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Review

An Update on the Impact of Climate Change in Viticulture and Potential Adaptations

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Abstract: Climate change will impose increasingly warm and dry conditions on vineyards. Wine quality and yield are strongly influenced by climatic conditions and depend on complex interactions between temperatures, water availability, plant material, and viticultural techniques. In established winegrowing regions, growers have optimized yield and quality by choosing plant material and viticultural techniques according to local climatic conditions, but as the climate changes, these will need to be adjusted. Adaptations to higher temperatures include changing plant material (e.g., rootstocks, cultivars and clones) and modifying viticultural techniques (e.g., changing trunk height, leaf area to fruit weight ratio, timing of pruning) such that harvest dates are maintained in the optimal period at the end of September or early October in the Northern Hemisphere. Vineyards can be made more resilient to drought by planting drought resistant plant material, modifying training systems (e.g., goblet bush vines, or trellised vineyards at wider row spacing), or selecting soils with greater soil water holding capacity. While most vineyards in Europe are currently dry-farmed, irrigation may also be an option to grow sustainable yields under increasingly dry conditions but consideration must be given to associated impacts on water resources and the environment.

Keywords: climate change; viticulture; adaptation; temperature; drought; plant material; rootstock; training system; phenology; modeling

1. Introduction

Like other agricultural crops, grape growing is impacted by environmental conditions, such as soil and climate [1]. The revenues from agricultural production are driven largely by yield, however, for wine grape growing the quality potential of the grapes is also important, as it can significantly affect the quality of the resulting wine and the prices consumers are willing to pay. In fact, wine prices can vary by a factor up to 1000 (e.g., from 1 to 1000 € per bottle), while yields generally vary by a factor of about 10 (e.g., from 3 to 30 tons/ha). Environmental conditions play an important role in determining not only yield, but also grape quality potential. In addition, depending on these conditions (and other factors like market access), profitability for growers in some regions can be driven by optimizing yields and reducing production costs, while in other regions it can be driven more by producing higher quality grapes for higher price wines.

The output of grape production in terms of yield and quality can be optimized through the choice of plant material, such as variety [2,3], clone [4,5], and rootstock [6], and through the choice of viticultural techniques, such training system [7], and vineyard floor management [8] (see also [1]). Production costs can be reduced largely through mechanization [9]. In established winegrowing regions, growers have historically adjusted their plant material selections and viticultural techniques through trial and error and research to achieve the best possible compromise between yield, quality, and production costs [3]. In each location environmental conditions are different, so there is no general recipe that can be applied everywhere. This explains why plant materials and viticultural techniques vary so much across winegrowing regions of the world.

High yields can be obtained when soil and climate provide for little or no limitation on photosynthesis, such as under moderately high temperature and non-limiting light, nitrogen and water conditions. However, if soil and climate induce a limitation on water and nitrogen, these can be augmented through irrigation and fertilization. Highest possible quality potential is generally achieved when environmental conditions are moderately limiting [10]. Ideal balance in grape composition at ripeness with regard to sugar/acid ratio, color, and aromas, is obtained when grape ripening occurs under moderate temperatures [3]. Excessive cool climatic conditions during ripening can result in green and acidic wines. High temperatures between véraison and harvest can result in unbalanced fruit composition, with sugar levels being too high, acidity too low, and an aromatic expression dominated by cooked fruit aromas [3,11], which result in wines lacking freshness and aromatic complexity.

Mild temperatures during grape ripening, which are favorable for better wine quality, are generally met late in the growing season, roughly between 10 September and 10 October in the Northern Hemisphere and in March or early April in the Southern Hemisphere. White wine production is optimized under cool ripening conditions, which are of particular importance in obtaining intense and complex aroma expression [12]. When varietal heat requirements match the critical temporal window to obtain ripeness, the best wine quality is obtained. For red wine production, water deficits at specific stages of grape development are favorable for wine quality, because they reduce berry size and increase phenolic compounds in grape skins [13–16]. Recently it has also been shown that vine water deficits positively influence aromatic expression in mature wines [17,18]. Moderate nitrogen uptake induces similar effects on grape composition, reducing berry size, and increasing skin phenolics [19]. For the quality of white wines, a limitation in vine water status is also desirable, although this limitation should be milder than for red wine production [20]. For white wine from thiol aroma driven varieties (e.g., Sauvignon blanc, Colombard, Sémillon, Riesling) vine nitrogen status should not be limiting [21].

Although soil and climate are both major environmental components in wine production, the latter is of greater importance for the development of yield components, vine phenology, and grape composition [19,22]. Until the end of the 20th century, soil and climate were considered stable in a given site, with the exception of year-to-year climatic variability. In the 1990s some European researchers became aware that the shifting climatic conditions due to climate change might possibly have a great impact on viticulture worldwide [23]. Progressively, over the first two decades of the 21st century, climate change has become a topic of increasing importance in the viticulture and enology research community. In 2011, 23 French research laboratories collaborated in the LACCAVE project to study the effect of climate change in viticulture and potential grower's adaptations [24]. Several peer reviewed scientific journals, including the Journal of Wine Economics [25], OENO One [24], and Agronomy (this issue, 2019) released special issues on this subject. Today, a substantial body of literature is available to assess the effects of climate change in viticulture and wine production, including effects on vine physiology, phenology, grape composition, and wine quality (among others see [2,26–28]). Several authors have also described potential impacts on pests and diseases [29,30].

Climate change will improve suitability in regions which are currently restricted by low summer temperatures (due to high latitude or elevation) and decrease suitability in warm and dry areas [28]. Several authors have produced suitability maps at global level [31], at the level of the European continent [32], or at the level of a country [33]. These studies, however, are most often conducted at low spatial resolution and underestimate fine-scale variability which may permit viticulture to remain viable under changing climatic conditions [28]. The impact of climate change on viticulture can also be studied by means of crop models which allow predicting the impact of changing temperatures, water availability, and ambient CO_2 levels on yield components and grape composition [34,35]. These predictions are complex, however, because all impacting factors interact. It has been shown that elevated CO_2 increases the optimum temperature for photosynthesis [36] and decreases transpiration [37]. Soil microbiology can also be modified under climate change and may indirectly impact drought resistance of crops [38]. Hence, to be accurate, these models need to be highly sophisticated. Beyond the study of traits related to adaptation, their responses to environmental variables could be studied as the phenotypic plasticity of these traits [39,40]. Given current climate change predictions, the selection of plant materials with an ability to adapt to environmental change will be of particular interest for perennial plants such as grapevine [28,41]. Such adaptative responses, (i.e., phenotypic plasticity), therefore need to be studied further to characterize the genetic variability available for selection [42]. Potential adaptations have been studied to help continued production of high quality wines with economically sustainable yields under changing climatic conditions, which is the main focus of this review

2. Temperature and Drought Effects of Climate Change

Temperature changes associated with climate change are not homogeneous around the globe. Temperatures are currently 1 °C higher on average compared to pre-industrial revolution [43], but the increase can be even higher in some regions. In Bordeaux for example, Average Growing Season Temperature (AvGST; [44]) has increased by approximately 2 °C over the past 70 years, with a remarkable jump between 1985 and 2006 (Figure 1a). Temperatures have become increasingly warmer during the period of grape ripening, as is shown by temperature summations >30 °C during 45 days before harvest (Figure 1b for Bordeaux). This can significantly affect the rate and timing of vine phenology and the final quality of the grapes. Additionally, as increased temperatures increase the evaporative demand driving both vine transpiration and soil evaporation, the soil water balance over the season will become increasingly negative (Figure 1d; [45]). In addition, while annual rainfall has not seen much change in long-term trends, there has been an increase in extreme wet and dry years (Figure 1c for Bordeaux). Taken together, increased temperatures resulting in higher reference evapotranspiration values (Figure 1d), and more frequent years with low rainfall have, and will continue to, induce more intense and frequent drought conditions for vineyards in Bordeaux and around the world.

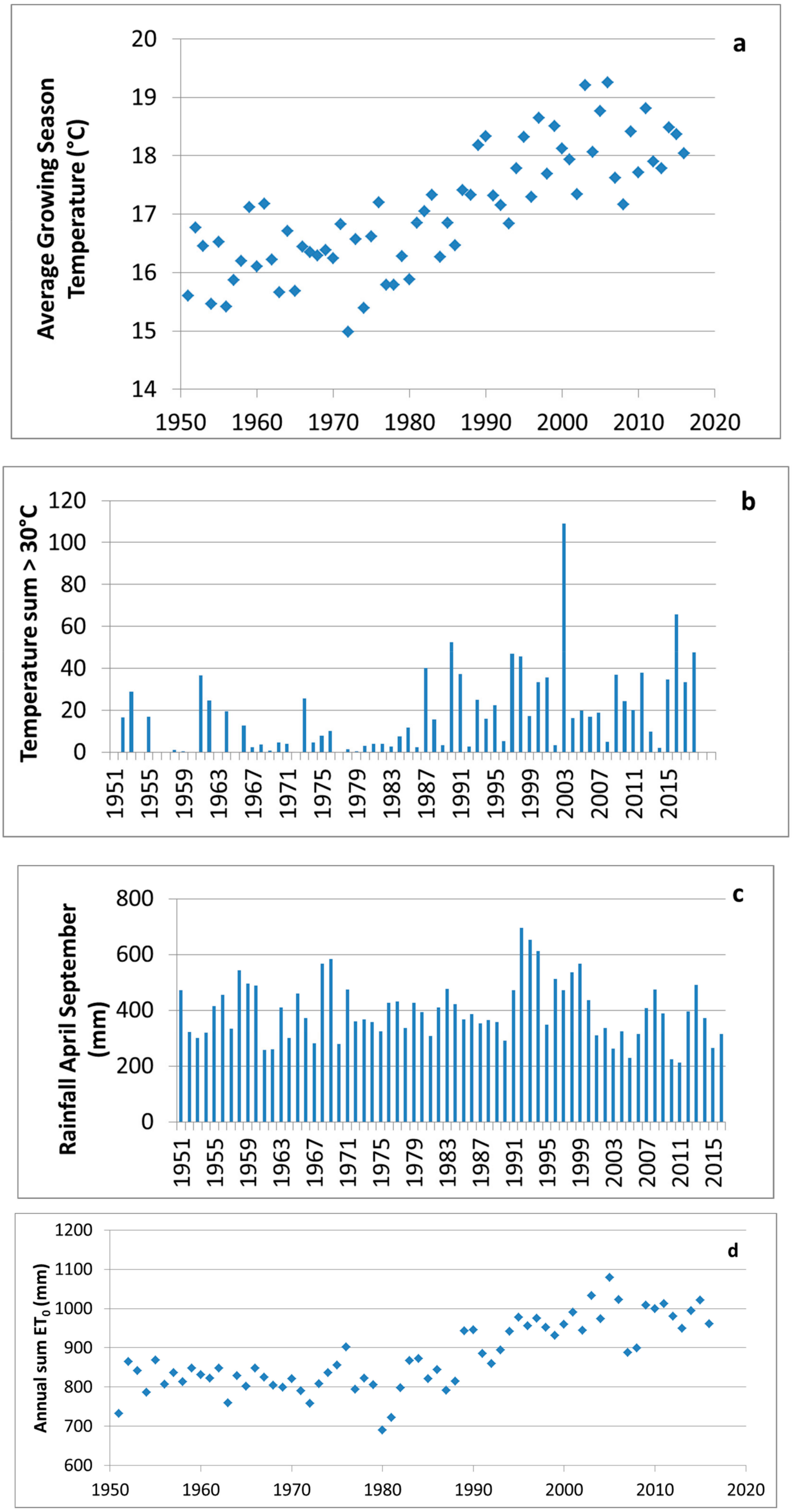

Figure 1. Climate data for Bordeaux (Bordeaux Mérignac weather station) from 1951 to 2018: (**a**) average growing season temperature, (**b**) temperature sum >30 °C during 45 days prior to harvest, (**c**) rainfall April–September, (**d**) annual sum of reference evopotranspiration (ET_0).

2.1. Temperature Effects

Temperature is the major driver of vine phenology [46]. Harvest dates have been used to reconstruct temperature series spanning several centuries [47]. Increased temperature as a consequence of climate change leads to advanced phenology [45,48]. In Alsace (France), over a 70-year timespan, budbreak has advanced by 10 days, flowering by 23 days, véraison by 39 days, and harvest by 25 days (Figure 2). Similar trends are observed in many winegrowing regions around the world [45]. Advanced budbreak may expose vines more frequently to spring frost, although this risk depends on the climatic situation of each specific winegrowing region [49–51]. Phenology varies widely among varieties [52,53], with varieties selected historically to perform best in a given winegrowing region based on their phenology [3]. With climate change, local varieties may move out of their ideal ripening window and, as a consequence, may be exposed to excessive temperatures during grape ripening [54]. Harvest in Alsace (France) for Riesling used to occur in the first two weeks of October. Today, in this region, harvests more frequently occur in the first week of September and sometimes even at the end of August (Figure 2). This evolution can be detrimental for the quality potential of the grapes, which are increasingly high in sugar content [48] and may eventually become less aromatic.

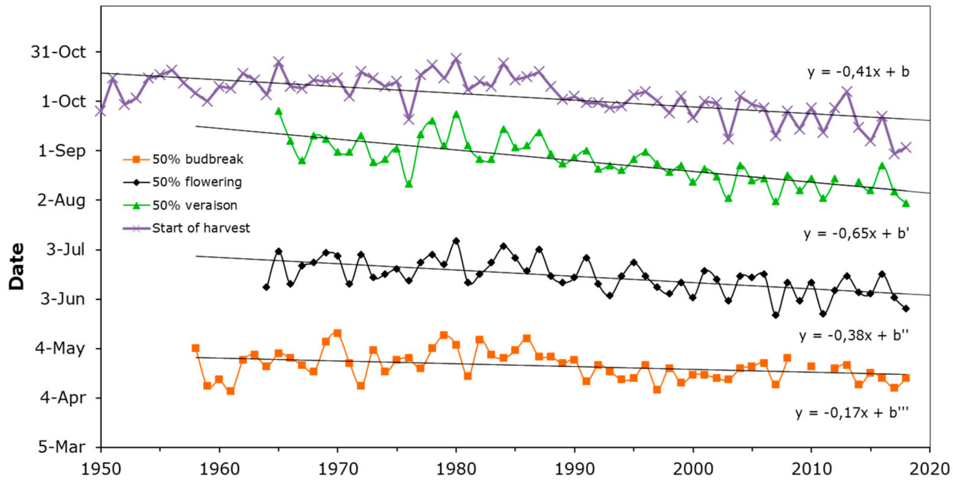

Figure 2. Long-term evolution of vine phenology for Riesling in Alsace. Data source: budbreak, flowering and veraison adapted from [48]; harvest dates from Conseil Interprofessionnel des Vins d'Alsace (CIVA).

In Bordeaux, major grapevine varieties include Sauvignon blanc, Merlot, Cabernet franc and Cabernet-Sauvignon. Harvest dates can be modelled by using the Grapevine Sugar Ripeness model (GSR) to predict sugar ripeness [55]. According to this model, 200 g/L of grape sugar is attained when a daily mean temperature summation reaches a value F^* (base temperature of 0 °C, start date day of the year 91, which is 1st of April in the Northern Hemisphere). F^* is variety specific, where a higher value indicates a later-ripening variety (Figure 3).

In the following example, the GSR model was used to predict the day when four major grapevine varieties grown in Bordeaux, i.e., Merlot, Cabernet-Sauvignon, Cabernet franc, and Sauvignon blanc, reach 200 g/L of sugar, with input temperature data from Bordeaux Mérignac weather station and F^* values retrieved from [55] (Figure 3). To predict harvest dates, five days were added for Sauvignon blanc, which is picked around 210 g/L of grape sugar (12.5% potential alcohol). For harvest dates of the three red varieties 15 days were added, because they are generally picked at 230 g/L of grape sugar (13.5% potential alcohol). When the model was run with average historical temperature data from 1951 to 1980, modelled ripeness was 22 September for Sauvignon blanc, 4 October for Cabernet franc, 7 October for Merlot, and 14 October for Cabernet-Sauvignon (Figure 4). These projections are perfectly in line with observed historical harvest dates from Bordeaux [45]. If the ideal window for grape ripeness is defined from 10 September to 10 October, when temperatures are not excessive but still high enough to achieve full ripeness, all varieties fall within this window except Cabernet-Sauvignon. This is consistent with the observation that during this period high-quality wines from Cabernet-Sauvignon could only be produced in early ripening locations on warm gravel soil. In the cooler parts of Bordeaux, wines from Cabernet-Sauvignon used to be green (high content in methoxypyrazines) and acidic. When the same projection is made with average climate data from 1981 to 2010, the following harvest dates were obtained: 7 September for Sauvignon blanc, 18 September for Merlot, 21 September for Cabernet franc, and 28 September for Cabernet-Sauvignon (Figure 4). At the turn of the millennium, Bordeaux has become suitable for growing high quality Cabernet-Sauvignon over most of the region, but has become marginally too warm for Sauvignon blanc. It is predicted that it will still be possible to grow high quality Sauvignon blanc in cooler locations of the region on North facing slopes or on cool soils. When 1 °C is added to the average 1981–2010 temperatures (which is close to temperature projections for around 2050), the Bordeaux climate is still perfectly suitable for producing high quality wines from Cabernet franc and Cabernet-Sauvignon (projected harvest 11 and 18 September respectively), but Merlot is moving out of the ideal ripening window (8 September) and the Bordeaux climate will be too warm to produce crisp and aromatic wines from Sauvignon blanc (29 August; Figure 4). Hence, among the traditional Bordeaux varieties, Sauvignon blanc and Merlot will be the first victims of climate change. During the past decade, Bordeaux wines containing a majority of Merlot, which is still the most widely planted variety in this region, are increasingly dominated by cooked fruit aromas and excessively high alcohol content [11].

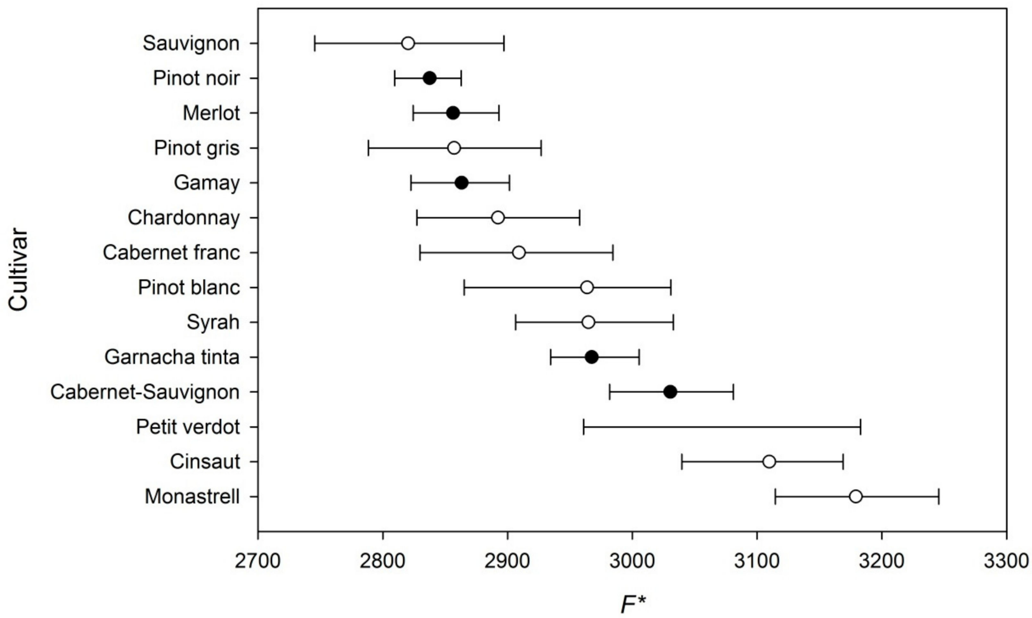

Figure 3. Temperature summation (F *) to reach 200 g/L of grape sugar according to Grapevine Sugar Ripeness (GSR) model for 15 major grapevine varieties. Horizontal bars represent 95% confidence intervals (CI) which were calculated using the optimization algorithm of Metropolis in PMP v5.4 and determined via the Fisher statistic ($p < 0.05$) as in [55]. Closed circles correspond to parameterizations where CI < 100, open circles correspond to CIs in the range 100–200 and no circle corresponds to CIs in the range of 201–350. (Cultivar synonyms: Monstrell = Mourvèdre, Sauvignon = Sauvignon blanc, Garnacha tinta = Grenache).

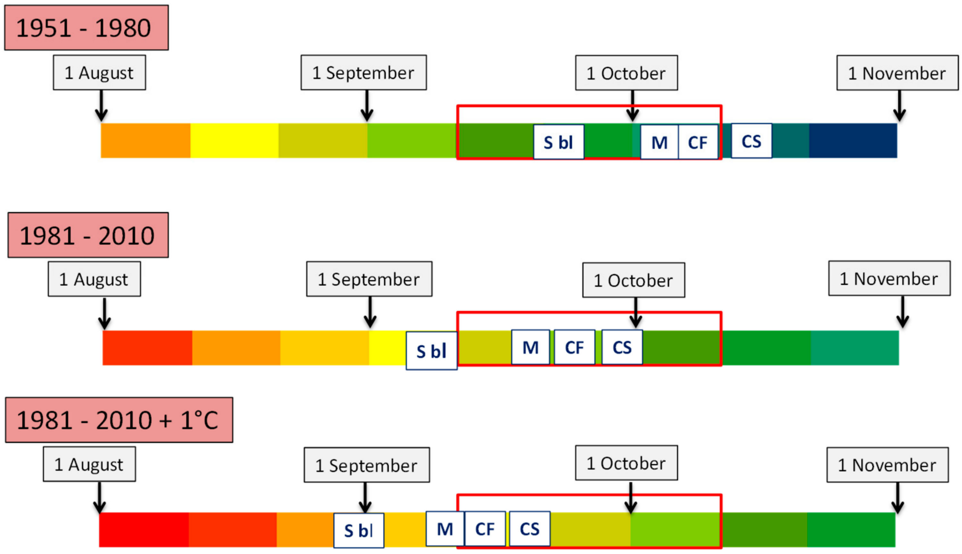

Figure 4. Modelled harvest dates for Sauvignon blanc (S bl), Merlot (M), Cabernet franc (CF), and Cabernet-Sauvignon (CS) in Bordeaux for the following periods: 1951–1980, 1981–2010, and 1981–2010 + 1 °C. Sugar ripeness is modelled with the grapevine Sugar Ripeness Model (GSR; [55]). Temperature data is from Bordeaux Mérignac weather station. Warm colors indicate higher temperatures and cold colors cooler temperatures.

In general, grape and wine compositions have dramatically changed over the past three decades worldwide. Mean data from Languedoc (France) shows that over a 35-year time span, alcohol in wine increased from 11% to 14%, pH from 3.50 to 3.75 and total acidity decreased from 6.0 to 4.5 g/L (Figure 5). Similar observations are made in many regions around the world [23,26,44,56].

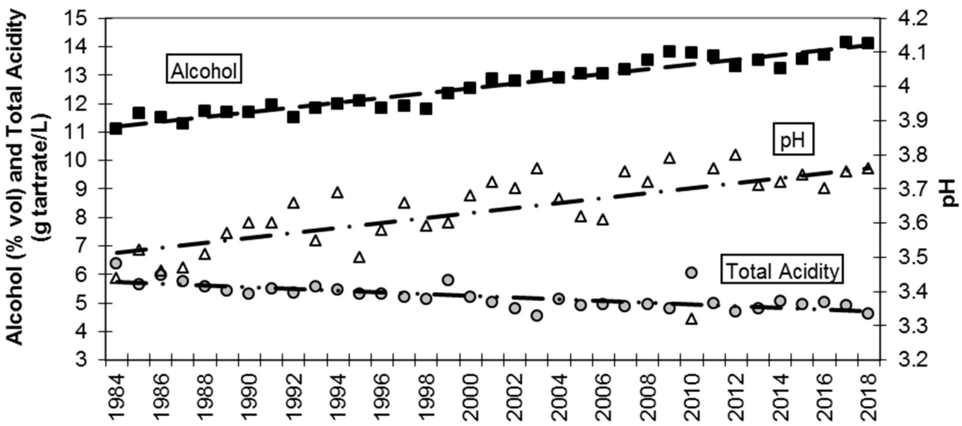

Figure 5. Evolution of red wine composition in the Languedoc region (France) from 1984 to 2018. Each data point is the average of several thousands of analyses of red wines just after alcoholic fermentation (data: Dubernet laboratory, F-11100 Montredon des Corbières).

2.2. Drought Effects

Climate change will also expose vines to increased drought, either because of reduced rainfall, or because of higher reference evapotranspiration due to elevated temperatures. This may lead to lower yields, because several yield parameters are impacted by water deficits, in particular berry size [14,15] and bud fertility [57]. On the other hand, water deficit has a positive effect on red wine quality because grape skin phenolics increase [14,15,58] and wines develop more complex aromas during bottle ageing [17,18]. So far, the best vintages in Bordeaux (where vines are not irrigated) are dry vintages [45]. The frequency of dry vintages has increased over the past three decades and this resulted in better vintage ratings in recent years. In white wine production only very mild water deficits are positive for wine quality, while more severe water deficits are detrimental [20]. For red wines, the general tendency under increased drought is lower yields and better quality (except situations of severe water stress); for white wine, not only yields can be negatively affected but quality can also be jeopardized.

In established wine growing regions, growers have optimized output in terms of quality and yield by choosing plant material, viticultural techniques, and wine making which are most adapted to their local environment. Now that the climate has become warmer and drier in most wine growing regions, this balance is threatened. Specific adaptations are needed to continue to produce optimum quality and yield in a changing environment.

3. Adaptations to Higher Temperatures

Higher temperatures advance grapevine phenology [46]. Hence, grapes ripen earlier in the season under warmer temperatures [49]. When grapes achieve full ripeness in the warmest part of the season (July–August in the Northern Hemisphere, January–February in the Southern Hemisphere) grape composition can be unbalanced (e.g., high sugar levels and low acidity), with red grapes containing less anthocyanins [59,60]. Wines from these grapes will lack freshness and aromatic complexity [12]. Hence adaptations to higher temperatures encompass all changes in plant material or modifications in viticultural techniques with the purpose of delaying ripeness [61].

3.1. Later Ripening Varieties

Grapevines have a wide phenotypic diversity regarding the timing of phenology [53]. In all traditional winegrowing regions in Europe, growers have planted varieties that ripen between 10 September and 10 October under local climatic conditions. This is the case for Riesling in the Rheingau (Germany), Chardonnay and Pinot noir in Burgundy (France), Merlot, Cabernet franc, and Cabernet-Sauvignon in Bordeaux (France), Grenache and Carignan in Languedoc (France), Tempranillo in La Rioja (Spain), Sangiovese in Tuscany (Italy), Nebbiolo in Barolo (Italy), Touriga nacional in Douro (Portugal), Agiorgitiko in Nemea (Greece), and Monastrell (Mourvèdre) in Alicante (Spain). Now that temperatures have increased, traditional varieties may move out of the ideal ripening window with detrimental effects on wine quality. In this context, potential adaptation to a changing climate is to plant later ripening varieties. The Ecophysiology et Génomique Fonctionelle de la Vigne research unit (EGFV) from the Institut des Sciences de la Vigne et du Vin (ISVV) near Bordeaux planted the VitAdapt vineyard experiment in 2009, where 52 varieties are planted with five replicates to study physiology, phenology, ripening dynamics, and wine quality (by small scale vinifications) to assess how these varieties behave differently in a warming climate [62]. The experimental set-up includes later-ripening varieties from warm locations, like Touriga nacional, Tinto Cao (Portugal, red varieties), and Assyrtiko (Greece, white variety; Figure 6). Data from this vineyard shows average véraison dates (2012–2018) span over 34 days, demonstrating the extent to which later ripening can be achieved by simply changing the variety (Figure 7).

In European wine appellations, the choice of varieties is regulated to allow only varieties that perform best in terms of quality and typicity under local climatic conditions. Under a changing climate, however, these regulations will need to be modified. Recently seven new varieties, including Touriga nacional, were accepted for planting in up to 5% of the area in Bordeaux winegrowing estates to allow testing with full-scale vinifications. This percentage may be increased if the experiments are conclusive. The choice of the varieties allowed for testing was based directly on results from the VitAdapt experiment. In New World winegrowing regions, grapevine varieties are not restricted by law, but surprisingly their diversity is even lower than in traditional Europeans winegrowing regions, due to the preeminence of well-known international varieties for marketing purposes. A wider range of grapevine varieties can be a useful tool for adaptation to climate change [63].

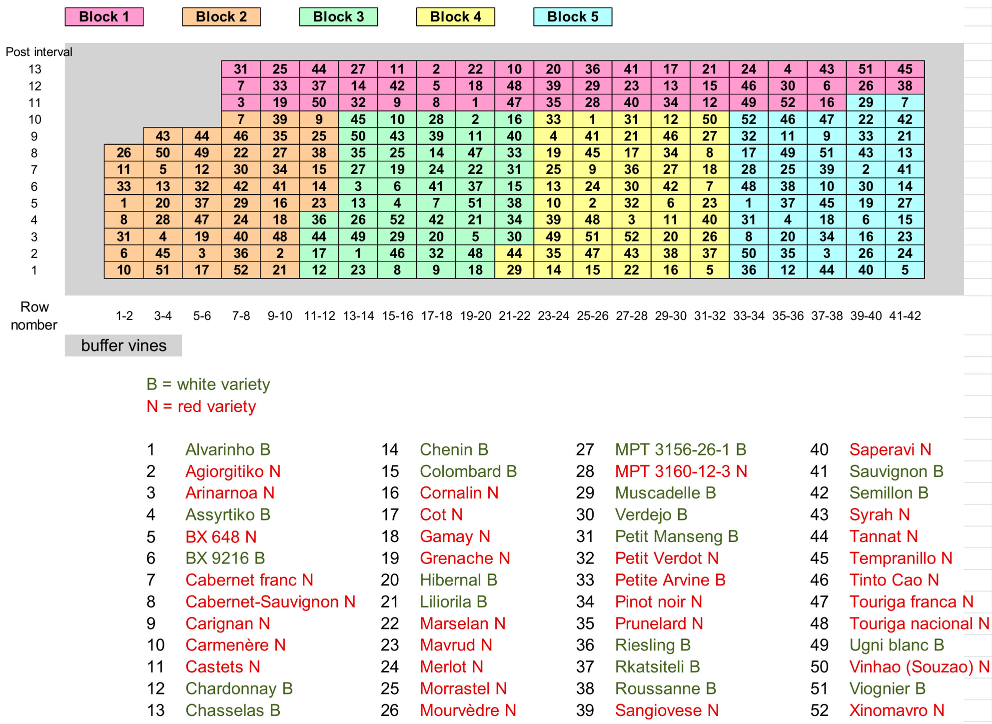

Figure 6. Layout of the 52 varieties planted in the VitAdapt experiment, with five replicates per variety and 10 vines per replicate.

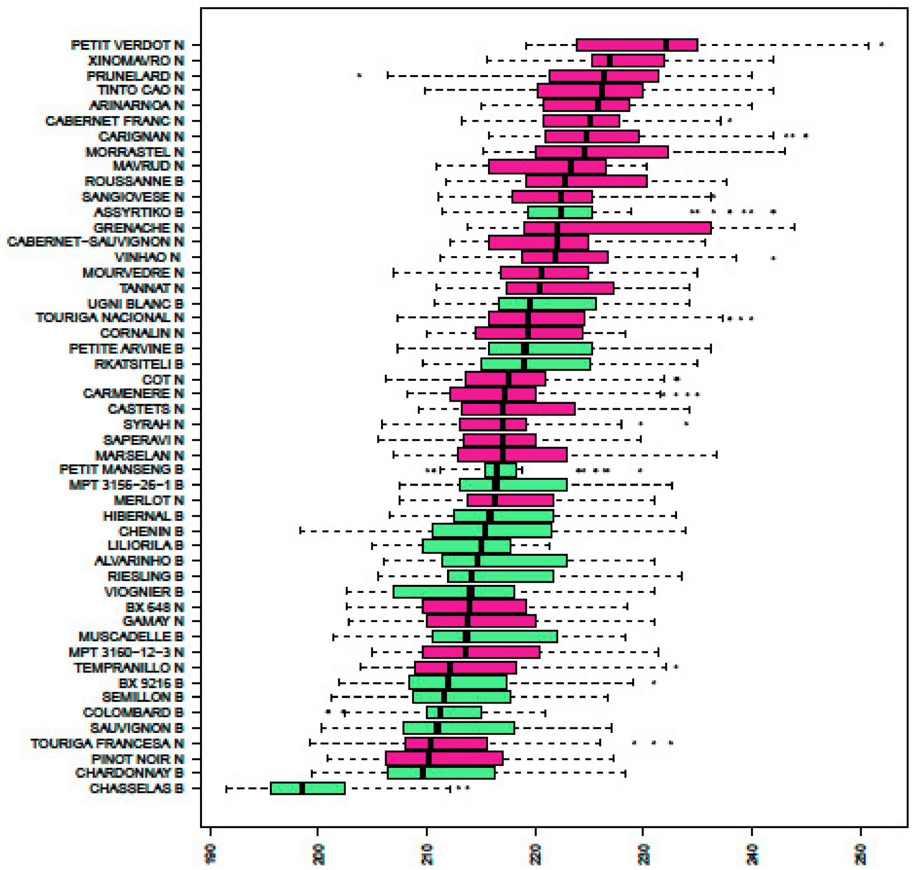

Figure 7. Boxplot of observed mid-véraison dates of varieties planted in the VitAdapt experiment (average day of the year from four replicates per variety over the period 2012–2018).

3.2. Later-Ripening Clones

Within a given variety a certain level of genetic variability exists, referred to as clonal variability. Historically, clones have been selected for traits such as high productivity, early ripening, and high sugar content in grapes. In the context of a changing climate it may be preferable to select new clones with the opposite characteristics. Sugar accumulation dynamics vary among clones, as shown from an example of a clonal selection trial on Cabernet franc [5] (Figure 8). At ripeness, differences in grape sugar concentration among clones can be over 17 g/L (1% potential alcohol). In the same clonal collection, differences in mid-véraison dates ranged from 6 to 9 days depending on the vintage (data not shown).

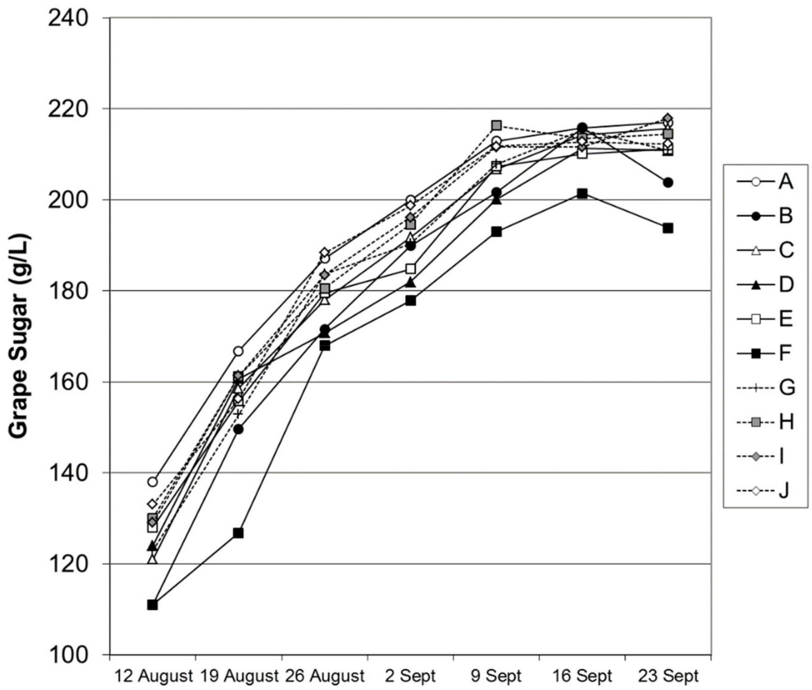

Figure 8. Sugar accumulation dynamics in 2013 from a private clonal selection program on Cabernet franc. A–J represent 10 different clones [5].

3.3. Later-Ripening Rootstocks

Rootstocks can influence the phenology of the grafted scion. Some rootstocks induce earlier phenology and ripening, while others induce a longer cycle [61,64]. Precise data on this effect is scarce in the scientific literature. In 2015 the GreffAdapt experiment was planted by the EGFV research unit from the ISVV. In this project, 55 rootstocks are phenotyped with five different scions in field condition. Each combination is planted with three replicates [65]. Over the coming years, this experimental vineyard will yield precise information regarding whether and how rootstocks may induce differences in grapevine phenology and timing of ripeness.

3.4. Increasing Trunk Height

Trunk height determines the distance from the soil to the grapes and can vary according to training systems from 30 cm to over 1 m. Maximum temperatures are higher close to the soil and the resulting vertical temperature gradient can be used to fine-tune the micro climate in the bunch zone through variations in trunk height. In Bordeaux, where the climate historically has been marginal for ripening Cabernet-Sauvignon, growers planted this variety on warm gravel soils and trained the vines with short trunks to have the bunches as close as possible to the soil. In warmer climatic conditions as caused by climate change, the temperatures may be too high close to the soil surface, in particular for early ripening varieties in the Bordeaux context like Sauvignon blanc and Merlot. An experiment was set up in the Saint-Emilion winegrowing region where temperature sensors were installed at 30, 60, 90, and 120 cm on vine posts with three replicates in four different vineyard blocks. The Winkler Index as measured in these canopies was 60 degree.days lower at 120 cm compared to 30 cm (Figure 9). Based on a 19 °C average temperature (which corresponds to 9 °C base of 10 °C) this difference may induce a delay of 7 days in grape ripening.

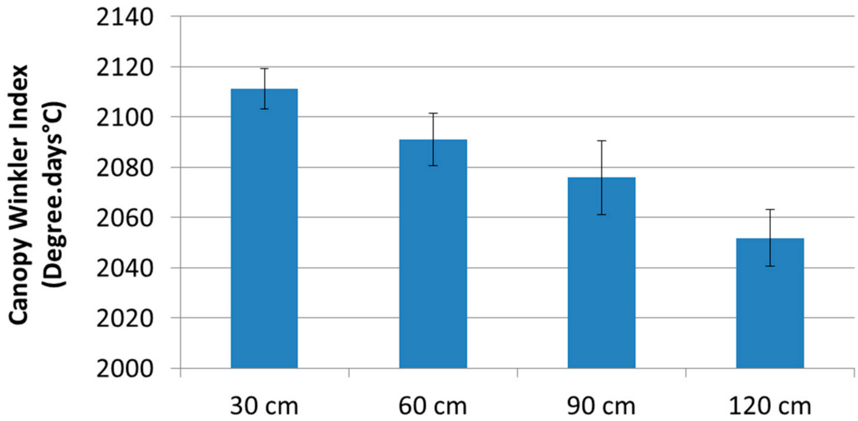

Figure 9. Variations in Canopy Winkler Index computed from temperature data acquired by sensors installed on vine posts at 30, 60, 90, and 120 cm in height.

3.5. Reducing Leaf Area to Fruit Weight Ratio

Leaf area to fruit weight ratio (LA:FW) is considered as an important parameter affecting the performance of a vineyard, both with regard to yield and grape composition [66]. A LA:FW of at least 1 m^2/kg is generally considered as necessary to ensure optimum ripening conditions and in particular sugar accumulation [67]. Lower LA:FW ratios can considerably delay véraison and sugar accumulation in grapes, with limited effect on total acidity [68,69]. Reduced LA:FW ratios, however, adversely affects anthocyanin accumulation in grapes, which makes this technique more easily applicable in white wine production than in red wine production. Studies in potted vines [70] and in field grown vines [71] found only a transient effect of leaf removal on vine physiology and small, or no effect of final grape composition. In these studies, however, leaf removal was less severe and LA:FW ratio was higher than 1 m^2/kg of fruit in all treatments. De Bei and co-authors [72] found an inconsistent effect of leaf removal on phenology and grape composition depending on the year and the grapevine variety, but LA:FW ratio was also above 1 m^2/kg of fruit in all treatments.

3.6. Late Pruning

When winter pruning is carried out late, budbreak is delayed by a few days [73]. However, differences tend to become smaller for subsequent phenological stages. Differences are more significant when pruning is carried out when the vines had 2–3 leaves, with no effect on yield or pruning weights the following season [74]. In this experiment, wine quality, as assessed by color intensity and sensory analysis, was improved by late pruning, probably because ripening occurred under lower temperature associated with delayed phenology [75]. Maturity is more substantially delayed when vines are pruned a second time, well after budburst [73,76,77]. This technique, however, is still experimental and long-term carry-over effects on vigor need to be studied.

3.7. Moving to Higher Altitudes

In mountainous areas, temperature decreases by 0.65 °C per 100 m of elevation. If other vineyard adaptations are not adequate, and if topography permits (Douro, Portugal; Mendoza, Argentina), moving vineyards to higher altitudes can be an effective adaptation to a warming climate. In Mendoza varieties are grown according to the altitude, where in very warm conditions at 800 m above sea level (a. s. l.) entry-level wines are produced from high-yielding vines. Finer wines are produced from Malbec and Cabernet-Sauvignon planted at 1100 m. a. s. l. and early ripening Chardonnay and Pinot noir planted at 1500 m. a. s. l. Moving vineyards to higher elevations, however, may have detrimental environmental effects associated with disruption to wildlife habitat and ecosystem services, which need to be considered [31].

3.8. Combination of Adaptations

The previously mentioned changes in plant material and viticultural techniques can be progressively implemented. Some of them do not require major changes in viticultural management (e.g., late pruning), while others may involve replanting vinyards with a potential change in wine typicity (e.g., change of varieties). To a certain extent, these techniques can be combined, but further research is needed to assess if the delaying effect by combining several techniques is additive. Overall, depending on the rate of climate warming, such adaptations should be effective for decades to come, except maybe for already very hot wine growing areas.

4. Adaptations to Increased Drought

Water deficits reduce yield but, except in situations of severe stress, it can have a positive effect by promoting red wine quality [10,58]. The production of high-quality white wines requires mild water deficits [78]. With increasing water deficits as a consequence of climate change, yields are negatively impacted, decreasing profitability of wine production. Hence, adaptations to drier growing conditions is becoming increasingly pertinent in viticulture worldwide. The vine is a highly drought resistant species. In the Mediterranean basin there are thousands of years of experience of growing vines in warm and dry conditions. In a context where water is an increasingly scarce resource it is important to take advantage of this expertise. Potential adaptations to increased drought include the use of drought resistant plant material, the implementation of specific training systems, locating vineyards where soils have greater soil water holding capacity, and possible use of irrigation.

4.1. Drought Resistant Rootstocks

Since phylloxera reached Europe in the second half of the 19th century, most vines in the world are grafted on rootstocks. Rootstocks vary considerably in their ability to resist drought. Several authors have addressed this issue [79] and recently a collation was made by Ollat et al. [6] (Table 1). Physiological mechanisms behind drought tolerance in rootstocks (as measured on the scion) were studied by Marguerit et al. [80]. This issue will be further investigated in field conditions in the GreffAdapt experiment in the EGFV research unit in Bordeaux [65]. The use of drought resistant rootstocks to sustain yields and avoid quality losses from excessive water stress is a powerful and environmentally friendly adaptation to increased drought, and once planted do not increase production costs.

Table 1. Drought tolerance among rootstocks (Adapted from Ollat et al. [6]).

Rootstocks	Usual Name	Phylloxera Resistance	Water Stress Adaptation
Riparia Gloire de Montpellier	Riparia Gloire	High to very High	Low
Grézot 1	G1	Low to Medium	Low
Foëx 34 École de Montpellier	34 EM	High	Low to Medium
Millardet et de Grasset 420 A	420 A	High	Very Low to Medium
Kober-Téléki 5 BB	5 BB	High	Low to Medium
Téléki 5 C	5 C	High	Low to Medium
Couderc 1616	1616 C	High	Low to Medium
Rupestris du Lot (St. George)	Rupestris	Medium to High	Low to Medium
Millardet et de Grasset 101-14	101-14 MGt	High	Very Low to Medium
Couderc 3309	3309 C	High	Very Low to High; mostly Low to Medium
Téléki-Fuhr Selection Oppenheim n°4	SO4	High	Very Low to High; mostly Low to Medium
Téléki 8 B	8 B	High	Low to Medium
Dog Ridge	Dog Ridge	High	Very Low to High
Schwarzmann	Schwarzmann	High to very High	Very Low to Medium
Couderc 1613	1613 C	Low to Medium	Low to Medium
Couderc 161-49	161-49 C	High	Low to Medium
Kober-Téléki 125 AA	125 AA	High	Medium
Millardet et de Grasset 41B	41 B	Medium to High	Very Low to High, mainly Medium
Castel 216-3	216-3 Cl	High	Medium
Fercal INRA Bordeaux	Fercal	Medium to High	Medium
Gravesac INRA Bordeaux	Gravesac	High to very High	Medium
Freedom	Freedom	Medium to High	Medium
Harmony	Harmony	Low to Medium	Medium to High
Foëx 333 École de Montpellier	333 EM	Medium to High	Low to High, mainly Medium to High
Richter 99	99 R	High	Medium to Very high
Börner	Börner	Very high	High
Castel 196-17	196-17 Cl	Low to Medium	Medium to High
Georgikon 28	Georgikon 28	High	High
Malègue 44-53	44-53 M	High	Medium to very High
Ramsey	Ramsey	High	Medium to very High
Paulsen 1103	1103 P	High	High to very High
Paulsen 1447	1447 P	High	High to very High
Richter 110	110 R	High	High to very High
Ruggeri 140	140 Ru	High	High to very High

4.2. *Drought Resistant Varieties*

Grapevine varieties are highly variable in their tolerance to drought [81]. This may be linked to the way different varieties regulate their water potential in response to increasing atmospheric demand and decreasing soil water content. Some varieties appear to control their water potential more closely (isohydric behavior) under drought conditions [82], although the characterization of this response has recently been challenged [83].

The way varieties modify their water use efficiency in response to drought is another useful indication of varietal drought tolerance. At the leaf level, water use efficiency is the amount of carbon assimilation (i.e., carbohydrates produced by photosynthesis) for a given amount of transpiration through the stomata (i.e., water loss). At the plant level, it is the yield of grapes and change in vine biomass compared to the amount of water consumed by the vine over the season [84]. Clonal differences in water use efficiency have been observed [85] and may be a useful tool for assessing the drought tolerance of different varieties. Analyzing the carbon isotope discrimination in grape berry juice sugars provides an integrative measure of the water use efficiency of a grapevine over the course of the berry ripening period [86] and comparison of changes in carbon isotope discrimination (i.e., water use efficiency) between wet versus dry years can help characterize the drought resistance of different varieties.

Most grapevine varieties originating from the Mediterranean basin (Grenache, Cinsault, Carignan) are considered drought tolerant, while varieties like Merlot, Tempranillo, or Sauvignon blanc are not. Some local varieties of Mediterranean islands, like Xinistery from Cyprus are reported to have a very high drought resistance and deserve experimentation outside this original region of production (Manganaris, personal communication). A study of the underlying physiological mechanisms of drought resistance is currently undertaken in the VitAdapt projects (EGFV research unit, ISVV Bordeaux; [87]. Planting drought resistant varieties in dry environments is a logical step in adapting to climate change, and therefore these varieties deserve increased attention.

4.3. Training Systems

Over centuries, wine growers in the Mediterranean basin have developed a training system which is particularly resistant to drought and high temperatures: the so-called Mediterranean goblet or bush vine. With this training system, it is possible to dry-farm vines in extremely dry environments, down to a mere 350 mm of rainfall/year [88,89]. Although goblet trained vines generally produce low yields, they are easy to cultivate at reduced production costs on a per hectare basis [9]. Hence, despite low yields, production costs expressed on a per kilogram basis are not necessarily high. They present the drawback, however, of being difficult to harvest by machine [90]. If harvesting goblet trained vines could be mechanized, this would further reduce production costs for this otherwise drought resistant training system.

An alternative solution to increasing drought resistance of a vineyard is to increase row spacing. Row spacing is traditionally high in regions where water deficit is not a major issue, like Bordeaux, Champagne, and Burgundy (France). Close row spacing optimizes sunlight interception, which allows producing high-quality wines at moderately high yields. When water is, or becomes, a limiting factor, close row spacing increases water use, because sunlight interception is providing the driving energy for transpiration. The effect of row spacing on water balance was recently modeled by van Leeuwen et al. [91] for three row spacings (2 m = 5000 vines/ha, 3 m = 3333 vines/ha, and 4 m = 2500 vines/ha) and three levels of total transpirable soil water (TTSW), a concept similar to soil water holding capacity [92]. The output of the water balance model is the fraction of transpirable soil water (FTSW), where the lower the FTSW, the greater the water deficit experienced by the vines. The output of the water balance modeling demonstrated that vine spacing had an important effect on water balance and water availability during grape ripening, except when TTSW was already low (Figure 10). It should be noted that increased vine spacing reduces both yield (and related revenue) and production cost, with profitability depending on the trade-off between these two effects. Modeling found production cost savings outweighing yield-related revenue loss when producing lower-value grapes, while the opposite is true for production of higher-value grapes [91].

4.4. Soil Water Holding Capacity

TTSW or soil water holding capacity has a major impact on vine water status. In the analysis described above and presented in Figure 10, average FTSW for the 30 days prior to modeled harvest is 0.43, 0.26, and 0.19 for TTSW of 300, 200, and 100 mm respectively. Note that vines do not face any water deficit when FTSW is between 1.00 and 0.40 and that water deficits are increasingly intense for FTSW between 0.40 and 0.00 [92]. TTSW depends on soil type (texture and content in coarse elements) as well as rooting depth. Under dry climates it makes sense to plant vineyards in soils with at least medium TTSW. Rooting depth can be promoted by through soil preparation, such as deep ripping [93].

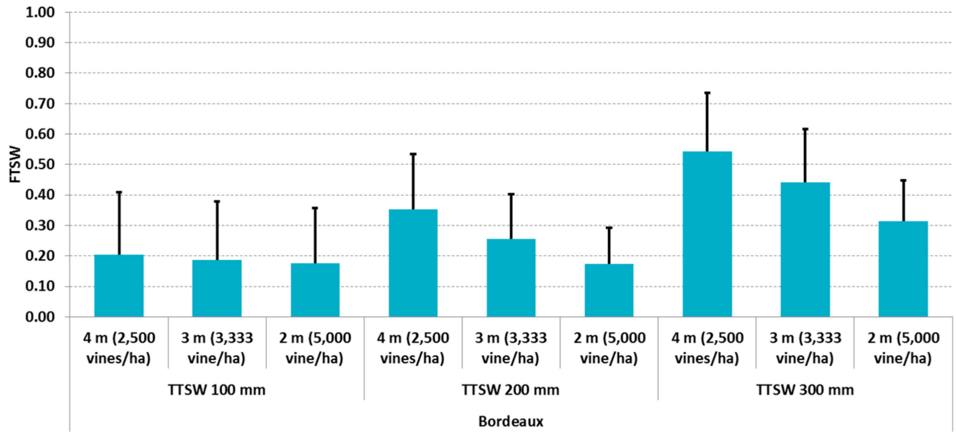

Figure 10. Modelled average fraction of transpirable soil water (FTSW) during 30 days prior to modelled harvest dates for three vines spacings (2, 3, and 4 m) and three levels of total transpirable soil water (100, 200, and 300 mm). Input weather data from 1981–2010, Bordeaux Mérignac weather station.

4.5. Irrigation

To avoid yield losses due to drought, irrigation is also an option when adequate water resources are available. Vineyard irrigation is not an historical technique in the Mediterranean basin, where the vast majority of vines are still dry-farmed. Although the acreage of irrigated vineyards is increasing, it is likely that there will never be enough water to irrigate the total area which is currently under vines. Hence, dry farming should be considered as a precious skill, of which the underlying mechanisms need to be better understood. Another drawback of irrigation is that in some situations (in particular when winters are dry), it can lead to increased soil salinity, which results in reduced long-term suitability of vineyard soils for cultivation.

When irrigation is chosen as a technique for vineyard management in dry climates, consideration must also be given to the potential negative impacts on regional surface and groundwater resources, including the effect on other potential users of water and the surrounding environment. If irrigation is implemented, techniques such as deficit irrigation should be used with precise vine water status monitoring (e.g., by measuring stem water potential) in order to limit, as much as possible, the amount of irrigation water applied. However, even with fine-tuned irrigation management, the blue water footprint of an irrigated vineyard is generally at least 100 times higher compared to a dry-farmed vineyard.

5. Conclusions

Due to climate change, vines are facing increasingly warm and dry growing conditions. The vine is, however, a plant of Mediterranean origin, which is well adapted to these conditions. However, higher temperatures shift phenology and the ripening period to a time in the season which is less favorable for the production of quality wine and increasingly dry conditions lead to yield reduction. In some situations, it promotes wine quality, in particular for the production of red table wines, while excessive water stress may jeopardize wine quality. Adaptations to climate change include modifications in plant material and viticultural techniques which delay phenology and grape ripening and increase drought tolerance. The use of late-ripening and drought resistant plant material (varieties, clones, and rootstocks) is an environmentally friendly and cost-effective tool for adaptation. The vast genetic diversity in vines for these traits constitutes a precious resource to continue to produce high-quality wines with sustainable yields in a changing climate.

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