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Review article

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Climate change impacts and adaptations of wine production

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Abstract

Climate change is affecting grape yield, composition and wine quality. As a result, the geography of wine production is changing. In this Review, we discuss the consequences of changing temperature, precipitation, humidity, radiation and CO_2 on global wine production and explore adaptation strategies. Current winegrowing regions are primarily located at mid-latitudes (California, USA; southern France; northern Spain and Italy; Barossa, Australia; Stellenbosch, South Africa; and Mendoza, Argentina, among others), where the climate is warm enough to allow grape ripening, but without excessive heat, and relatively dry to avoid strong disease pressure. About 90% of traditional wine regions in coastal and lowland regions of Spain, Italy, Greece and southern California could be at risk of disappearing by the end of the century because of excessive drought and more frequent heatwaves with climate change. Warmer temperatures might increase suitability for other regions (Washington State, Oregon, Tasmania, northern France) and are driving the emergence of new wine regions, like the southern United Kingdom. The degree of these changes in suitability strongly depends on the level of temperature rise. Existing producers can adapt to a certain level of warming by changing plant material (varieties and rootstocks), training systems and vineyard management. However, these adaptations might not be enough to maintain economically viable wine production in all areas. Future research should aim to assess the economic impact of climate change adaptation strategies applied at large scale.

Sections

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Key points

- Climate change modifies wine production conditions and requires adaptation from growers.
- The suitability of current winegrowing areas is changing, and there will be winners and losers. New winegrowing regions will appear in previously unsuitable areas, including expanding into upslope regions and natural areas, raising issues for environmental preservation.
- Higher temperatures advance phenology (major stages in the growing cycle), shifting grape ripening to a warmer part of the summer. In most winegrowing regions around the globe, grape harvests have advanced by 2–3 weeks over the past 40 years. The resulting modifications in grape composition at harvest change wine quality and style.
- Changing plant material and cultivation techniques that retard maturity are effective adaptation strategies to higher temperatures until a certain level of warming.
- Increased drought reduces yield and can result in sustainability losses. The use of drought-resistant plant material and the adoption of different training systems are effective adaptation strategies to deal with declining water availability. Supplementary irrigation is also an option when sustainable freshwater resources are available.
- The emergence of new pests and diseases and the increasing occurrence of extreme weather events, such as heatwaves, heavy rainfall and possibly hail, also challenge wine production in some regions. In contrast, other areas might benefit from reduced pest and disease pressure.

Introduction

Grapes are the world's third most valuable horticultural crop, after potatoes and tomatoes, counting for a farm-gate value of US$68 billion in 2016 ref. 1. Global production in 2020 was 80 million tonnes of grapes, harvested from 7.4 million hectares[2]. Of the produced grapes, 49% were transformed into wine and spirits, while 43% were consumed as fresh grapes and 8% as raisins. Wine, as a commodity, can be valued over a price range from US$3 to over US$1,000 per bottle, depending on quality and reputation[3]. Hence, financial sustainability does not only rely on the balance between yield and production costs, as for most agricultural products, but also on quality and reputation. The region of production is a major driver of reputation and value[4]. This regional variation in wine quality is not surprising, because the climate, or more precisely the 'right variety in the right climate', is a well-identified attribute of premium wine production[3]. The effect of climate conditions on grape composition at harvest (and thus, wine composition and quality) seems to be even more important than the soil type[5].

With climate change, this fundamental regional influence on wine quality and style is changing[6]. For example, a substantial advance in harvest dates and/or an increase in wine alcohol level have already been observed in many regions such as Bordeaux and Alsace (France)[7–9]. The suitability for wine production in established winegrowing regions is likely to change during the twenty-first century[10–13]. Pressures from temperature rise and drought could challenge production in already hot and dry regions to the point where suitability will be lost, with enormous negative social and economic consequences. Mid-latitude wine regions could be increasingly exposed to spring frost events, owing to earlier budburst[14,15]. Projected increased hailstorm severity can result in crop and plant damage[16]. However, some of these projections are overly pessimistic, because they do not take into account the possibility for growers to adapt to the changing conditions[17]. For example, major technical levers for adaptation include changes in plant material, training systems and/or seasonal management practices[18–20].

In addition, new winegrowing regions could emerge in previously unsuitable areas, as cool and subhumid climates see increasing temperatures, creating economic opportunities but also threatening wild habitats when these emerging regions do not result from converted farmland[10]. If these new vineyards are irrigated, this will increase competition for freshwater resources. Even converting existing farmland to winegrowing means less arable land dedicated to food production.

In this Review, we synthesize climate change effects on viticulture and wine production. Many articles have been published on regional impacts of climate change on wine production, and our aim is to assemble these results to produce a global picture of the changing geography of wine. We discuss the impacts of changing temperature, radiation, water availability, pests and diseases, and CO_2 on viticulture and wine. Potential adaptation measures and their limits are discussed, for example, existing producers can adapt to a certain level of warming by changing plant material (varieties and rootstocks), training systems and vineyard management. However, these adaptations might not be enough to maintain economically viable wine production in all areas. Finally, implications of viticultural expansion are discussed and compared with historical shifts in production.

Shifting geographies of wine production

Wine grapes are cultivated from the tropics to Scandinavia[21,22] and can be grown at elevations of over 3,000 m [23], revealing the remarkable adaptability of grapevine to a wide range of climate conditions. Vineyard management aims at locally adapting vine cultivation to match terrain, soil and climate conditions. In cool and subhumid environments, such as vineyards in northwestern Europe, important climate-related challenges are grapevine diseases and difficulties in obtaining fully mature fruit. Hence, vineyards are commonly planted on slopes to optimize light interception and runoff, on shallow soils to promote mild water deficits that enhance ripening, with early ripening grapevine cultivars, and using training systems that maximize exposed leaf areas per unit of ground surface[24]. In such regions, the impacts of climate change are predominantly positive, as warmer conditions and higher evaporative demand make it easier for grapes to ripen[25] and limit disease-triggering humidity. In drier and warmer regions, the main challenge is plant water availability. Adaptation to water scarcity depends on local practices, favouring either irrigation or systems that use low water consumption, such as cultivation of drought-resistant varieties cropped as bushvines and/or at low planting density (number of vines per hectare). In warm and dry regions, climate change is a threat requiring immediate adaptations because of excessively high temperatures[26] and increased water scarcity[27].

Climate change is having a growing impact on the wine industry, potentially altering the geography of high-quality wine production. After segmenting each continent and its wine-producing areas into macro-regions defined by specific climate-driven conditions (see Supplementary note and Supplementary Table 1 for definitions), we estimate a substantial risk of unsuitability (ranging from moderate to high) for 49–70% of existing wine regions, contingent on the degree of global warming (Fig. 1). Simultaneously, 11–25% of existing wine regions might experience enhanced production with rising temperatures, and new suitable areas might emerge at higher latitudes and altitudes (Fig. 1). These assessments on the future risks and opportunities for wine production worldwide are based on an exhaustive literature review (see Supplementary Table 2) and exhibit specific features across continents.

North America

Currently, most of the wine production in North America (10% of global wine production[2]) is concentrated on the west coast[28], particularly in northern California, including Napa Valley, which stands out both in terms of production and value (Fig. 1a). Moderate levels of global warming are projected to maintain the suitability of coastal regions of California for high-quality wine production[10,29]. However, winemakers in this region will face increasing risks of drought, heatwaves and wildfires, necessitating the proactive adoption of adaptation measures[30]. If global warming exceeds 2 °C, coastal California will transition to a very warm and arid climate for viticulture, probably resulting in a decline in wine quality and economic sustainability[12,26]. The interior regions of California might experience this decline earlier and will need to adopt more radical adaptation measures even below 2 °C of global warming[31]. The southern part of California, already characterized by a warm and dry climate, is expected to become unsuitable for high-quality wine production under global warming scenarios exceeding 2 °C[10,12]. Overall, the net suitable area for wine production in California could decline by up to 50% by the end of the twenty-first century[12]. Similar risks exist for Mexico, the southwestern United States and those regions of the east coast south of New Jersey[10]. The northernmost wine regions of America (that is, New British Columbia, Washington State, Oregon on the west coast, Great Lakes region and New England on the east coast) are likely to shift from cool to intermediate, or even warm, climate viticulture in the future, thus increasing their potential for premium wine production[10,12,29,32]. However, global warming surpassing 2 °C is likely to result in antagonistic effects. On one hand, it can enhance climate suitability, with suitable areas in these regions (excluding Oregon) probably more than doubling[10,12]. On the other hand, it would introduce unprecedented risks of heatwaves and increased disease pressure[26,33], particularly considering that these regions are predominantly classified as humid.

South America

Current wine production in South America (10% of global wine production[2]) is primarily concentrated in the middle to high altitudes of Chile and Argentina, benefiting from favourable temperatures and sunlight along the foothills of the Andes Mountains (Fig. 1b). Given the extensive irrigation already adopted over the driest wine regions, such as Mendoza, projections in precipitation over traditional South American vineyards do not indicate substantial changes in suitability[34]. Consequently, the future suitability in these regions will be primarily dependent on temperature increase, ground and surface water availability[35], and the frequency of extreme events. For a limited level of warming, the Pacific sector of South America is expected to experience a low risk of suitability loss, but this risk increases for the Atlantic regions such as Brazil and Uruguay. Cool-climate winegrowing regions, such as the Pampa region, might be improved under these conditions[34,36]. For more severe warming, the resilience of the northern Argentinian wine regions might require a shift from lowlands to higher slopes of the Andes[34,36], while the Atlantic sector will offer poor opportunities for winemaking[10,12]. Expanding into newly suitable areas could imply movement southward into Argentinian Patagonia[34,36] or potentially an exploration of the high altitudes of the Ecuadorian and Colombian Andes[10,12]. In general, the projected decrease in suitable areas in the Pacific South America will probably be balanced by the potential emergence of new suitable areas[10,12].

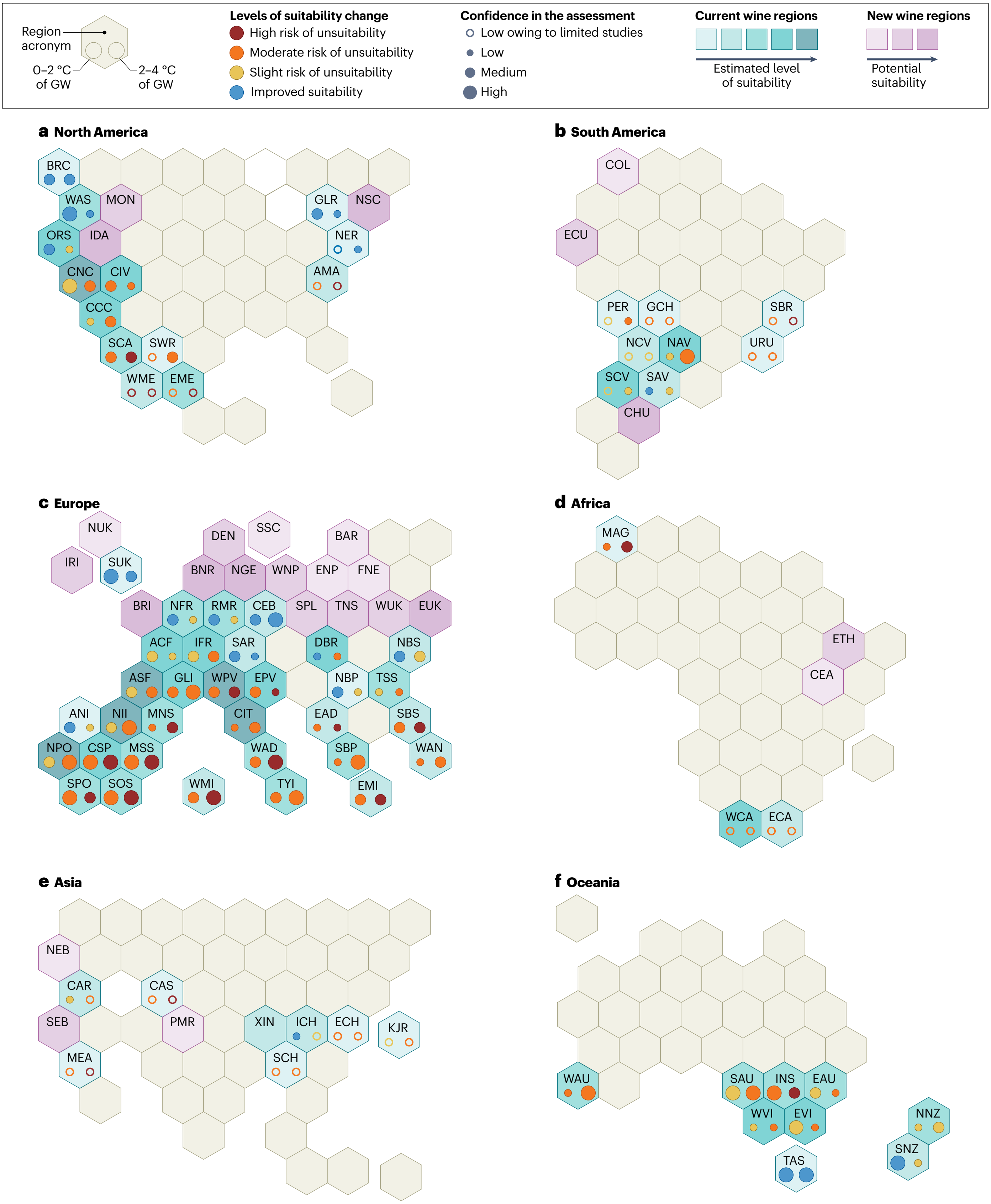
Europe

Europe is recognized as the primary producer of premium wine worldwide, with a substantial production located south of approximately 50° N. Spain, France, Italy and Germany collectively contribute to half of global wine production[2] (Fig. 1c). However, climate change is expected to shift suitable regions towards higher latitudes and altitudes[10,12]. Under low levels of global warming (<2 °C), most traditional wine-producing regions will maintain suitability, albeit contingent on the implementation of adaptation measures, notably in southern Europe[13]. The combination of rising temperatures and reduced rainfall will induce severe risk of drought over south Iberia, Mediterranean France and Spain, the Po Valley, coastal Italy, the Balkan Peninsula and the southwestern Black Sea regions[13,27,37,38]. The risk of widespread water scarcity might render unsustainable any extensive increase in irrigation intended to preserve the suitability of these areas. Moreover, warmer conditions and increased sunburn exposure will negatively affect both yield and wine quality in these areas. For more severe warming scenarios, most Mediterranean regions might become climatically unsuitable for wine production, and vineyards below 45° N might be so challenged that the only feasible adaptation would be to relocate to higher altitudes[11,13,39–41]. About 90% of the traditional wine regions situated in the lowlands and coastal regions of Spain, Italy and Greece could be at risk of disappearing by the end of the century[12]. Only a minor portion of this loss (less than 20%) can be potentially compensated for by shifting vineyards towards mountainous areas, considering elevations of up to 1,000 m[11,42].

Atlantic sectors of Iberia and France, along with the western Black Sea regions, will face lower risks than the Mediterranean[13,43–45]. With limited global warming, the implementation of viticultural techniques that delay ripening and alleviate water stress seem sufficient to preserve high-quality wine production[46]. More severe warming scenarios are likely to necessitate the transition to later-ripening grape varieties in these regions[12,13]. Conversely, Galicia, the northern Balkans, and in general areas north of 46° N are expected to benefit from global warming, at least for limited levels of temperature increase[10,13,27]. Over certain regions, early budburst might lead to an increased risk from spring frost[14,18,47]. Overall, the suitable surface area of traditional wine-producing regions is expected to decline by 20–70% by the end of the century, depending on the severity of the warming scenario[13]. Simultaneously, new wine regions are expected to expand northward, notably along the Atlantic sector[10–12,14,27], resulting in a net increase of climatically suitable areas in Europe by up to 60%[13]. However, such an expansion is purely theoretical and pertains solely to climate conditions, without considering soil quality, pre-existing land use and other crucial factors for establishing new vineyards.

Africa

Africa has a relatively low level of wine production (3.8% of global wine production[2]), with South Africa being the primary producer, while other countries such as Morocco, Tunisia and Algeria (Fig. 1d) have a much smaller scale of production[2]. The scientific literature on future wine


Region acronym
0–2 °C of GW
2–4 °C of GW
Levels of suitability change
High risk of unsuitability
Moderate risk of unsuitability
Slight risk of unsuitability
Improved suitability
Confidence in the assessment
Low owing to limited studies
Low
Medium
High
Current wine regions
Estimated level of suitability
New wine regions
Potential suitability
a North America
BRC
WAS
MON
GLR
NSC
ORS
IDA
NER
CNC
CIV
AMA
CCC
SCA
SWR
WME
EME
b South America
COL
ECU
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URU
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f Oceania
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Fig. 1 | Global changes in winegrowing suitability at temperature increases of 2 °C and 4 °C. a–f, Current suitability across continental regions is noted by the green shading of the hexagons, from less suitable (light green) to more suitable (darker green), for North America (panel **a**), South America (panel **b**), Europe (panel **c**), Africa (panel **d**), Asia (panel **e**) and Oceania (panel **f**). This current suitability was based on the actual production area and on published studies (see Supplementary information). Future suitability change in these regions is noted by the colour of the dots within the hexagons according to the key; the left dot represents the change for a scenario in which there is global warming (GW) of up to 2 °C and the right dot the change for warming of 2-4 °C. The size of the dot represents the confidence of the assessment (the larger the dot, the higher the confidence). The potential suitability of emerging wine regions is noted by hexagons that are shaded purple, from less (light purple) to more (darker purple) potential suitability based on consensus from the literature. The methodology to produce the maps is explained in the Supplementary information. The acronyms of all regions delimited by hexagons are provided in Supplementary Table 1, and references used for the assessments are available in Supplementary Table 2. Out of the 73 globally identified traditional wine-producing regions, an assessment on future climate suitability was feasible for 72: for global warming below (above) 2 °C, 18 (8) show improved suitability, 19 (13) show a slight risk of suitability loss, 34 (30) a moderate risk of suitability loss and 1 (21) a high risk of suitability loss. Simultaneously, 26 new potential emerging wine regions have been identified.

production in South Africa is limited, resulting in a low-confidence assessment of a moderate risk of suitability loss in both the more productive western region and the eastern region[10,12]. In contrast, a richer body of literature focused on the Mediterranean basin, considering different levels of global warming, indicates a moderate-to-high risk of suitability loss in the Maghreb region[27,48], whose possibility of future wine production presupposes the movement to higher altitudes, for example the Atlas Mountains. Potential emerging wine regions in Africa include the highlands of Kenya and notably the highlands of Ethiopia, where the wine industry is in its early stage of development[10,12].

Asia
The main winemaking regions in Asia (about 3.5% of global wine production[2]) include the Caucasus and China (Fig. 1e). The assessment of future Asian climate suitability for wine production is uncertain owing to limited studies, especially for Xinjiang, one of the major wine-producing regions of the continent. The inland Chinese regions (for example Ningxia), characterized by a mountain climate, might benefit from warming below 2 °C, expanding suitable areas[12,49]. However, further warming could render parts of this region substantially warmer and more arid, posing challenges for premium wine production[12,49]. The Caucasian and eastern Asian regions will face low-to-moderate risks of unsuitability depending on warming levels[10,12,41], and this risk is higher for the arid areas of Middle East and Central Asia, possibly leading to completely unsuitable conditions for temperature increases above 2 °C[12]. Emerging regions such as the northeastern Black Sea coasts, eastern Anatolia and Pamir–Himalayan Mountains show potential for future wine production[10,12].

Oceania
Projected climate change in Oceania (6% of global wine production[2]) will lead to overall warmer and drier conditions, making those regions that are already relatively warm and arid the most vulnerable (Fig. 1f). Although limited global warming (<2 °C) will generally bring better temperature conditions to southern regions, a moderate risk of suitability loss is expected in the inner region of New South Wales[50,51]. This risk remains low in the rest of mainland Australia and northern New Zealand[52]. If global temperatures rise above 2 °C, the risk of suitability loss will substantially increase, and the traditional inland regions of Australia might become unsuitable[52]. Conversely, Tasmania and southern New Zealand will benefit from limited warming, which might offer more favourable conditions for premium wine production. Tasmania, in particular, shows higher potential for premium wine production in both moderate and more severe warming scenarios[10,51,52], while New Zealand's high-quality production can probably be ensured through management adaptation alone[12,53]. Overall, depending on the degree of global warming, up to 65% of the traditional Australian vineyards might become climatically unsuitable, whereas wine-producing regions in New Zealand have the potential to expand by 15–60% by the end of the century[12].

In summary, on a global scale, approximately 25% of current wine regions might benefit from a temperature increase capped at 2 °C, and around 26% are likely to maintain their current suitability with proper management practices. This implies that global warming levels below 2 °C can be deemed a safe threshold for over half of traditional vineyards. Conversely, for temperature increases beyond 2 °C, 70% of existing winemaking regions might face substantial risks of suitability loss. Specifically, 29% might experience too extreme climate conditions, preventing premium wine production, while the future of the remaining 41% will hinge on the effective feasibility of effective adaptation measures. Further investigation in this direction is warranted to assess the environmental and economic impact of these potential strategies.

Adapting to a hotter and drier future
To maintain environmentally sustainable viticulture – that is, the production of wines with marketable quality and yield levels assuring profitable operations – adaptation is mandatory. Growers can adapt through the choice of plant material (rootstocks and varieties) or by modifying training systems and vineyard management practices. Adaptation to warmer temperatures and increased drought should be considered separately (Fig. 2). However, Mediterranean summer conditions with combined stresses, such as extreme temperatures, high radiation levels, strong winds, and long periods of water deficit combined with mineral stresses, are more likely to occur in the future, with non-additive and more deleterious effects than each stress taken separately[54,55].

Increased temperatures
Wine quality is very sensitive to temperature during grape ripening[9,56]. When temperatures are too low, wines tend to exhibit a green and acidic profile. Conversely, when temperatures are too high, wines possess high alcohol and low acidity levels, featuring cooked fruit aromas rather than fresh fruit aromas[57]. By choosing grape varieties in relation to local climate (for example early-ripening varieties in cool climates and late-ripening varieties in warm climates), ripening under ideal temperatures can be achieved under a wide range of climate conditions[3]. As a result, under current climate conditions, optimal harvests take place in September to early October in the Northern Hemisphere (March or early April in the Southern Hemisphere) in most renowned wine regions, when temperatures are neither too low nor too high.

Phenology is considered one of the most robust biological indicators of ongoing climate change[58], and for grapevine many long-term records of major phenological stages exist (for example records

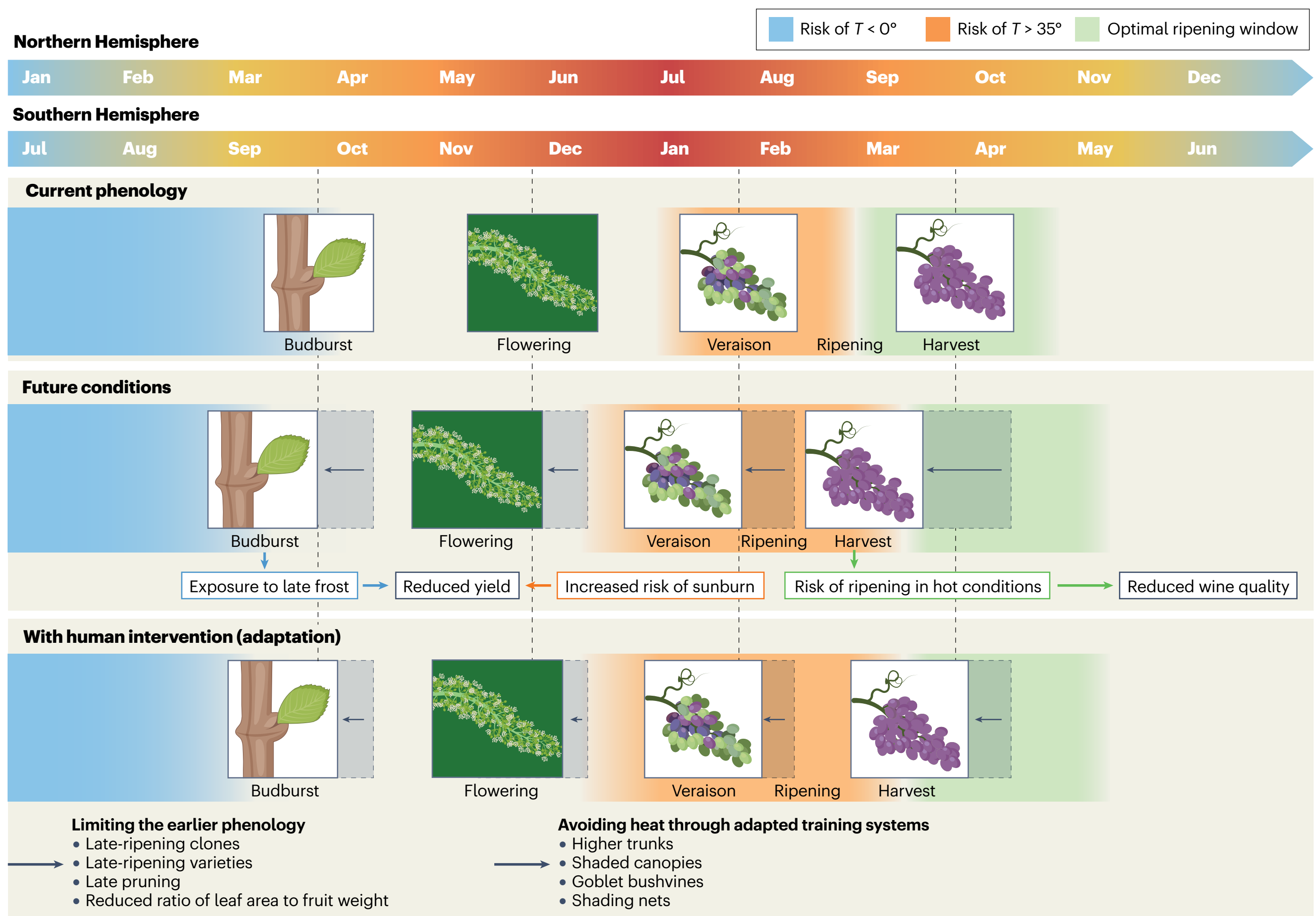


Fig. 2 | Expected changes in phenology, yield and wine quality in response to increased temperatures and potential adaptations. The timing of phenology is key in the production of high-quality wines. When the end of the ripening period takes place in September (March in the Southern Hemisphere), temperatures are high enough to ensure full ripeness of the grapes, but generally without excessive heat[3]. Increased temperatures under climate change advance the end of the ripening period to July or August (January or February in the Southern Hemisphere) when excessive heat can impair grape quality potential and threaten yields. Adaptive measures aim at retarding the ripening period to later in the season when temperatures are cooler. These include changes in plant material, training systems and management practices. Also, different means to obtain a cooler microclimate in the bunch zones are effective adaptations to a warmer climate. Hence, grape growers should avoid as much as possible the advancement of the ripening period.

of budbreak, flowering and veraison — the colour change of grape berries that marks the onset of ripening). These records almost universally indicate advanced phenology for the grapevine due to higher temperatures, in particular since the late 1980s[7,8,19,59]. For example, both budbreak and flowering advanced by 15 days in Alsace (France) during the period 1965 to 2003, meaning that the length of the period between budbreak and flowering remained the same[7]. Because the stages have shifted in concert, this advance in phenology could possibly shift flowering to a cooler period of the year when less favourable conditions could reduce yields[60] (Fig. 2). In some regions, dormancy release of latent buds might be impaired when autumn and winter temperatures increase, which can delay budbreak[8]. Delayed budbreak, as a result of climate change, is, however, an exception, and the general trend remains advanced budbreak. Harvest date is not a true phenological stage as it is influenced by human perception of desired ripeness level for the intended wine style and might be influenced by disease pressure. Nevertheless, harvest date is still largely linked to climate, and long-term harvest records have been used for climate reconstructions since the fourteenth century[61,62]. In most winegrowing regions around the globe, grape harvests have advanced by 2–3 weeks over the past 40 years[19,63,64] (Fig. 2). Earlier phenology means that ripening will occur in a warmer period of the year. Because of this shift in phenology, every 1 °C increase in temperature during the growing season results approximately in 2 °C warmer temperatures during grape ripening[65].

As a result, wine quality and typicity are changing (Fig. 3). Alcohol levels and wine pH are increasing[6,19], while acidity is decreasing[66,67] (Fig. 3). This decreased acidity induces lower microbiological stability, which can lead to off-flavours like those produced by the wild yeast *Brettanomyces bruxellensis*[68] (Fig. 3). Phenolic compounds, such as tannins, which give the structure to red wine, and anthocyanins, which are responsible for its colour, are reduced in grapes under high temperatures[69–71]. Moreover, sugar and anthocyanin accumulation in grape berries are decoupled under high temperatures, making harvest decisions increasingly difficult[72].

The amount of humidity that the air is able to contain increases with temperature[73]. Hence, vapour pressure deficit and reference evapotranspiration (ET_0) increase with temperature. As a result, even if precipitation levels remain unchanged, plant water use will increase with higher temperature, increasing the risk of drought[74].

Excessive temperatures can negatively affect yield, because of increased competition for carbohydrates during bunch initiation in primary buds[75], a decrease in the number of flowers per bunch[76], reduced fecundation[77], reduced berry size due to limited carbohydrate resources[75,78], or increased drought[79]. However, reduced yields have not been observed for a temperature increase of 2 °C above current temperatures in South Australia[80].

Plant material choices are a key lever for adapting to increasing temperatures[81], and the thousands of existing *Vitis vinifera* varieties display great differences in the timing of their phenology[82–84]. Varieties and clones with a long phenological cycle delay the ripening period to a later period in the season when temperatures are cooler. As a first step, later-ripening clones can be chosen within the existing varieties that are grown in a particular region[19,85]. Although the differences in phenology might not be as great, making use of clonal diversity alleviates the need to change varieties. If more phenological diversity is needed, the proportion of late-ripening varieties can be increased. Genetic diversity from niche environments (in particular from the Mediterranean islands, such as Baleares, Cyprus, Cyclades) should be explored to access extremely late-ripening varieties[86]. Later-ripening varieties can also be created through breeding, although simulation using genetic models indicates that even the most ideal late-ripening variety might not ripen late enough in extreme climate change scenarios[87]. The temperature requirements for major phenological stages across varieties are available in the literature[83,84], and these can serve as guidelines for selecting varieties adapted to future climate conditions[88].

Exposure to direct sunlight increases bunch temperature substantially. As a result, the effect of radiation and temperature are not easy to separate[89]. A potential avenue to adapt to higher temperatures is adopting resilient training systems that prevent grapes from excessive exposure to direct sunlight. These training systems mitigate the heating of bunches to temperatures far above ambient air temperatures, which reduces the risk of sunburn. Examples of such training systems are the traditional goblet bushvine[20,90] or more sprawling canopies that shade fruit[91]. Establishing vines with higher trunks increases minimum temperatures, while reducing maximum temperatures in the fruit zone[92]. Elevating the fruit zone has the effect of reducing the exposure of grapes to both spring frost and heatwaves. Minimal pruning delays maturity but increases water use[93]. Applications of chemically inert mineral particles such as zeolite and kaolin can substantially reduce leaf temperature[94].

Some annual vineyard management practices also have the potential to delay maturity[95], such as establishing a reduced ratio of leaf area to fruit weight[96,97], or late pruning[98]. Shading nets reduce temperature in the canopy and fruit zone but substantially increase production cost[99]. Simply choosing to harvest earlier (for example by reducing the time from the onset of ripening to harvest) can avoid excessive sugar and alcohol in the resulting wine and can reduce cooked fruit aromas[100]. Finally, when possible, vineyards can be moved to higher altitudes where temperatures are cooler[34]. However, this option might have important environmental impacts[10], as we discuss in the section on the impact of viticultural expansion.

Radiation

The quantity and quality of solar radiation influence the morphological development of the grapevine, its physiology, and the production of metabolites that play a key role in wine quality. Managing sunlight interception by leaves, buds, flowers and grapes through planting density, row height and canopy management is crucial to grapevine production[101]. The intensity of photosynthetic activity depends on both temperature and sunlight[102], and the photosynthesis saturation threshold for light increases with air temperature (optimum between 25 and 30 °C)[103]. Like all plants, grapevine biomass production increases with light availability[104], except in hot and dry conditions, which can reduce photosynthesis despite non-limiting light conditions[105]. Solar radiation contributes to grape yield as it has a key role in fruitfulness[106]. It also triggers secondary metabolism and favours the production

Fig. 3 | Wine quality impairment under climate change. Climate change (in particular, increased temperatures) might impair wine quality. Major effects of increased temperatures and drought include: a modification of the aroma profile, with more overripe and cooked fruit aromas replacing fresh fruit aromas; excessive alcohol levels; increased pH, resulting in wines with less perceived freshness and increased risk of microbiological spoilage. ABV, alcohol by volume. Credit: right inset, bhofack2/Getty images; left inset, LauriPatterson/Getty images.

of polyphenols (tannins, anthocyanins)[107] and many aromatic compounds that contribute to wine quality[108]. The role of ultraviolet light needs particular attention, as high-elevation viticulture is developing with climate change. Ultraviolet light decreases photosynthetic activity[109], increases polyphenols in fruit and can potentially decrease the incidence of some major grapevine diseases[110], such as grey mould or powdery mildew[111].

The projected change in incoming solar radiation over wine-producing areas of the world is heterogeneous. By the end of the twenty-first century, solar radiation in Europe and northeastern America might experience a rise of 5–12%[112,113], specifically during summer[114], whereas little or uncertain change is projected in other major wine-producing regions. In hot winegrowing regions, grape ripening speed and sunburn risks are tempered through training systems that limit grape exposure to sun (for example bushvines, sprawling canopy, pergolas)[20]. Row orientation[115], shading nets[116] or adjustable above-canopy solar panels[79] are additional strategies to cope with risks related to excessive sunshine (drought, excessive heat, sunburn).

Drought

Agricultural droughts – defined as periods of abnormal soil moisture deficit, due to shortage of precipitation and excess evapotranspiration, that affect crop production – are already increasing in a number of regions around the world, partly owing to human-induced climate change[117]. In the future, this observed trend will continue, and soil moisture will strongly decrease in various wine regions (Fig. 4). Globally, agricultural droughts might occur 2.4 or 4.1 times more frequently for a 2 °C or 4 °C global warming level, respectively[117]. Europe and most notably the Mediterranean region might be strongly affected by such an increase (Fig. 4c), given that the frequency and intensity of drought have already substantially increased since the mid-twentieth century in the Mediterranean region[117].

Water fluxes through the soil–plant–atmosphere continuum are regulated by leaf stomata[118]. Under drought, plants activate stomatal closure to prevent damage from excessive water losses (Fig. 5). Because CO_2 enters the leaf mesophyll through these stomata, water deficit also reduces photosynthesis, leading to a reduction in crop productivity[119,120]. The mechanisms triggering stomatal closure are complex and involve hydraulic[121] and hormonal signalling[122], resulting in important differences in drought resistance across grapevine varieties[123,124] and rootstocks[125]. Water deficit reduces shoot growth more quickly than it reduces transpiration, in particular for secondary stems[126]. As a result, leaf area is reduced under drought, which further reduces water losses through transpiration, but also reduces plant productivity[127].

Water deficit negatively affects all yield components. Under drought, bunch initiation in latent buds is impaired, resulting in a lower number of bunches per shoot[128]. Limited availability of carbohydrates in dry conditions further reduces fruit set, limiting the number of berries per bunch[129]. Finally, berry weight is lower under drought[130], in particular when occurring before veraison[131], and more severe pre-veraison water deficits can reduce yield in the following season[132]. Owing to a reduced carbohydrate availability, effects on yield losses are cumulative after multiple dry years[133].

The composition of grapes is also affected by water deficit. Because photosynthesis is reduced under severe drought, the sugar import in berries is impaired, resulting in lower sugar content (when expressed in mg per berry). Berry growth is, however, also severely restricted, so sugar concentration (expressed as $g l^{-1}$ sugar in grape juice) is not necessarily lower in water deficit conditions[134,135]. Compared with well-watered vines, berries actually ripen faster under mild water deficits, whereas ripening slows down under severe water deficit[136]. Water deficit reduces berry malic acid content, resulting in lower total acidity and higher pH[137]. Berries of red grapevine varieties accumulate more anthocyanins under water deficit, which improves red wine quality[138–140]. Water deficit also has positive impacts on most aroma compounds in grapes and red wines[141,142]. Hence, in general, red grape and wine quality is improved when vines are grown under water deficit, except when severe[137]. The relationship with water deficit is less straightforward for white grapes and wines[143], because more polyphenols in white grapes do not necessarily translate into improved quality[144].

Adaptation methods to mitigate drought damage are economically sustainable and possible with annual rainfall as low as 350 mm yr^{-1} (ref. 137). The choice of drought-resistant plant material is a major means for adaptation (Fig. 5). Typical Mediterranean varieties such as Grenache, Carignan and Cinsault produce good yields and high-quality wines in dry conditions with rainfall as low as 350 mm yr^{-1} without supplementary irrigation[145,146]. The mechanisms of varietal differences in drought resistance involve the complex interaction between many traits, which include lower maximum transpiration and stomatal conductance, and earlier stomatal closure[124,146]. Water-use efficiency also varies among clones at the intravarietal level[147]. Cultivated vines are generally grafted on rootstocks, and these display variability in drought resistance resulting from differences in their ability to explore the available soil volume (the plant's vigour) together with differences in their ability to regulate transpiration of the variety grafted on top of the rootstock[148,149]. The training system is another key driver of drought resistance in grapevines (Fig. 5). For example, Mediterranean goblet bushvines are highly resilient to drought because of their reduced ratio of canopy surface area to vineyard surface area[90,150]. Bushvines grow near the ground where friction limits wind speed, reducing plant transpiration. Reduced planting density accomplishes the same reduction in the ratio of canopy to vineyard surface area, limiting light interception and transpiration on a per hectare basis. Thus, decreasing the number of vines per hectare, by increasing the distance between the rows, limits seasonal water consumption[19]. Applications of chemically inert mineral particles such as zeolite and kaolin increase midday leaf water potential, water-use efficiency and yield[94,151]. Short- and long-term adaptations to increased drought are extensively reviewed[152].

The vine is a deep-rooting plant species, which is one of the drivers of its drought tolerance, because soil water holding capacity increases with rooting depth[153]. Before establishing the vineyard, deep soil preparation by means of a ripper favours deep rooting and increases plant available water reservoir[154,155] (Fig. 5).

Irrigation is another option to manage drought in vineyards. It promotes higher yields in dry conditions but also consumes limited freshwater resources[156]. Vines were traditionally dry-farmed in the Mediterranean basin but are usually irrigated in emerging winegrowing regions. In some of these regions (Mendoza, Argentina; Murray River Basin, Australia; Central Valley, California, USA), rainfall is at or below 300 mm yr^{-1}, and vines either cannot be grown, or yields would be prohibitively low, without supplementary irrigation[157]. To achieve higher yields, irrigation is now expanding in countries where vines used to be dry-farmed, like Spain. This growing use of irrigation is increasing competition for the limited freshwater resources in these countries[158,159]. Drip irrigation reduces the amount of irrigation water applied[160] but increases the risk of soil salinization[161].

Increased CO_2

In the future, atmospheric CO_2 concentrations might reach 600 ppm or over 1,000 ppm by the end of the twenty-first century, depending on the emission scenario[117,162]. Generally, elevated CO_2 positively affects photosynthesis and enhances plant growth in C3 plants, owing to the CO_2 fertilization effect[163]. However, some negative effects have also been reported on plant mineral status[164] and in the control of cellular oxidation status and associated regulatory pathways to stress responses. Together, these effects could underlie acclimation processes[165].

The few pluriannual enriched CO_2 experiments (free-air CO_2 enrichment, known as FACE, and open-top chamber experiments) in the field have shown a consistent increase in CO_2 assimilation, biomass accumulation at the vegetative and reproductive levels, water-use efficiency at the leaf level, and advanced phenology[166–168]. The effects on stomatal conductance and transpiration were inconsistent and depended on variety and other climate parameters such as evaporative demand and the tested CO_2 concentration. Berry sugar, organic acids and secondary metabolites such as polyphenols and aromas were only marginally affected by increased CO_2 concentration, and the effect was not consistent across years[167,169].

Nevertheless, it is now clear that at the global level the positive effects of CO_2 on assimilation and biomass production are already offset by limiting abiotic factors such as increased vapour pressure deficit, drought and temperature[170–172]. When high temperatures (+2 °C) were combined with high CO_2 (650 ppm), synergetic effects on carbon assimilation were observed, but an antagonist effect on stomatal conductance and transpiration, resulting in temperature neutralizing the positive effect of CO_2 on water-use efficiency[166]. Under high-temperature, high-CO_2 climate change conditions (700 ppm [CO_2] and temperatures +4 °C) applied in a greenhouse during a single growth cycle, a decrease of anthocyanin to sugar ratio was observed[109,173], similar to ratios observed under elevated temperature only, suggesting that the effects of elevated temperature alone predominate.

Extreme events

Global warming is already modifying the occurrence of some extreme events, and this trend is likely to worsen during the twenty-first century regardless of the emission scenario considered. Summer heatwaves have become more frequent and are stronger in amplitude[117]. For a scenario of 4 °C global warming, heatwaves that occurred once every decade in the pre-industrial era are projected to occur almost every year, exhibiting a 5 °C increase in amplitude as compared with heatwaves from the preindustrial era[117].

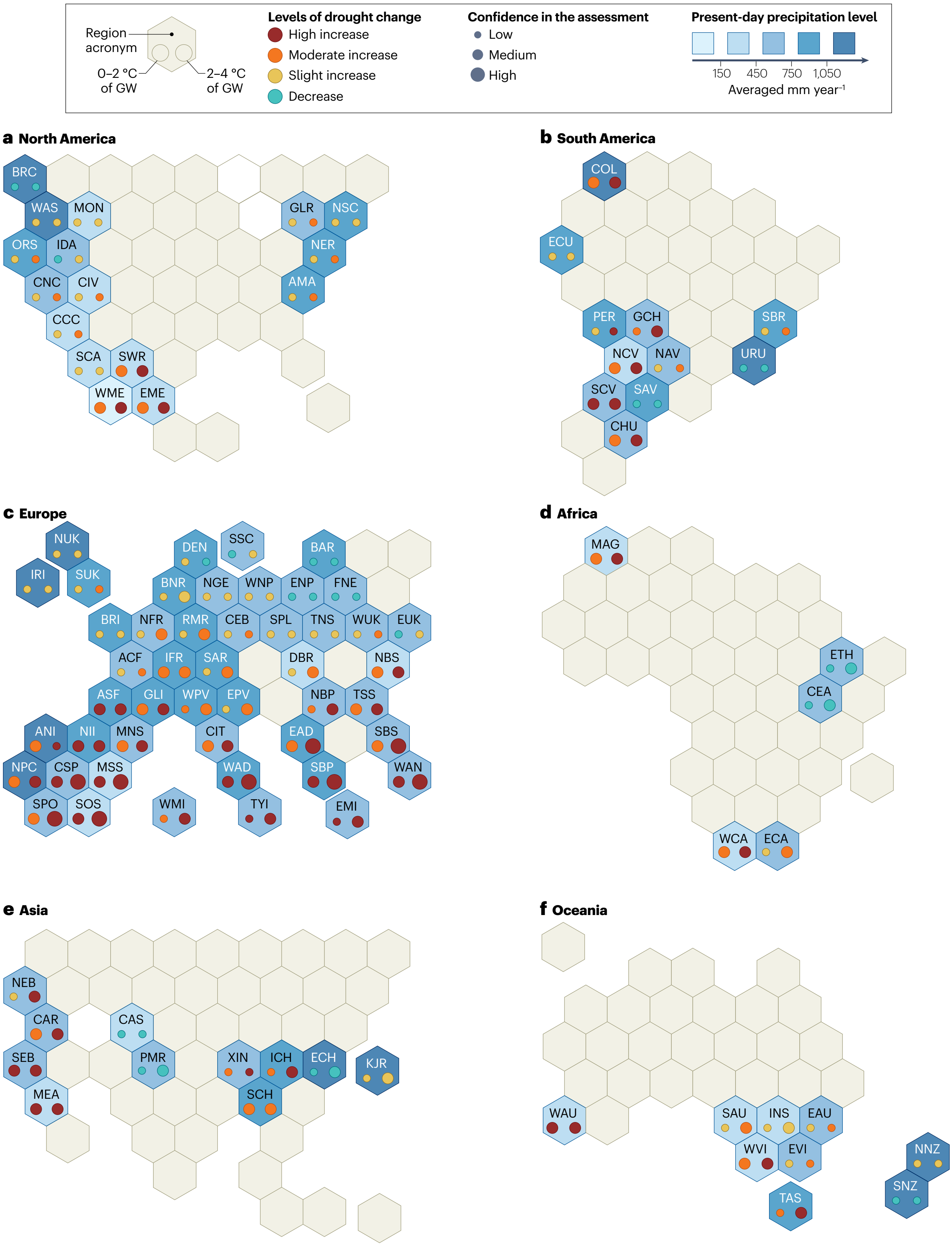
Temperatures above 35 °C have a range of developmental, physiological and biochemical impacts on grapevines that depend on interactions with other climate variables (for example drought and wind) and on the timing of their occurrence relative to the vine's growth cycle[174]. Extremely high temperatures (above 40–45 °C) can limit photosynthesis owing to damage to photosystem II and cause irreversible burning of leaves and berries[175], with severe negative impacts on fruit yield. Yield losses up to 30–45% have been reported due to heatwaves[175,176]. However, these data are rare, and it can be hypothesized that yield losses could be even more severe if heatwaves occurred during or just after flowering, causing flower abortion and a reduction of bunch biomass[78,177], and/or in combination with extreme drought events[174,178]. In addition to yield losses, heat stress negatively affects ripening and berry composition. For example, heatwaves during the green stages of berry development delay the onset of ripening[179,180]. Exposure to extreme heat events during ripening can affect sugar accumulation, organic acid and amino acid metabolism, as well as secondary metabolites that have a strong impact on berry composition and wine quality, such as polyphenols and aromas[108,180,181]. Shading the vines with nets or photovoltaic panels can be efficient options to mitigate the effects of heatwaves. Row orientation and training systems allowing more shade on canopies and clusters are also long-term adaptation means to lower the detrimental effects of extreme temperatures[178].

The combined effects of more frequent drought and heatwaves increase the likelihood of wildfires[182]. Areas planted with vineyards can buffer the progress of wildfires[183] and might serve as natural firebreaks, because of biomass discontinuity and limited burning capacity[184]. Nevertheless, vines subjected to wildfires can be damaged to various degrees by flame, heat and smoke, in particular under warm and dry climates. Vines heavily affected by heat present reduced growth, starch concentrations in canes and buds, and fertility during the following season, with recovery taking up to 2 years[185]. When wines are produced with berries exposed to wildfire smoke during ripening, smoke taint is a major concern depreciating wine quality[186]. It provokes unpleasant 'smoky' and 'ashy' aromas and flavours caused by volatile phenols produced during the combustion of plant biomass but also by endogenous berry metabolic pathways through the shikimic acid and phenylpropanoid pathways[187]. Although volatile phenols decrease quickly following grape exposure to smoke[188], unripened berries can also induce smoky aromas in wines. The accumulation of metabolites of the aforementioned glycosidic and shikimic pathways can be further transformed into undesirable compounds. Keeping vineyard surroundings free from bushy vegetation and vineyard soils free from grasses could mitigate wildfire damages in vineyards[189].

Extreme precipitation events are already occurring more frequently in many regions, and there is a high confidence that this trend will continue[117]. It is predicted that at the global scale the frequency of extreme precipitation events will increase by 2.7 times on average, with about a 30% increase in volume per event for a 4 °C global warming scenario[117], which might strongly increase the risk of flooding events. For a 2 °C global warming scenario, the frequency of heavy rain events is predicted to increase by 1.7 times, with a 14% increase in volume per event.

Flooding can affect both vineyards and buildings associated with winemaking, with short- and long-term consequences, which have subsequent major direct and indirect economic impacts on the production[190]. Flood damage modelling efforts have been aimed at evaluating the risks and the potential economic consequences of increasing flood frequency, mainly for compensation and insurance purposes[190,191]. In the vineyard, impacts are threefold: the soil might be affected with erosion or soil displacement, the vines can be uprooted and the canopy partly or totally damaged, and finally the crop can be destroyed when flood occurs during the season before harvest[190]. To mitigate flood damage to the vineyard, under-vine vegetation can be grown to improve infiltration of rainwater and limit erosion in case of heavy rain events. Competition for water from the cover crop is generally limited or non-existent, because under-vine vegetation enhances deeper rooting, promoting the vine's roots to access deep water reserves[192]. Equipment and stored wines can be destroyed by flooding if the winery is located in a risky area, which should be avoided as much as possible.

Although projections place high confidence in extreme precipitation increase in the future, the change in hailstorm frequency and intensity remains uncertain. An assessment suggested that hailstorm frequency might increase in Australia and Europe, but decrease in



Region acronym
0–2 °C of GW
2–4 °C of GW
Levels of drought change
High increase
Moderate increase
Slight increase
Decrease
Confidence in the assessment
Low
Medium
High
Present-day precipitation level
150
450
750
1,050
Averaged mm year⁻¹
a North America
BRC
WAS
MON
ORS
IDA
CNC
CIV
CCC
SCA
SWR
WME
EME
GLR
NSC
NER
AMA
b South America
COL
ECU
PER
GCH
SBR
NCV
NAV
URU
SCV
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IRI
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BAR
BNR
NGE
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ENP
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BRI
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ETH
CEA
WCA
ECA
e Asia
NEB
CAR
CAS
SEB
PMR
XIN
ICH
ECH
KJR
MEA
SCH
f Oceania
WAU
SAU
INS
EAU
WVI
EVI
NNZ
SNZ
TAS

Fig. 4 | Drought projections for winegrowing regions under warming of 2 °C and 4 °C. a–f, Projections for agricultural drought (soil moisture deficit) in major current and future winegrowing regions for temperature increases of 2 °C (left dot) and 4 °C (right dot), given the present-day level of precipitation, for North America (panel **a**), South America (panel **b**), Europe (panel **c**), Africa (panel **d**), Asia (panel **e**) and Oceania (panel **f**). Abbreviations of each winegrowing region are listed in Supplementary Table 1. Precipitation data are averaged on the period 1979–1999 from Global Precipitation Climatology Project (GPCP) data[254] and expressed in mm yr^{-1}. The projections data are taken from CMIP6 climate models, gathered in Figure SPM.5 of the 2021 IPCC report[117]. The level of confidence reflects the agreement among models as well as the size of the region concerned. In most regions, water availability will decline, in particular in the Mediterranean basin.

East Asia and North America, while hail severity will increase in most regions[16]. However, hail results from severe convective storms, including complex and fine-scale phenomena, which suffer inaccurate simulations by climate models[16]. Hail can partly or totally destroy the annual vegetation of the vines, as well as the crop, with risks of pest and disease infections and secondary effects over several seasons. The fruit quality might also be impaired[193]. Damage on latent buds can affect the production of the following year[194]. When there is high risk of hail, damage can be prevented by using nets or alternative vine-covering systems[195].

Finally, projections of the risks of future spring frost show large uncertainties. Although the number of frost days is decreasing and the date of the last spring frost is advancing, budbreak dates are also advancing. The relative rates of change of these events in the future are strongly model-dependent, thus prohibiting a robust assessment[14,15,196,197]. Several methods have been developed for frost protection in vineyards, including wind machines, over-vine sprinklers, budbreak delaying techniques[198] and the increase of trunk height[92].

Climate change implies that vineyards are increasingly subjected to constraining climate conditions, such as elevated temperature and heatwaves, drought or extreme precipitation, leading for example to increased risks of floods and wildfires. These hazards can alter the quantity and the quality of harvested grapes as well as long-term vineyard sustainability. Adaptation strategies implemented by growers, either annually, such as pruning date or cover-crop management, or over the long-term, such as varietal choice, training systems and plantation sites, might substantially reduce the vulnerability of vineyards.

Changing impacts of pests and diseases

Winegrowers are challenged by a multitude of pathogens and insects (hereafter termed bioaggressors), causing major yield and quality losses which sometimes limit economically viable wine production. The current control of vineyard bioaggressors is mainly based on pesticide applications, leading to soil and water pollution[199], affecting global health[200], and leading to substantial global financial losses[201]. The impact of bioaggressors is strongly affected by climate, and climate change is modifying the spatial distribution, frequency and intensity of bioaggressors[202–204].

These changes may have negative, positive or neutral effects for viticulture (Fig. 6). Negative effects include more favourable conditions for the development of pests[201] and diseases[202], immigration of pathogen vector[203], increasing the speed of growth, and/or increased plant susceptibility[204]. Positive effects include conditions becoming unfavourable for the pathogen, more adapted conditions for a bioaggressor's natural enemies, improvement in the plant's defences, and/or reduction in the plant's susceptibility period[205–209]. All these interactions might be affected in parallel and to a greater or lesser degree, making it very difficult to determine the direct impact of climate change on bioaggressors.

Climate change might favour the expansion of invasive species in new territories (Fig. 6). For example, the spotted wing drosophila (*Drosophila suzukii*, native to Southeast Asia), which damages various fruit crops including grapes, has been spreading in Europe and the United States since the early 2000s. Even if pest immigration is also related to increasing globalization, climate change affects the survival and continued spread of this species, owing to milder winters and improved conditions for development during summer[210].

Studies of the consequences of climate change on grapevine insects are mostly focused on *Lobesia botrana*, a moth from the Tortricidae family, which inflicts damage on buds, flowers and berries worldwide. Its lifecycle traits, in particular its reproductive cycle, are mostly driven by temperature conditions[211]. Hence, warming is changing its phenology with earlier emergence[212] and increased voltinism[213] (number of generations per year; Fig. 6). Yet an increase in the number of generations does not necessarily produce additional damage, as higher temperatures lead to an earlier harvest[214,215]. In hot production areas (southern California, southern Spain, Syria, Lebanon, Israel and Palestine), where summer temperature approaches the upper thermal limit of this species, a decrease in *L. botrana* abundance is projected, whereas an increase is simulated during the twenty-first century in northern California and most of Europe[216,217].

Fungus or fungus-like related diseases do not only depend on temperature, but are highly sensitive to humidity and precipitation changes. Downy and powdery mildews are considered the most important fungal threat for many wine-producing regions worldwide with a diversity of climate conditions[218]. These two diseases are caused by polycyclic pathogens whose development is strongly dependent on the weather conditions of the growing season. *Plasmopara viticola*, causing downy mildew, requires rainfall and leaf wetness to contaminate grapevine at every stage of its development[219]. Owing to uncertainties in precipitation changes in many regions at mid-latitudes[117], projected changes in downy mildew risks yield contradictory results. In northeast France, less favourable conditions are expected owing to decreases in the duration and occurrence of leaf wetness and to temperatures exceeding the optimum for infection[220]. In contrast, in northern Italy[221] and in many European wine regions[222] the disease severity is expected to slightly increase with rising temperature. Similar uncertainties exist for *Erysiphe necator*, the causal agent of powdery mildew[214,223,224].

Climate change might affect other major grapevine diseases such as grape grey mould, a ubiquitous disease worldwide[218], caused by *Botrytis cinerea*, or grapevine trunk diseases (a syndrome causing grapevine decay and caused by a large diversity of fungal pathogens[225]). As grey mould epidemics are strongly related to humidity conditions[226], one could expect reduced grey mould where drier conditions during grape ripening period are expected (Fig. 6). However, investigations regarding these pathologies are few, rendering projections of their possible evolution during the next decades uncertain.

In conclusion, while climate optimum ranges are identified for development rate, spreading and virulence of many grapevine bioaggressors[219,227–229], projection of climate change impacts on grapevine phytopathology are challenging because of the existence

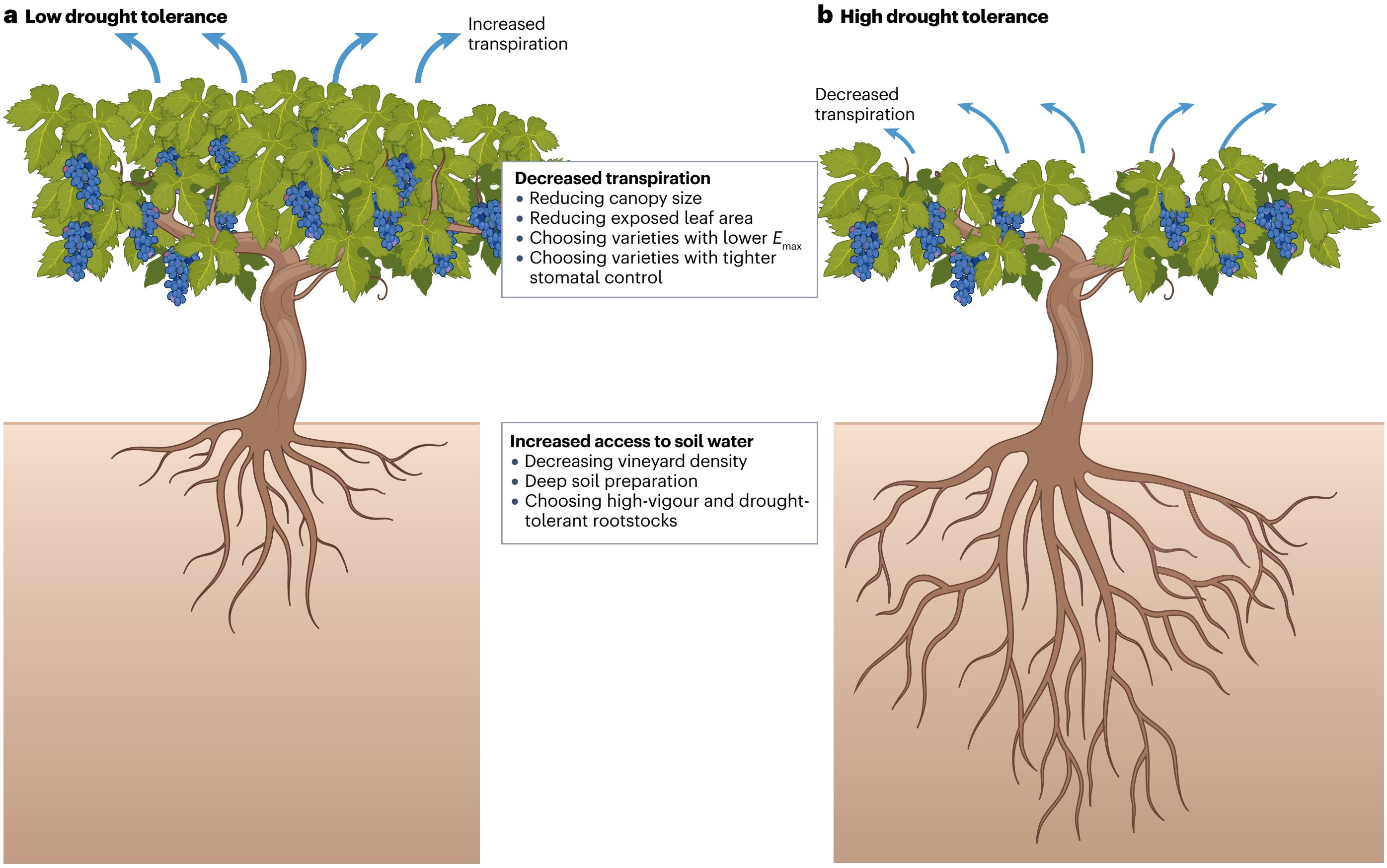

Fig. 5 | Drought-tolerance adaptation mechanisms in vines. Adaptation can be achieved through either limiting transpiration or increasing access to soil water. Limiting transpiration can be achieved by reducing canopy size and/or choosing varieties with more conservative stomatal control. Increasing access to soil water can be achieved by decreasing density, choosing high-vigour drought-tolerant rootstocks and/or establishing vineyards in a manner that promotes deeper rooting. Successfully adapting vineyards to drought is likely to require combining many of these adaptation mechanisms. E_{max} denotes maximal transpiration. Adapted from ref. 255 under a Creative Commons licence CC BY 4.0.

of complex interactions, including the genetic evolution of bioaggressors (leading to adaptation to new climate conditions), microbial ecology at plot and plant levels[230], and pest–plant–parasites tritrophic interactions[231,232].

The impact of viticultural expansion

As detailed above, climate change threatens long-established viticultural regions throughout the world, and predicting future threats to these regions has garnered a lot of attention. What is less studied is the potential impact of viticultural expansion into new regions. Changes in climate are predicted to make large areas previously considered unsuitable or undesirable for viticulture into desirable regions[10,13,37]. Most of these newly suitable regions are predicted to be at higher latitudes and/or altitudes. For example, suitable land area increases ranging from 80% to more than 200% (dependent on the degree of warming) are predicted for the northerly regions of Europe and North America[10]. In addition, the expansion of newly suitable viticultural areas in Europe is predicted to greatly outpace losses, resulting in a net increase of as much as 40% by the end of the century[13]. Regional studies have made similar predictions. For example, vineyard area in the United Kingdom has expanded approximately 400% between 2004 and 2021, and studies predict emerging viticultural suitability across large portions of the country[233].

Viticultural expansion requires either the conversion of existing agricultural land and/or the conversion of wild habitats. Thus, viticultural expansion will have major impacts on land use and natural resources. Even within established wine regions, changing suitability could potentially threaten wild lands. As temperatures increase, higher elevations might become increasingly suitable for viticulture, but this upslope expansion could encroach on wild habitats in mountain regions[234,235].

Unfortunately, studies that detail changes in land use resulting from viticultural expansion are scarce. One such study, examining expansion and changes in land use in the Prosecco region of Italy, demonstrated that impacts on wild lands can be important. During a 5-year period from 2007 to 2012, conversion of existing cropland accounted for approximately 65% of the new expansion[236], while the remaining 35% was planted on converted grass and woodlands. We would expect the impact of viticultural expansion on wild habitats to be highly variable across different regions, but clearly, this expansion poses a real threat. Governmental authorities would be wise to monitor these conversions in order to quantify the extent to which wild lands are being impacted.

Making accurate predictions regarding viticultural expansion is difficult because it is dependent on many factors. The suitability predictions outlined in this Review are all based on environmental constraints, but changes in vineyard area are dependent on additional factors, most notably market forces. In the early 2000s, a period of rapid growth of viticulture in South Africa, warnings were made that increasing local suitability could drive viticultural expansion into surrounding wild lands[237]. In reality, there has been a reduction in vineyard area in the region since the 2000s, because of decreased market demand[238]. Although the warnings were correct to point out the threats posed by viticultural expansion, this expansion was never realized because of other constraints.

Throughout history, vineyard locations have changed continuously, at the local, national and international levels. Geopolitical issues, social demands, market forces, issues around transportation, natural crises such as disease outbreaks, and changes in environmental conditions have been the main drivers of change[239–243]. There are numerous historical examples. Archaeological excavations show that viticulture existed in Great Britain during the Roman period[244] when climate conditions in the Northern Hemisphere were almost as warm as the 1960–1990 reference period[245,246]. It disappeared after the sixteenth century because of increased imports from abroad[247] and probably also because of the colder conditions of the Little Ice Age, which lasted about 500 years from the fourteenth to mid-nineteenth century, with average temperatures 0.4–0.7 °C lower than for a reference period defined as 1961–1990 in the Northern Hemisphere and Europe[246,248].

In Europe, the largest vineyard expansion occurred from the mid-eighteenth to the mid-nineteenth centuries, despite relatively cool conditions. In France, vineyards increased by 43% between 1808 and 1870 ref. 249, followed by a sudden collapse because of the phylloxera outbreak. This expansion was mainly linked to the large social demand due to the industrial development around major cities. In 1827, a detailed statistical analysis about vineyard location in France showed that only the northwest of France had no vineyards at this time[250], presumably because of unsuitable climate conditions. In many of the emerging wine regions, viticulture development was first linked to colonial expansion, with economic motivations being important drivers of vineyard development[247,251].

The extent to which viticulture will expand into new regions remains an open question and depends to a large extent on market forces. This potential expansion holds economic opportunities but also risks the loss of wild lands and increased consumption of freshwater

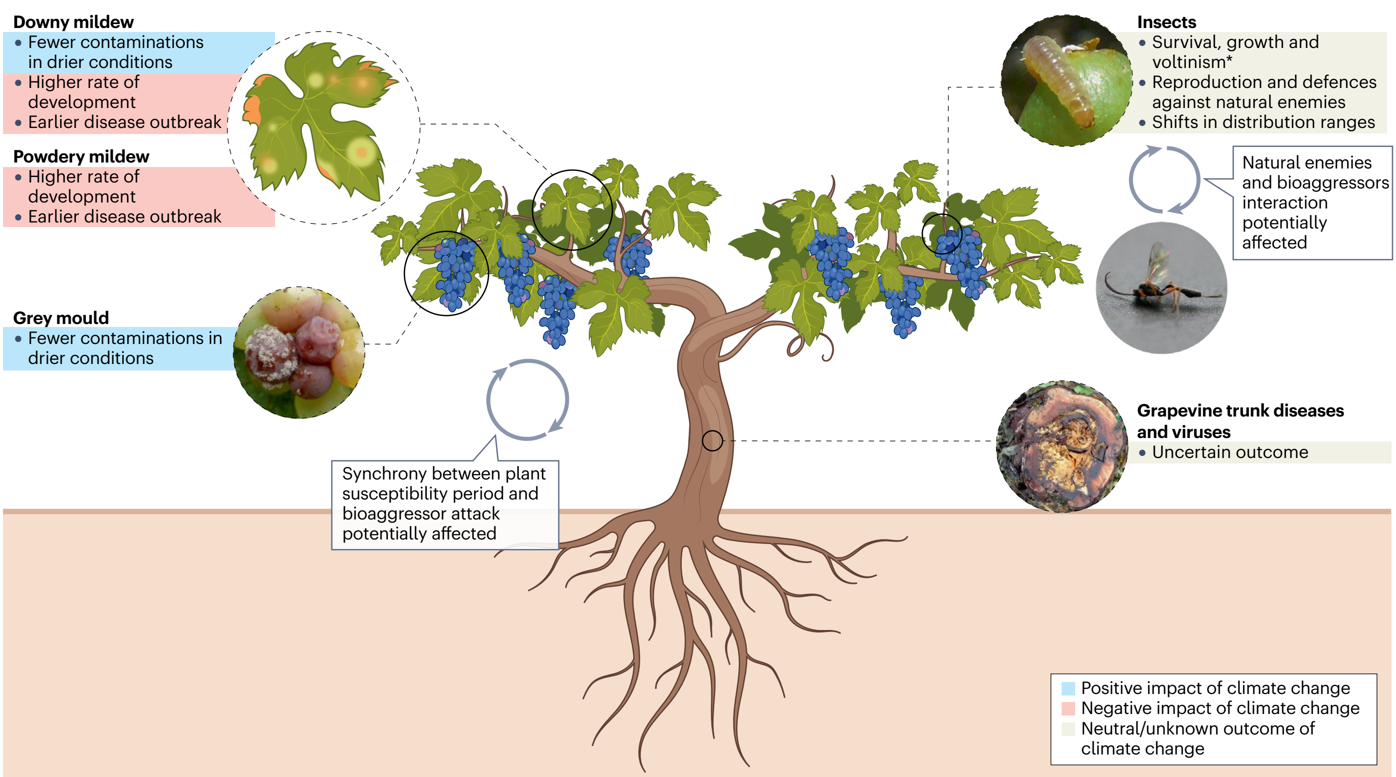

Fig. 6 | Potential positive and negative impacts of climate change on major pests and diseases in vines. For each bioaggressor, coloured backgrounds to each statement identify the positive or negative expected consequences of climate change as reported or hypothesized in the scientific literature. In subtropical to mid-latitude wine regions where drier conditions during the growing season are expected, downy mildew pressure should decrease as a result of reduced contamination. In contrast, powdery mildew pressure should increase owing to earlier and faster development of the pathogen. Insects, which either transport virus and phytoplasma or provide direct damage to grapevine, will show various changes in their life traits that might either limit or increase their harmfulness. Phytopathology depends not only on the bioaggressors' biological features but also on plant vulnerability to pests and diseases[232]. Moreover, interactions (depicted by circular arrows) of bioaggressors with their natural enemies or trophic competitors, such as parasitoids, might modify pest and disease issues in the vineyard[256]. As a result, pest-related damages, as well as the outcomes of grey mould, viruses and grapevine trunk diseases in a changing climate, remain highly uncertain. Credit: insets showing grapevine pests and diseases courtesy of Marielle Adrian, Anais Pertuizet, and Fanny Vogelweith.

resources when new vineyards are irrigated. Regions where this expansion is likely to occur should be proactive about mitigating these negative impacts on natural resources.

Summary and future perspectives

This Review outlines the huge challenges that climate change is presenting for viticulture and provides a consensus map on suitability gains and losses that details potential changes to the distribution of winegrowing regions globally. The exact extent of these changes remains unknown and will depend on the magnitude of climate change along with the ability to adapt to these challenges. The primary threats are increased heat and drought, extreme weather events, and unpredictability with regard to changing pest and disease pressure. The regions that are most at risk are those with already hot and dry climates. Without radical adaptation, some of these regions are clearly threatened. Change also brings with it opportunities, as some regions will benefit, and new wine regions will surely emerge. However, these changes are not without consequences either, and expanding viticulture could bring with it impacts on natural resource consumption and wild habitats.

Where possible, these climate challenges need to be met with robust science-based adaptation strategies. Some adaptations to hotter and drier climates are already known and embody simple, sound agronomic principles. For example, heatwave damage can be mitigated through changing canopies to increase the shading of fruit, and vineyard water use can be reduced through decreased planting density and smaller canopies. Given the geographical range across which grapevine is cultivated, it can be argued that it is a highly tolerant crop, but concrete climate thresholds for losses in fruit and wine quality, and the knowledge of how these thresholds vary with variety, rootstock and management practices, are still lacking. The difficulty in predicting hard thresholds for decreased fruit quality and production is probably due to the plasticity of grapevines, which readily adapt to climate challenges even within a single season, and to the adaptations brought about by the winegrowers themselves.

Grapevine varietal diversity is probably the most promising adaptation lever for climate change, and probably the most underused. The limited use of genetic diversity is almost certainly due in part to market forces that have homogenized diversity across most regions[81,252]. Still, there are hundreds to thousands of different varieties and clones waiting to be explored, many of which will have valuable phenotypes for adaptation to climate change. Guiding the use of this diversity is problematic because we do not clearly understand the physiological mechanisms and genetic basis for most traits, making screening varieties laborious and time-consuming. Advancement in the understanding of these mechanisms, and their genetic underpinnings, will speed the identification of varieties adapted to specific climate extremes. This will require identifying and accurately phenotyping key traits across a wide diversity of grapevine genotypes.

As the climate becomes more extreme, some viticultural regions are starting to hit these thresholds. Exceptionally hot and dry vintages across Europe, for example in Spain and Portugal, have driven some rainfed vineyards in the hottest and driest regions to their breaking point, resulting in stunted vines, defoliated canopies and severe yield losses. We need to learn from these events through monitoring programmes that quantitatively follow these extreme climates and their impacts. For example, in many dry-farmed regions, water status monitoring is conspicuously absent, and implementing such monitoring could reveal threatening levels of water stress and allow mitigating actions[137]. As viticulture expands into new regions, impacts on natural ecosystems and biodiversity need to be considered and negative impacts mitigated. This could mean avoiding the conversion of wild lands, designing new vineyards to be dry-farmed wherever possible to eliminate the need for irrigation, and/or emphasizing sustainability and environmental stewardship.

The most important aspect of wine production is the finished product. All adaptations to climate change must preserve the economic sustainability of production through maintaining adequate yields and quality that meet consumer demands[152]. Working with the market and the consumers can be the biggest challenge, and sometimes highly effective adaptation options remain unused because of market constraints (for example new hybrid varieties and genetically modified varieties). Marketing wine by the region of origin and not by the variety is a route to consumer's acceptance of the use of less-known varieties, which might potentially be better adapted to the changing climate[253].

One thing is certain: climate change will drive major changes in global wine production in the near future. Having the flexibility to adapt to these changes will be essential.

Data availability

The suitability assessment compiled in Fig. 1 can be obtained by applying, for each region identified in Supplementary Table 1, the methodology explained in the Supplementary note and in Supplementary Tables 3, 4 and 5, for each specific reference selected in Supplementary Table 2.

The data underlying Fig. 3 are freely available, for the observed precipitations at http://gpcp.umd.edu/ and for drought projections at https://catalogue.ceda.ac.uk/uuid/1b91153925dd474387bb696d59adbd15.

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Author contributions
C.v.L. acted as lead author and designed Fig. 2. G.S. implemented an extensive literature review for Fig. 1, designed that figure and participated in writing. G.S. also wrote the methodology in the Supplementary Data section. D.S. designed Fig. 4 and participated in writing. B.B. and S.Z. designed Fig. 6 and participated in writing. N.O. participated in writing. G.G. designed Fig. 5, participated in writing and edited the manuscript.

Competing interests
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