climates [148], there are suitability limits that cannot be exceeded to maintain viticulture both environmentally and socioeconomically sustainable in a given region.

4.3. The Role of Soils under Changing Climates

Within the complex interactions between soil, plant functioning, fruit quality, and an evolving climate, the role of soils, the changes associated with soils, and the impacts resulting from these changes onto the soil-plant-atmosphere-continuum have been the least studied [149]. However, soil temperature has increased, at least at a rate similar to air temperature, over the past more than 100 years [150], and this has also been shown for soils in a vineyard region [151]. In the latter study, summer (NH; June, July, August (JJA)) soil temperatures (50 cm depth) were about 6 °C warmer than autumn temperatures (September, October, November (SON)) over most of the last century until about 1980. After this, JJA temperatures increased much faster than SON temperatures and reached average values today around 4 °C higher than about 40 years ago and about 8 °C warmer than SON temperatures [151]. These temperature increases are much larger than those observed over the same period for air temperature, and there is a high propensity that this already has profound effects on microbial community characteristics and activity [152]. Soils store about 2500 billion tons of carbon—more carbon than the atmosphere (780 billion tons) and plants (560 billion tons) combined on the planet [152] and, depending on cultivation practices, part of the carbon may be either released or additional carbon may be sequestered by the soil. A change in temperature may also alter the potential emission of some greenhouse gases from the soil, but this strongly interacts with soil water content [153].

The temperature may play a potent role, because, depending on organic matter content; water holding capacity; pore size distribution; precipitation rates; and other climate variables, such as solar radiation, the temperature has a large effect on the mineralization rate [154,155]. A comparison of the simulated rates of nitrogen mineralization during the growing season, for 30 year periods since 1961, showed increasing rates over the past 50 years, with substantial differences between soils [156,157]. This analysis suggested that modifications in temperature and water relations in some vineyard sites already had a substantial impact on the release of nitrogen, which might have increased the risk for bunch rot development on these sites. However, independent measurements to validate model simulations are lacking, and a recent study on warming effects on microbial communities in temperate vineyard soils, which would be involved in N mineralization, did not find substantial changes [158].

Soil temperature also has a direct effect on root and shoot hydraulics, which will affect the transpiration rate, which is so far under-rated in the quantification of possible climate change effects on plant water use. These increases in hydraulic conductance have been attributed to changes in membrane fluidity and permeability [159,160], or changes in water viscosity [161], but most likely are a combination of both [162]. For a vineyard situation, attempts have been made to estimate these currently hypothetical changes, and the results show substantial possible effects on transpiration [151].

5. Climate Change Adaptation Strategies

Suitable adaptation measures need to be applied by the winemaking sector to face climate change impacts, mainly by planning adequate strategies at regional/local scales [163–165], particularly in regions that will experience the most adverse impacts. Grapevine growers are becoming gradually more aware of the threats, whereas timely and strategic planning against its negative impacts may provide competitive advantages [166]. As such, it is up to the stakeholders and decision-makers to take action against climate change. Some adaptation measures in viticulture are discussed in the following subsections, although an exhaustive discussion is not envisioned. Even though changes in oenological practices may also have important adaptation potential [167], they are out of the scope of the present review. In general, the effectiveness of each measure strongly depends on the local situation and regional climate change signal. The overall approach should always be the adoption of a combination of local solutions to cope with a global problem.

5.1. Short-Term Adaptation Strategies

Short-term adaptation measures can be considered as a primary protection strategy against climate change and are commonly focused on specific threats. Short-term adaptation strategies are hereby defined as vineyard interventions that can be applied within a grapevine growing season. These measures generally imply changes in management practices, and some of them are briefly outlined in the following sub-sections.

5.1.1. Crop Cultural Measures

Short-term adaptation strategies may involve crop cultural practices and techniques [165]. There are multitudes of possibilities to delay ripening to move the decisive stages in maturity after veraison into the cooler part of the season. Among these, of note are changes in canopy geometry, reduction of the assimilation surface by leaf removal above the cluster-zone, reduction of canopy size to minimize water consumption, application of anti-transparent substances/materials to reduce both carbon assimilation and water consumption, use of shadow nets, and earlier harvest to achieve moderate sugar levels and adequate acidity [3,168]. Cluster-zone leaf removal, which nowadays represents a standard measure in many viticultural regions where bunch rot represents a major threat due to its strong phytosanitary effects [169,170], may be questionable in the future due to higher susceptibility towards sunburn damage.

5.1.2. Protection against Extreme Heat and Sunburns

The negative impacts of extreme heat, water scarcity, and high irradiance in vineyards urge short-term adaptation strategies, such as the application of exogenous compounds that could maintain, or even improve, plant growth and development under these environmental stresses. Several sunscreen materials that form an inert particle film upon the leaves, such as calcium carbonate ($CaCO_3$), kaolin ($Al_2Si_2O_5(OH)_4$), and potassium silicate (K_2SiO_3), or the use of shade nets, have been studied to increase canopy and fruit zone reflective capacity [171,172]. Currently, one of the most commonly used compounds in viticulture is kaolin, a white clay, which is chemically inert and has excellent reflective properties. Glenn et al. [173] were the first to test the effects of this mineral on apple productivity. More recently, several studies developed for grapevines grown under severe summer stress corroborated that the use of kaolin has a positive impact on leaf cooling, minimizing the scorching of leaves and clusters during the hottest summer days [139,140]. Additionally, structure and function of the photosynthetic machinery and water relations were significantly improved [140,174,175], in part as a response to altered hormonal relationships (abscisic acid (ABA) decreased; indoleacetic acid (IAA) increased) [176]. In terms of yield and quality attributes, it was also shown for cv. Touriga-Nacional that kaolin application improved the antioxidant capacity in berries, as well as the amounts of some secondary metabolites, such as total phenols, flavonoids, and anthocyanins [174,175]. In another study, it was found that these compounds, qualitatively associated with the increase of colour, flavour, aroma, texture, astringency, antioxidant capacity, and stabilization of wines, were synthesized in greater quantity due to a more favourable stimulus of biosynthetic pathways (especially the phenylpropanoid and flavonoid synthetic pathways) and associated gene expression [47,177].

5.1.3. Irrigation

Records of grapevine irrigation date back to ancient times (2900 BC) [178], and is a common practice in many countries, especially in the "New World" (e.g., Australia, USA). Even in countries where grapevines are traditionally rain-fed (e.g., France, Spain, Portugal, or Germany), irrigation has increasingly been implemented and local guidelines have slowly been adapted for this practice. However, for the production of high-quality wines (e.g., Brunello di Montalcino in Italy or Port Wine in Portugal), the current regulation only permits "rescue" irrigation.

Irrigation is used to improve and standardize crop yield and quality, whenever rainfall is too low to meet the defined grapevine water requirements. The management of vineyard irrigation is based on deficit irrigation (DI) strategies (e.g., regulated deficit irrigation, sustained deficit irrigation, partial root drying) to take advantage of the relationship between grapevine water status and the yield/quality [179]. Taking into consideration these strategies, drip irrigation is generally implemented as the most efficient water saving method [180,181], although sprinkler and furrow irrigation systems are still being used [182]. The implementation of DI strategies can be used to enhance water savings, which is particularly needed in wine regions with greater water deficits [183]. Furthermore, these cultural practices may be maximized with automated and smart irrigation (with real-time control and optimisation) systems [184].

A common methodology for DI implementation consists of the selection of a defined percentage of the computed crop evapotranspiration [185]. However, soil and/or plant water status indicators and respective thresholds should be used, preventing a continuous decrease in root-zone water content. Although measurements of soil water content (or soil water potential) may roughly determine the amount and the timing of irrigation, strong under- or overestimations may occur because the real depth of the root system is not taken into account. If this is the case, direct plant water status indicators are particularly useful [186,187]. Among those indicators, stem and leaf water potential have been extensively used. More recently, other techniques, such as trunk diameter variations and sap flow measurements have been implemented, with the advantage of possible automation [188,189].

Using a deficit irrigation technique, no yield reduction was observed for Godello grapevines [190]. Improvements in quality attributes were also found using these strategies on other varieties [191–193]. Hence, a sustainable water use strategy together with available water resources can be quite advantageous and cost-effective for the growers [194]. Nonetheless, the assessment of the real benefits and costs (including terrain factors, water distribution systems, technological options, on-farm *versus* catchment or basin-scale water savings, and socio-economic conditions) for implementing irrigation under future climates is critical for the adoption of these adaptation measures [184,195], particularly in Southern Europe, where water availability is predicted to diminish [10,112].

5.1.4. Pest and Disease Control

Under future climate conditions, wine regions may struggle with increased risk of pests and diseases, in principle demanding more intense plant protection measures at times where environmental impacts from phytosanitary treatments need to be reduced [196]. A recent general simulation study on possible changes in the fitness status of insect pests as a function of latitude showed that fitness level will decrease close to the equator, but increase poleward of the 30° latitude parallels [197]. Data from three decades on grapevine pests point to changes in the phenology of grape berry moths, shifts in distribution ranges of leafhoppers as vectors of grapevine diseases, and range expansion of grapevine mealybugs [142]. Pest and disease control is a dynamic process that requires monitoring, continuous innovation, and adaptation, because pests and diseases adapt to their environment, as well as to the control actions taken by growers. Adaptation can either take place by technology transfer from regions where the pest is already successfully controlled or by novel pest management approaches, such as the application of various natural compounds, but research gaps still exist that are hindering their widespread use [198]. In some cases, climate change may also lead to lower disease pressure and, in such cases, awareness of the decreased need for disease control should be raised among growers as an adaptive measure. In any case, to derive adaptive measures, a deeper understanding of tri-trophic interactions in vineyards is needed [142].

5.1.5. Soil Management

Soil management is an essential adaptation tool, critical for soil and plant protection, water fluxes, greenhouse gas emission (GHE) rates, and possible carbon storage. In terms of water and carbon conservation, tillage is no longer advised, particularly in shallow soils on steep terrain, as it may also negatively affect yield and quality [199,200]. Moreover, mechanical cultivation affects most soil microbes and their functioning (e.g., arbuscular mycorrhizal fungi) and promotes the mineralization of organic matter and soil erosion, which is one of the most important environmental problems aggravated by conventional agriculture. Eroded soils have low fertility and low water-holding capacity, which limits water use efficiency. The consequences of erosion are of major relevance, as climate change and extreme events may exacerbate erosion rates, and many vineyards in Europe are on slopes, which aggravates potential erosion. Higher yields are usually achieved when the soil is managed with herbicides. However, bare soil reduces water infiltration and does not protect against erosion [201]. In addition, problems of ground-water contamination; changes on soil structure; the significant increase of resistant weed populations; and, in some situations, residues in grapes and wine are a source of concern that encourages the adoption of more sustainable solutions. For all these reasons, other practices should be implemented in order to safeguard soil fertility and preserve non-renewable resources. The use of compost obtained from different materials, such as municipal solid waste, green waste and urban sludge, wood ash, leaves, pruned vine-shoots, winery sludge, grape stalks, and other biomass residues from the farm, can be a good option. The application of compost increases soil microbiome, organic matter content, soil porosity and soil structural stability, nutrient supply, and water retention capacity, also reducing soil erosion. However, when applying a compost, the nutrient input into the vineyard has to be considered, because, for instance, high nitrogen freights might cause nitrate leaching into groundwater and lead to excessive plant vigour, dense foliage in the cluster zone, and compact clusters, which are directly linked to a higher predisposition towards bunch rot [170,202,203]. Likewise, the use of synthetic (e.g., black polyethylene and geotextile) and organic mulches, including compost, bark, or straw, may have positive effects on soil water content [204] and yield under future warmer and drier conditions [205]. Mulches also moderate soil temperatures and suppress diseases and harmful pests.

In all vineyards, the soil should be covered by green vegetation (spontaneous or cultivated herbaceous cover crops), at least during the rainy season, and by dead material (as in the case of Mediterranean viticulture) or partial cover crops as in intermittent rainfall areas, during the dry part of the season. The species used as cover crops should be selected on the basis of the local pedoclimatic conditions. Under low water availability, these species should have minimal competition for water (e.g., with short vegetative cycle) and make a positive contribution to soil fertility, as some self-reseeding annual legume species are comparatively less competitive for water than grasses and can fix atmospheric nitrogen [206]. A mixture of different species and cultivars should be chosen, as it increases the likelihood of success under variable weather conditions, being also advantageous to soil properties. On the other hand, in conditions of high-vigour environments, grasses could be inserted into the mixture. Cover crops keep the soil protected against erosion; reduce soil compaction, water evaporation, and dust; increase water infiltration, organic carbon, and trafficability; provide habitats for beneficial insects, and prevent nitrate leaching, resulting in enhanced yield and quality [207], as long as competition for water and nutrients will not cause deficits for the crop [208]. Furthermore, cover crops enable tractor passages for crop protection, particularly in sloped vineyards during intense rainfall periods and are, hence, safeguarding yield. Thus, well-designed cover crop mixtures may benefit soil and water quality, as well as the adaptive capacity of grapevines to climate change, and may also act as an ecosystem service [209].

5.2. Long-Term Adaptation Strategies

Long-term adaptation strategies are measures employed by growers to adapt to climate change throughout several growing seasons or before the planting of a vineyard. In effect, grapevine as a perennial crop remains economically productive for several generations. The adoption of some long-term adaptation measures may be crucial, although their application may also bring significant socio-economic impacts. Although significant changes in bioclimatic conditions are expected to occur in the future [113], the potential of the different adaptation strategies may still prevent dramatic changes in viticultural suitability [210]. Some examples of long-term adaptation strategies are provided in the following sub-sections.

5.2.1. Changes in Training Systems

The joint effect of growing temperatures with abiotic and biotic stresses projected for the upcoming decades will require changes in the current/traditional training systems, which may also be undertaken by optimizing canopy management practices [211]. Changes in training systems may target the following objectives:

(i) Delay of the maturation period (see also Section 5.1.1). To avoid grapes ripening under high-temperature conditions, training systems that delay ripening may be beneficial under future climate conditions. Minimal pruning systems in their various forms (i.e., semi-minimal pruned hedge) can delay maturity and bunch rot formation [212].

(ii) Lower sugar accumulation. To achieve reduced sugar content of grapes and thus reduced alcohol content, the leaf area to fruit weight ratio can be manipulated. Higher crop load per unit leaf area may, however, cause undesired lowering of wine quality, whereas a reduction of leaf area to fruit weight ratio by limiting the canopy height may cause the opposite [168].

(iii) Reduced radiation in the cluster-zone. Modifications of canopy geometry, such as row orientation, will influence light interception and wind velocity, and may also provide high adaptive potential [213,214]. For example, higher canopies, as well as closer distances between rows, may increase shadowing effects and, hence, decrease sunburn risk. However, both changes might lead to conflicts of objectives, such as higher water consumption and potential earlier maturation (high canopies) concomitant to unfavourable microclimatic conditions in the cluster-zone, fostering bunch rot (narrow rows) [215]. Vineyard orientation should be optimized whenever possible, as it may significantly change radiation interception [213,214,216].

(iv) Higher water use efficiency. Regions under extreme dryness should promote higher water use efficiency [183] by adopting training systems that promote shorter trunks, such as the Gobelet [211] or Guyot systems [3].

Changes in the training systems can also be combined with changes in planting density and/or in trunk height, as they are inter-dependent. In general, higher planting densities lead to enhanced root competition, lower vegetative growth, deeper root penetration, and larger available soil volume, which can be useful in temperate humid climates. If canopy geometry remains the same, higher density at similar row distances reduces water stress [14]. However, when row distance changes concomitant to density, water deficit may be exacerbated [14].

5.2.2. Varietal/Clonal and Rootstock Selection

Because the suitability for the successful cultivation of different varieties is largely temperature dependent, long-term adaptation strategies may consist of changes in the varietal spectrum [12]. A recent study postulated dramatic changes in arable viticultural land under strong warming, showing that in situ varietal selection may provide important climate change adaptation potential under moderate climate change scenarios [217]. Cooler northern European winemaking regions may benefit from a wide range of varieties from southern Europe [114], whereas southern Europe will be limited to varieties well adapted to very dry and warm climates. Some heat-tolerant varieties, such as Cabernet Franc, Cabernet Sauvignon, Malbec, Merlot, Syrah, or Tempranillo, have already been identified [32]. Hence, grapevine breeding should be focused on the development of heat-tolerant vine varieties [106]. A framework for genetic breeding of new varieties that will be more adapted to future climates has already been proposed [218]. The selection of appropriate varieties might be guided by mid-term climate change projections and bioclimatic indices describing the thermal demand of specific cultivars, such as the Huglin heliothermic index [77] or the average growing season temperature [56]. However, it needs to be kept in mind that these indices describe the lower temperature threshold for a variety, whereas the upper threshold is mostly unknown. This has previously led to substantial misconceptions concerning the prediction of future suitability of grape-growing regions [113,210]. Therefore, preserving the existing biodiversity of autochthonous grapevine varieties is vital, as some varieties may thrive in future climates and may thereby open new adaptation opportunities [219,220].

Because most of the sensory properties and the fame of many terroir wines rely on specific varieties [12], their replacement with more resistant ones is challenging in viticulture [12], as immediate varietal changes may cause economic losses. Accordingly, to fully exploit the potential of varietal selection, the preference of retailers and consumers for specific varieties needs to be changed, for instance by marketing wine from better-adapted varieties under a specific climate change adaptation label. The clonal selection has also a very important adaptation potential, as different clones from a given variety are more resilient to future abiotic and biotic stresses, at the same time contributing to the maintenance of local or regional wine typicity.

Rootstocks can also confer plant resistance, particularly to soil-borne pests and pathogens, but they also differ with regards to their resistance to abiotic stress. Planting new vineyards on rootstocks with enhanced resistance towards the primary abiotic stresses, present in a particular region or predicted to become the dominant stresses, can become a key element in adaptation [221]. More adapted rootstocks will be beneficial to yield, quality, and other vine physiological parameters [222,223]. Many studies have been performed to assess rootstock effects under different soil water conditions [223–225]. Rootstocks may present the single most effective cultural strategy to find a long-term solution concerning water availability, without tapping into the public water supply in the form of irrigation. However, to achieve this, the genetic potential of *Vitis* germplasm needs to be further explored in order to enhance water use efficiency and maintain yield and quality [226].

Grafting *Vitis vinifera* scions to phylloxera-resistant American *Vitis* rootstocks is commonly used in (Western) European countries, where hybrids (or interspecific hybrids) are generally not yet accepted for "quality wine" production [227]. However, the use of hybrids has increased worldwide in recent years (e.g., Brazil, China, and the USA). Especially in the emerging grape growing regions in northern Europe, new vineyards are frequently planted with interspecific crossings, with reduced susceptibility towards fungal diseases (the so-called "Piwis"). Furthermore, the OIV has been developing and discussing some project resolutions regarding this subject. This plant material is considered to be particularly resistant to fungal diseases and severe climate conditions [228]. Thus, the use of resistant hybrids can be a possible option and a challenge for the wine sector, in terms of perception of producers and consumers and regulation adaptations [227].

5.2.3. Vineyard Relocation

These measures comprise modifications in vineyard location, as some regions may become excessively warm and dry for sustainable viticulture [229]. Shifts to cooler sites, such as those located at higher latitudes [230], at higher elevations [231], at coastal zones, or in areas with overall lower solar radiation (such as poleward exposed sites), are long-term measures that should be envisioned when choosing new vineyard sites [232]. Nevertheless, the use of these strategies must be carefully evaluated by considering the relevant economic consequences [233].

6. Knowledge Gaps and Research Challenges

Although research on potential impacts of climate change on viticulture is already largely developed, when compared to other crops, some important knowledge gaps remain. The use of climate projection datasets linked to grapevine simulation models represents the most feasible approach for predicting plant behaviour and production in the future [98], which can be complemented by climate chamber experiments, among others, for model development, calibration, and validation. In this regard, more experiments carried out under similar conditions and measuring the same variables are needed for a better comparison between studies and quantification of effects. Nonetheless, the evaluation of climate change impacts on any cultivated crop is sensitive to uncertainties in the future climate projections, deriving from model parameterizations, sub-grid scale processes, model initializations, intrinsic biases, radiative forcing scenarios, and other sources. Natural variability of the climate system needs also be taken into account, increasing the level of uncertainty with increasing distance into the future. These uncertainties need to be more thoroughly incorporated in the climate change projections and impact assessments, using more comprehensive probabilistic and risk analyses. This information should also be better communicated to stakeholders and decision-makers, instead of providing only ensemble means or other central tendency measures, which can be misleading and may impede or misguide an effective adaptation. Furthermore, these projections are available on platforms that are frequently not user-friendly, with data formats, as well as temporal and spatial scales, not being suitable for knowledge transfer to decision-makers [234]. A good example of an easy-to-use interface that is focused on cereal crops is the NASA (National Aeronautics and Space Administration) Harvest Crop Monitor interface, using remote sensing data to forecast crop conditions (https://cropmonitor.org/index.php/data-and-tools/cmet/).

Although grapevine simulation models, usually process-based, are already able to satisfactorily reproduce different interactions between the soil–plant–atmosphere continuum at a very detailed level, further enhancements and integrations are undeniably necessary to improve model reliability. As an illustration, estimations of bud break occurrences are often based on forcing models, without considering the effect of chilling during dormancy. This shortcoming frequently leads to erratic estimations of bud break under warmer climates, with obvious implications throughout the simulation of the phenological cycle [235]. Although the isolated effects of CO_2 and temperature on the radiation use efficiency and transpiration have already been extensively reported, their opposite impact on evapotranspiration, and their combined effect in future warmer climates, are not fully understood yet [235,236]. Furthermore, simulation models should incorporate the incidence level of pests and diseases [237] and the impact of nitrogen and water stress [238,239], which are expected to have more impact on plants in a climate change context. Modelling approaches that would be able to incorporate aspects of grape quality will play a key role in understanding changes in berry metabolites [86]. Thus far, only a few grapevine models are currently available, and a very limited number of varieties can be simulated. More models, and more versatile models, are needed in order to implement multi-model ensemble scenarios, thereby enhancing the robustness of the projections. For a broader assessment on the effects on different varieties, the incorporation of key variables describing varietal behaviour is also lacking thus far.

The need to describe the plant processes at a very detailed level, using a high number of inputs, may currently preclude the applicability of simulation models as decision support tools for farmers. However, models coupled with the use of new technologies (e.g., drones and automatic plant-based irrigation systems) may determine the most appropriate management practices in the future. New projects using IoT (Internet of Things) platforms will be an effective way to tackle these challenges. Despite many proposed measures to cope with climate change, their corresponding adaptive potential under a wide range of local conditions is not yet sufficiently investigated and precise. Additionally, it is not sufficiently clear how the interplay between socioeconomic and ecological factors will affect decision-making in adaptation [240].

7. Conclusions

Even though grapevines have an array of survival strategies, their development is strongly controlled by weather and climate, over a wide range of processes and timescales. Wine style and wine typicity of a given region, recognised by consumers, are strongly connected to local terroirs, thus exacerbating the vulnerability of the whole wine sector to climate change. Threats to viticultural suitability have already been reported for several winemaking regions worldwide. Some changes have already been noticed on different levels by the winemaking sector. The 2019 ProWein Business Report mentions that viticulturists are already experiencing significant changes in their vineyards and are already responding. Among the adaptations considered most urgent in many regions are changes in vineyard locations, grapevine varieties, and some cultivation practices to avoid stronger irregularity in production and prevent an increase in the market volatility. In general, climate change is perceived as an important risk for viticulture, threatening in some cases, or challenging in most cases, viticulture and the winemaking sector. The adoption of timely, cost-effective, and suitable adaptation strategies may significantly contribute to risk reduction, thereby decreasing the susceptibility of the sector and enhancing its resilience under a changing climate. Even though the potential of the different adaptation options in reducing detrimental impacts still comprises many uncertainties and demands further research, the implementation of a blend of effective measures in the vineyard, tuned to local terroirs and local climate change projections, will contribute to the future environmental and socio-economic sustainability of existing wine regions. For that purpose, the communication channels between science, stakeholders, and consumers should be improved to enhance capacity building and knowledge transfer to the wine sector and increase acceptance to necessary changes by the consumer.

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