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Spatial complexity and temporal dynamics in viticulture: A review of climate-driven scales

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ABSTRACT

Viticulture is a complex and dynamic system, where climate is a key environmental component of plant suitability and productivity. From field to farm level, climate also plays a prominent role in ongoing practices, shaping winegrowers' decision making and adaptive management. With a changing climate, the wine sector faces many environmental and socio-economic challenges, to which winegrowers are required to adapt. Given the perennial nature of grape growing, there is a need to develop strategies that deal with both short- and long-term climate changes, while likewise accounting for contextual vulnerability. The content of this article aims to provide an overview of climate-driven scales, outlining the spatial complexity and temporal dynamics in viticulture. In addressing these aspects, this literature review offers a framework of scale and cross-scale interactions for policymakers and stakeholders to use when considering responses to attenuate climate change and to reduce its impacts on grape and wine production. The article concludes by discussing the local and context-dependent nature of viticulture in a changing global climate, by emphasizing that the question of scale is fundamental to assessing expected impacts, understanding uncertainty and framing sustainable policies and responses over space and in time.

1. Introduction

Cultivated and shaped by human uses for many centuries, the grapevine (*Vitis vinifera L.*) has a rich geographical spread, covering more than seventy countries today (OIV, 2018). Given the genetic diversity found in grapevine varieties (This et al., 2006), it can be grown in diverse climates, ranging from Mediterranean (e.g. Mediterranean Basin) to continental (e.g. Hungary), oceanic (e.g. New Zealand), dry subtropical (e.g. Argentina) and humid subtropical conditions (e.g. Uruguay). Over these geographical areas, long-term climate structures influence regional grape growing and winemaking potential (Tonietto and Carbonneau, 2004), while seasonally, affects grape productivity and wine quality (Salinger et al., 2015; Real et al., 2017). Many studies have demonstrated this central role of climate on vine parameters such as perennial biomass, yield and berry composition (Buttrose et al., 1971; Coombe, 1987; Jackson and Lombard, 1993; Jones and Davis, 2000; Van Leeuwen et al., 2004). As wine structure and flavour are much dependent on grape attributes (Cadot et al., 2012; Bindon et al., 2013), any climate changes impact wine quality and volume produced, resulting in considerable effects on the economic viability of the wine sector (Haeger and Storchmann, 2006; Ashenfelter and Storchmann, 2016). For example, world wine production was 8.2% lower in 2017, than compared with 2016, particularly in the European Union following an extreme frost event in April (OIV, 2017). Viticulture is therefore highly sensitive to changing climate conditions, both temporally and spatially (Jones and Webb, 2010).

Although until the year 2000, few studies about climate change and its impacts on viticulture emerged (Dry, 1988; Smart, 1989; Kenny and Harrison, 1992; Bindi et al., 1996), this topic has received much attention in recent years. Across wine growing regions, climate change has essentially resulted in regional warming (Jones et al., 2005; Cook and Wolkovich, 2016), and to some extent, though less spatially coherent and statistically significant, in greater variability in seasonal rainfall (Laget et al., 2008; Ramos et al., 2015). In response to increasing temperatures and declining soil water contents (Webb et al., 2012), grapevine phenology has shifted earlier by several days (Jones and Davis, 2000; Tomasi et al., 2011), while a warmer ripening period has resulted in changes in berry composition, increased alcohol contents and altered wine sensory profiles (Orduna, 2010; Neethling et al., 2012). With climate playing a key role in viticulture, a changing climate raises many questions ranging from regional wine quality and style to issues such as geographical shifts in suitable grapevine varieties and

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production areas over the long term (Schultz and Jones, 2010; Ollat et al., 2016). Vineyards planted over the next decade, and remaining economically productive for many years, are likely to be exposed to unprecedented climate conditions (Mora et al., 2013). Adjusting grape growing and winemaking practices and techniques are therefore an immediate priority to attenuate climate change and to reduce its impacts (Van Leeuwen and Darriet, 2016).

When addressing these issues, one of the key challenges is strategically planning mitigation efforts and adaptation measures across and within different sectors and scales (Tol, 2005). Firstly, they act at different time periods, where for instance the beneficial effects of mitigation efforts may take many years to emerge (Meehl et al., 2012). Secondly, despite the global extent of climate change (IPCC, 2014), the relevant factors and processes that contribute to increasing greenhouse gases or the consequences of a changing climate are local and context-dependent in nature, varying from one location to another (Mimura et al., 2014). Hence, the question of scale is central to understanding the challenges, or even the opportunities, brought by a changing climate (O'Brien et al., 2004). For viticulture, the understanding of scale and cross-scale interactions is specifically important as produced wines are the result of complex interactions between physical, biological and human factors (Van Leeuwen and Seguin, 2006), taking place at different levels and times, known as the components of terroir (OIV, 2010). The content of this article aims to provide an overview of climate-driven scales, outlining the spatial complexity and temporal dynamics in viticulture. In the context of climate change mitigation and adaptation, the article concludes with a discussion of the implications of this literature review on assessing expected impacts, understanding uncertainty and framing sustainable policies and responses in viticulture.

2. Spatial complexity in viticulture

The concept of spatial scale is fundamental to viticulture (Vaudour, 2002). At large scales, it explains wine geography and varietal distribution, while at fine scales, it accentuates the variability that exist from one location to another, enhancing wine identity and diversity (White et al., 2009). Since vine behaviour is much dependent on climate, the spatial description of viticulture closely follows its organizational structure (Asselin et al., 2001; Vaudour et Shaw, 2005), where two aspects are vital. Firstly, climate has a multi-level structure of four spatial scales with distinct features (Geiger et al., 1995): the macroclimate applying to a large geographical area (e.g. horizontal range greater than 200 km); the mesoclimate corresponding to the climate of a region of a variable size, ranging from 1 km to 200 km; the local climate which is the climate of a smaller area; and lastly, the microclimate referring to a very small geographic unit (Fig. 1). The horizontal or vertical boundaries of the four levels vary with the nature of the underlying surface (Geiger et al., 1995). For instance, the local climate has a horizontal distance of 10 km in a flat area, while a characteristic distance of 1 km in a mountain area (Guyot, 1999).

Secondly, the hierarchical organization of climate must be considered, as lower spatial levels (i.e. with a finer spatial resolution) are embedded or nested within higher levels (Ackerly et al., 2010; Quénol and Bonnardot, 2014). The reason for this organization is related to the functioning of the atmosphere, knowing that the same air mass will generate similar weather patterns for an extended territory, and it is certain that at a smaller spatial entity within this territory, common climate features will be present (Geiger et al., 1995; Guyot, 1999). The higher level therefore provides a climatic context that imposes conditions and constraints in a top-down approach towards lower levels (Wu and David, 2002). Still, local terrain effects (e.g. altitude and aspect) lead to large climate variations at smaller scales (Geiger et al., 1995; Quénol, 2014), which means that lower levels also impose climate feedbacks that modify large-scale patterns, by following an upward or bottom-up approach. The individual characteristics of the grapevine are

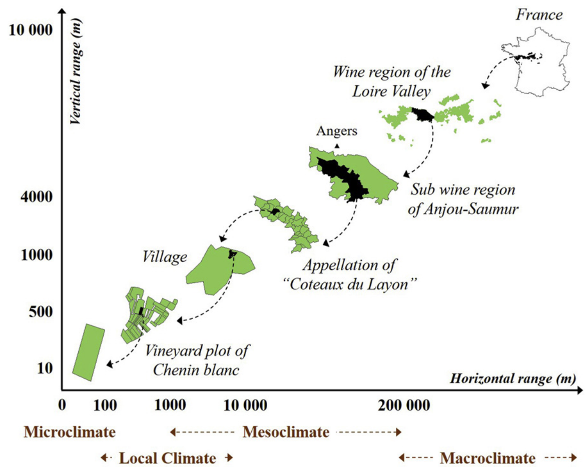

Fig. 1. Example of the schematic representation of the different spatial levels of viticulture for cv. Chenin blanc in the Loire Valley, France, from national to field level.

therefore dependent on these environmental processes, taking place at different spatial levels. As each level has its own attributes, it is important to understand what are the main influencing factors that emerge (Willis and Whittaker, 2002), while also knowing that spatial heterogeneity becomes increasingly important at finer scales (Quénol, 2014).

2.1. Global level

Apart from a few exceptions (e.g. Brazil, India), the main wine producing regions are roughly located between latitudes 30 to 50 degrees, in both hemispheres. This geographical distribution of wine grape varieties is shaped by the spatial variability of large-scale macroclimatic conditions, which are strongly determined by the latitudinal differences in solar energy intercepted at the surface of the earth (Geiger et al., 1995; Ricklefs and Miller, 2005). As the equator receives more incoming radiation during the year, the average annual temperature decreases with latitude, from the equator to the poles (Guyot, 1999). Consequently, it appears that favourable macroclimate conditions for cultivating grapevines are found between annual isotherms of 10 °C to 20 °C (De Blij, 1983; Spellman, 1999). Schultz and Jones (2010) indicated that the geographical extension of viticulture is best represented by growing season isotherms of 12 °C to 22 °C. Regions with seasonal average temperatures below 12 °C are unfavourable due to short growing seasons and low amounts of sunshine hours and accumulated heat (Jones et al., 2012). In these areas, the high frequency and intensity of extreme cold temperatures (e.g. winter or spring frosts) also makes grapevine growing very difficult. Conversely, in regions with mean seasonal temperatures above 22 °C, grapevines are regularly exposed to very warm summers and extreme heat events. And depending on the seasonal rainfall rhythm, they may also be subject to either very arid conditions (e.g. North Africa), or very humid conditions where pest and disease pressures are particularly high (e.g. Thailand). Regarding the distribution of the most recognized cultivars (e.g. Cabernet Sauvignon), Jones (2006) also showed that the production of high quality wines from these varieties is located between isotherms 13 °C and 21 °C. While there are more than 6 000 wine grape varieties known (This et al., 2006; Myles et al., 2011), 13 cover more than one-third of the world's vineyard area and 33 varieties cover 50% (OIV, 2017).

2.2. Regional level

The wine sector is growing every day with emerging wine regions and markets. In response to an increasingly competitive global industry, each region seeks to differentiate itself by promoting wines with a strong identity (Hayward and Lewis, 2008; Easingwood et al., 2010). In order to maintain a premium in the market by ensuring high quality products, the cultivated grape variety and in particular its ripening period must be in relation with the surrounding environment (Jackson and Lombard, 1993). When berry maturation is reached too late, grapes remain unripe, with high acidity, low sugar contents and herbaceous flavours, whereas reached too soon, grapes are rich in sugars, low in acidity, giving place to unbalanced wines that lack in aromatic complexity (Van Leeuwen and Seguin, 2006). Since vine phenology and ripening earliness are measurable (Parker et al., 2013), berry maturation under favourable conditions is usually achieved when varieties are grown at their northern limits in the northern hemisphere, or southern limits in the southern hemisphere. In European wine regions, extended grape growing through several centuries has allowed the emergence of the most adapted varieties in regional climates that are representative of their northern limits (Barbeau et al., 2015). For example, Pinot Noir and Chardonnay are the emblematic varieties of Burgundy wines, Cabernet Sauvignon and Merlot of Bordeaux red wines (France), Sangiovese of Tuscany red wines (Italy) and Riesling of Rheingau white wines (Germany). Conversely, in new world wine regions, one of the main challenges in defining their success and competitiveness has been to identify the most fitted grapevine varieties (Van Leeuwen and Seguin, 2006). Varietal suitability is strongly related to the regional attributes of growing season accumulated heat (Tonietto and Carbonneau, 2004; Jones et al., 2012), i.e. sum of daily temperatures above a threshold where vine development is active. Still, for a given variety, cultivated in different regions but under similar heat sums, climatic properties, such as rainfall regime and thermal conditions during ripening, contribute to the unique traits of produced wines (Shaw, 2012). With this context, several studies have led to the conception of bioclimatic indices, specific to viticulture. By integrating, in one way or another, the temperature factor, there are simple or complex indices (i.e. mono- or multi-factorial), which enables to define a region's ability to produce wine, varietal suitability and vine phenology, possible environmental risks and to some extent, potential wine styles. Today, the application of these indices allows an understanding of the spatial variation in viticultural potentialities and limitations, as e.g., in Australia (Hall and Jones, 2010), Chile (Montes et al., 2012), United States (Jones et al., 2010), New Zealand (Anderson et al., 2012). Fig. 2 illustrate the regional climate differences and their viticultural potentialities encountered over Europe, which are essentially due to latitudinal position and degree of continentality (e.g. rainfall patterns).

2.3. Local level

Within a wine growing region, viticultural potentialities and limitations are described by local terrain features. Indeed, atmospheric boundary layer characteristics are dependent on surface conditions that modify fine-scale environmental conditions (Geiger et al., 1995). Accordingly, each wine region is composed of various local climates depending on its terrain complexity (Fig. 3). Through interactions with the atmosphere and different weather patterns, topographical factors (e.g. elevation, aspect) influence heat and moisture exchange at the earth's surface, shaping topoclimates (Jacquet and Morlat, 1997; Orlandini et al., 2006; Bonnefoy et al., 2012). Besides the topographic context, soil parameters (e.g. texture, depth) and other proximity features (e.g. water masses, forests) also have significant effects on local climate or pedoclimate conditions (Guyot, 1999). The latter refers to soil moisture and temperature, which is a key factor of the earliness of grapevine growth in spring (Morlat and Jacquet, 1993). All the elements of the surrounding landscape generate a strong spatial climate variability, as for example described in the Coteaux du Layon France (Neethling et al., 2014), Saint Emilion France (De Rességuier et al., 2016), Canelones Uruguay (Fourment et al., 2013), Uco Valley Argentina (Grassin et al., 2014), Douro Valley Portugal (Jones and Alves, 2012) and Stellenbosch South Africa (Bonnardot et al., 2012). This spatial heterogeneity in local climates is a critical element in viticulture, making it possible for winegrowers to mitigate the conditions and constraints imposed by the zonal climate (Quénol, 2014). For example, air temperature generally decreases by 1 °C per 150 m increasing elevation, except during thermal inversions (Guyot, 1999). In areas with very warm regional climates, the effects brought by ascending in elevation are beneficial for growing wine grapes, as in the Uco Valley (1000 m–1200 m, Argentina), or the Central Valley of Tarija (1600 m–2150 m, Bolivia). At higher altitudes, vines profit from lower temperatures, allowing slower berry maturation and higher concentrations in organic acidity (Miguel-Tabares et al., 2002). The light intensity is also higher, favouring phenolic compound synthesis in red varieties. Conversely, in cool climate regions, it is worth mentioning the importance of slope orientation and inclination, the latter describing the angle between orientation and incoming sunlight. In high latitude regions of the northern hemisphere (e.g. Burgundy), south facing slopes allow for a higher amount of solar radiation reaching the surface, whereas the steeper slopes of esteemed plots (e.g. Burgundy crus) increases light and heat energy interception (Huggett, 2006; Jackson, 2008). Although steep slopes enlarge erosion risks, they enable cold air to drain away during radiative frost events, a frequent event in high latitude vineyards. Similarly, in warm and dry Mediterranean climates (e.g. Western Cape South Africa), vineyards may benefit significantly from the cooling effect brought by sea breezes (Bonnardot et al., 2005), whereas in Oceanic climates with regular rainfall patterns (e.g. Loire Valley France), soils with low water holding capacities favour grapevine earliness and wine production (Barbeau et al., 1998). Each wine growing region therefore consists of unique environmental contexts, providing winegrowers with a range of local climates and different viticultural potentialities.

2.4. Field level

The grapevine is a perennial crop and requires a few years to reach reproductive maturity, remaining then economically productive for many years (Orlandini et al., 2009). As the lifespan of a plot may correspond to two generations of winegrowers, management decisions prior to planting are very important. At this level, decision making is closely related to winegrowers' production objectives and the physical attributes and constraints of planting sites (Coulon-Leroy et al., 2012). To ensure sustainable productivity, winegrowers strive for appropriate measures in terms of perennial practices in order to optimise seasonal grapevine growth and fruit development. These practices vary considerably, from the choice of plant materiel to decisions involved in vineyard design and layout, each practice affecting microclimate conditions at field levels (Smart, 1988; Matese et al., 2014). For example, row orientation greatly affects light interception and wind velocity and as a result, canopy and fruit temperature (Giacosa et al., 2015; Hunter et al., 2016). For vertically positioned shoots with East-West orientated rows, less direct sunlight is reach in fruits than compared to North-South orientated rows (Hunter et al., 2016). East-West orientated rows also expresses greater thermal variations between exposed and shaded leaves. These alterations in light exposure explains the greater suitability of North-South orientated rows in cool growing areas. Other notable perennial practices are the choice in planting density (Archer and Strauss, 1989, 1990), training system (Reynolds and Vanden Heuvel, 2006) and trunk height, where these practices are to some extent interconnected. For example, planting density is likely to determine the fitted training system, whereas the latter may condition trunk height. Vineyards with higher planting densities generally display improved crop yield and quality (i.e. per ha), which are mainly due to greater root competition (Jackson, 2008). Increased root competition leads to lower vegetative growth and an enhanced microclimate, while also allowing for deeper root penetration and a greater soil volume to be explored. Still, in shallow soils with low water availability, high

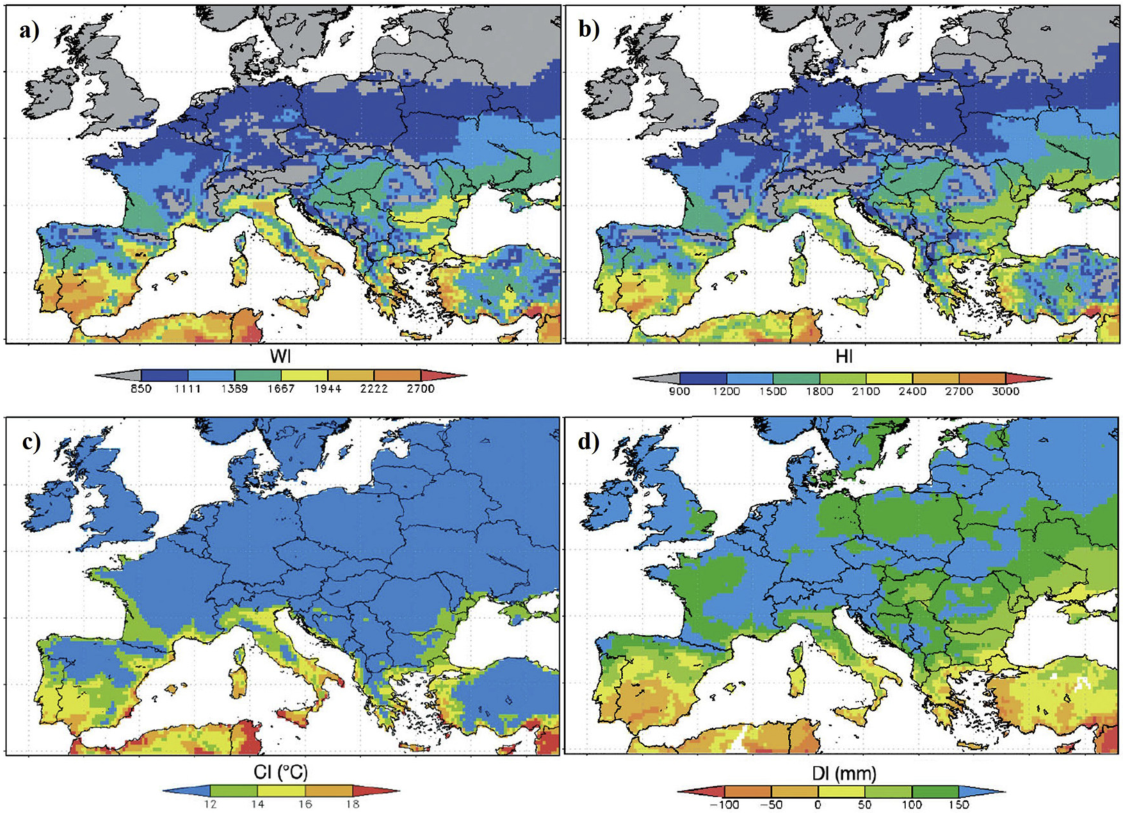

Fig. 2. The average values of a) Winkler Index (WI), b) Huglin Index (HI), c) Cool Night Index (CI) and d) Dryness Index (DI), calculated at the European scale for the period from 1950 to 2009 (adapted from Santos et al., 2012).

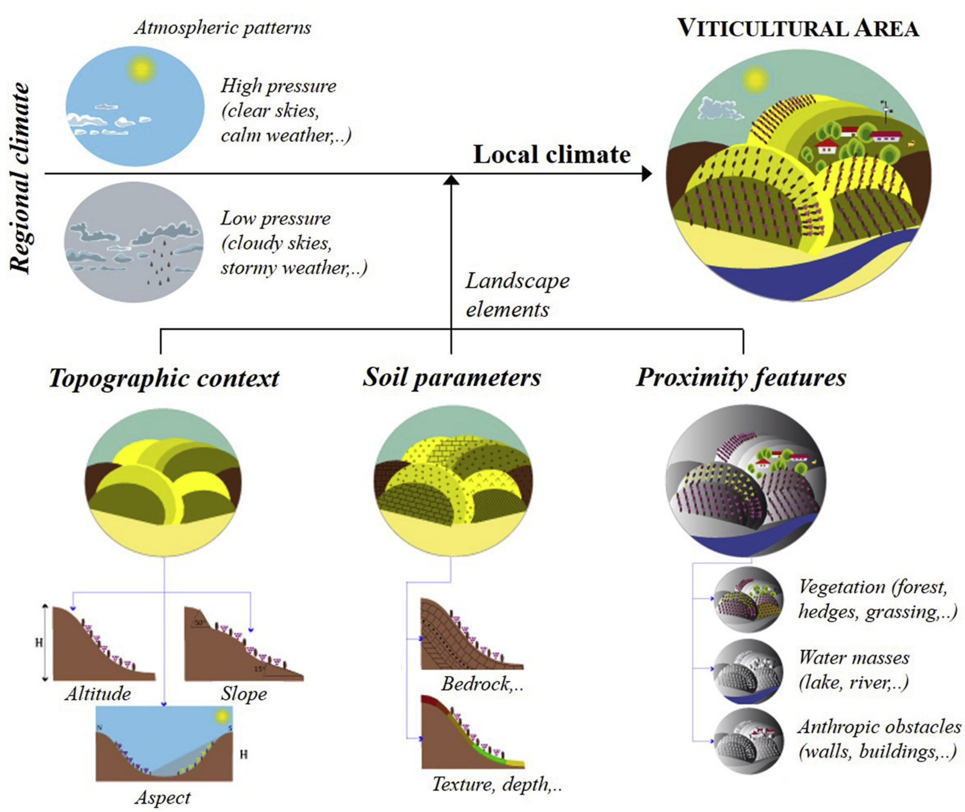

Fig. 3. Nested within a specific zonal climate, local climate conditions in viticultural areas are shaped by different landscape elements, which varies strongly over space (adapted from Quénol, 2011).

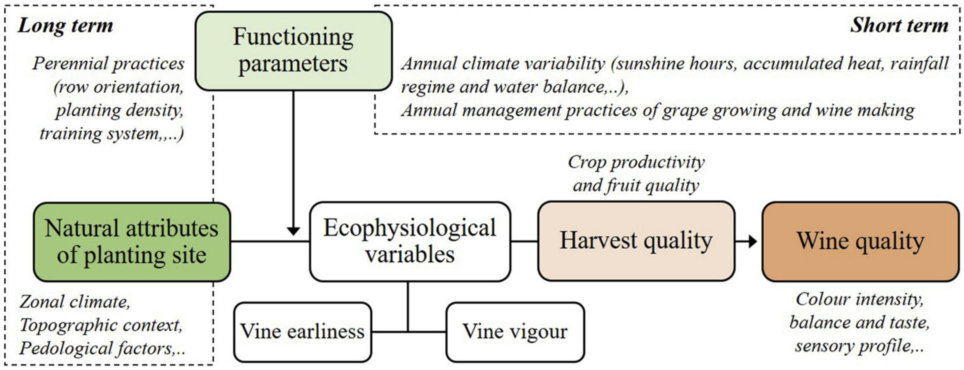

Fig. 4. Temporal representation of long- and short-term factors affecting vine ecophysiological variables and subsequently, harvest and wine quality.

planting densities are likely to cause severe vine water deficiencies, or conversely, excessive vegetative growth in fertile soils with high water and nutrient availability. In this context, the microclimate is strongly dependent on human decisions, which makes the spatial variability in viticulture even more complex. Winegrowers are therefore able to influence plant exposure to different climate conditions (e.g. sunlight and air temperature) and resources (e.g. soil water and nutrition). They accordingly intervene at field levels and further modify the viticultural potential of their vineyard sites, by implementing practices that attenuate the undesirable impacts of the natural environment.

3. Temporal dynamics in viticulture

The notion of temporality is also central in viticulture. In the long term, natural attributes of a vineyard site (e.g. zonal climate, topographic context) largely determines its viticultural potential, which can be expressed according to two ecophysiological variables, namely vine earliness and vine vigour (Bodin and Morlat, 2006; Coulon-Leroy et al., 2012). Perennial practices are then fixed and superimposed on natural site features and act as a functioning parameter over many years (Fig. 4). In this context, these long-term practices will either enhance or modify vine earliness and vigour as conferred by the planting site. Indeed, grapevine performance is predictable depending on the timing and duration of its phenological stages (i.e. level of vine earliness) and the rhythm and amount of vegetative growth (i.e. level of vine vigour). These variables are strongly linked with vine water supply (Morlat et al., 1997; Barbeau et al., 1998), which is a key determining factor of crop productivity and fruit quality at harvest (Matthews et al., 1990; Kennedy et al., 2002; Van Leeuwen et al., 2009). As they are measurable in time, these two ecophysiological variables are used by winegrowers to monitor achieved harvest and wine quality (Coulon-Leroy et al., 2012), depending on annual functioning parameters, namely climate variability and management practices (Neethling et al., 2017).

3.1. Annual climate variability

Annual climate variability, known as the vintage effect, refers to the natural variation of climate conditions between adjacent years. Given its strong temporality, i.e. between and within growing seasons, short-term climate variations are key influencing factors of seasonal fruit yield and quality (Jackson and Lombard, 1993; Van Leeuwen et al., 2004; Ubalde et al., 2010). Climate conditions (e.g. air temperature, rainfall) and associated factors (e.g. soil water supply) influence grapevine behaviour and characterize vine earliness and vine vigour according to their means or sums, critical thresholds or distribution during vine growing cycle (Jones et al., 2012). Warmer than normal growing season conditions results in higher heat accumulation to which generally vines respond by an earlier onset of phenological stages. Depending on the cultivated variety and its geographical position, improved vine earliness is likely to favour grape quality, as for example in high latitude vineyards, where vine earliness shifts berry ripening to a warmer period of the year (Barbeau et al., 1998). Conversely, cooler than normal growing seasons are challenging as accumulated heat is lower than culture requirements, causing delayed vine phenology and unripe grapes (e.g. low sugar contents, high acidity levels). For red varieties, insufficient amounts of heat also affect fruit phenolic and flavour ripeness (Barbeau et al., 2004). Climate thresholds, especially critical air temperatures (e.g. during spring frosts), may also greatly affect the intended outcome of yield (Neethling et al., 2017). Other examples are episodes of extreme weather events (e.g. hail, heatwaves) or the seasonal distribution and timing of rainfall. Seasonal rainfall distribution plays a central role in vine water supply and fungal pathogen outbreaks, whereas rainfall timing is associated with vine phenology when dry conditions are crucial (e.g. during bloom). Annual climate variability is therefore a decisive factor of vine productivity (e.g. plant biomass, yield) and fruit composition. Strongly linked to berry biochemical characteristics (Cadot et al., 2012; Bindon et al., 2013), the qualitative attributes of wines (e.g. its sensory profile, aging potential) are also much climate dependent (Grifoni et al., 2006; Sadras et al., 2007; Baciocco et al., 2014). In this perspective, and in relation to its impact on the amount volume produced, annual climate variability has considerable effects on the economic viability of the wine sector (Haeger and Storchmann, 2006; Ashenfelter and Storchmann, 2016).

3.2. Annual management practices

In time, winegrowers continually deal with inter- and intra-seasonal climate variability (Neethling et al., 2017). As climate influence vine growth and development, winegrowers seek to optimize its behaviour by selecting a fitting technical itinerary for each plot (Jackson and Lombard, 1993; Hunter et al., 2010). This itinerary involves all annual practices, from winter pruning to harvest date, including the different techniques of soil, vigour and disease management. Depending on seasonal climate conditions, a vineyard plot may follow various technical itineraries, which will consequently cause different grape qualities at harvest (Coulon-Leroy et al., 2012). Likewise, the same attributes in berry qualities can be achieved through different combinations of practices and techniques. In this context, the long-term viticultural potential of a plot can be mitigated by farming strategies. For example, winegrowers are able to manage temporal variations in vine water supply through different vine inter-row soil management techniques (Wheeler and Pickering, 2003). Within a growing season, most adaptive responses generally occur at harvest or in the cellar (Neethling et al., 2017). During fruit development, winegrowers will closely follow the berry ripening process in order to adjust their harvest management decisions and pick grapes at the most adequate period (Coulon-Leroy et al., 2012). From here, winegrowers will use an array of winemaking techniques to produce a wine with a distinct structure, style, and sensory profile (Cadot et al., 2012). Still, the impacts of climate variations are not new and adapting to those conditions has always been a constant challenge faced by winegrowers. Through constant learning experiences, decision making in viticulture is an ongoing process, where winegrowers perform various forms and types of adjustments to their existing management practices and techniques (Nicholas and Durham, 2012; Lereboullet et al., 2013; Neethling et al., 2017). To that end, the term practice describes the action exercised, while technique refers to the knowledge of exercising the activity (Landais et al., 1988). Adaptation in viticulture is an iterative process, involving many factors that assist or constrain the process of adjusting practices and techniques, and understanding this dynamic nature of viticultural and winemaking activities is crucial (Neethling et al., 2017).

4. Discussing viticulture in a changing climate

In viticulture, contemporary climate change is positioning itself as a major environmental challenge. Regional climate changes and its impacts are taking place at a substantial rate, affecting grapevine productivity and fruit quality. As temperatures are projected to continue warming, with likely changes in rainfall patterns and extreme weather events (IPCC, 2014), the findings reported in this review disclose that the territorial identity of wine growing regions may significantly evolve over time. This identity being shaped by a distinct product quality and style, which are strongly related to its geographical origin. In the short-term, as vine earliness is expected to keep improving under higher seasonal temperatures, resulting in warmer ripening periods, berry metabolism and hence wine composition and sensory properties will strongly be altered. In the long-term, varieties currently cultivated at their upper suitability threshold may accordingly become less fitted with future climate changes, where a varietal change will substantially modify the territorial product identity. While the latter has a temporal characteristic, evolving according to context, the evidence of rapid climate changes brings strong attention to the socio-economic impacts on the wine sector. With a changing climate, review findings show likewise that important geographical shifts in viticultural potentialities are likely to occur. At field to local levels, land considered limiting for viticulture in the past could develop into favourable planting sites (e.g. sites with cooler facing slopes or with larger water holding capacities). At the same time, traditional planting sites may become less adapted to continued climate trends, creating an important relocation of growing areas within wine regions, placing policy pressure on existing boundaries of geographical indications. At regional to global levels, the northern and southern limits of vine distribution are also likely to shift, an event already occurring with developing regions in Canada, Denmark and even Sweden. Conversely, with increasing vine water demands in warm and dry regions, such as in the Mediterranean Basin, the substantial loss in crop productivity may hinder the long-term economic viability of those traditional wine regions (Costa et al., 2016).

Global climate change is affecting more than just the local growing environment, as it also denotes an increase in uncertainty (Dessai et al., 2007). Indeed, the extent to which climate will evolve as a result of natural processes and human activities is unclear, and likely to remain unknown. Besides temporal uncertainties in climate estimates, the review has demonstrated that each vineyard site is unique, defined by specific natural, biological and human properties and interactions. These results support the growing and urgent need for addressing spatial uncertainties in expected vulnerability, which will vary considerably with location, relative to its exposure to extrinsic environmental changes and to the intrinsic features defining its sensitivity (e.g. site and plant characteristics) and adaptive capacity (e.g. resources, technology, skills) to such changes and impacts. Although this strong heterogeneity in natural site attributes lowers the transparency of adaptation and mitigation actions, review findings suggest that it should also constitute an important buffer in response to future climate changes, allowing producers to spatially manage expected climate changes. The review has highlighted the influence of a strong seasonal climate variability on ongoing practices and techniques. Temporal and spatial uncertainties are therefore likely to be further aggravated by the difficulty of separating the effects of long-term climate changes from natural and short-term climate variations. This may hinder the perception of climate changes and the recognition of its impacts, resulting in delayed implementations of mitigation and adaptation priorities (Neethling et al., 2017).

In response to global climate change, adjustments made in practices and techniques will need to be place-based and context-specific, as the relevant factors and processes contributing to increasing greenhouse gases or the consequences of a changing climate are local in nature (Mimura et al., 2014). To that end, many different strategies are being discussed with ongoing research projects, for example, changes in the areas of cultural practices related to vigour or soil management. Still, based on the results of this literature review, flexibility and robustness become two key elements in framing sustainable policies and responses over space and in time (Hallegatte, 2009; White et al., 2009). Flexibility refers here to the ability of a viticultural system or itinerary to adjust to changing circumstances, strengthening its resilience and lessening its vulnerability to climate change. Whereas robust strategies should allow winegrowers to manage uncertain climate impacts, by developing practices and techniques that are able to deal with various climate outcomes. Taking the example found in regions like the Douro Valley in Portugal, robust strategies can imply planting various varieties, and clones of the same variety, each developing and ripening at different stages, allowing producers to be more responsive to climate impacts. Winegrowers can also look at implementing no-regret strategies (Hallegatte, 2009), which can benefit grape and wine quality in the absence of a changing climate. For instance, adjusting rootstock varieties to actual environmental conditions and site-specific soil properties. Goulet and Morlat (2010) illustrated that very few vineyards in the middle Loire Valley (France) are planted with the most suitable rootstock variety. As in the past with other global drivers of change (e.g. ramifications caused by Phylloxera), there is also a great need for policy and research to assist winegrowers. They may range from informing and educating stakeholders to providing institutional and technological support (e.g. varietal creation, flexible regulations). While winegrowers will seek to manage and adapt to the expected changes in grapevine performance and wine quality, consumers will in like manner have to adjust. The latter will need to be educated about the issues brought about a changing climate and its impacts on the wine sector.

5. Conclusion

Through time and space, climate has always played a central role in viticulture. The literature review provided in this article has identified the role of climate, outlining the spatial complexity and temporal dynamics in grape growing and wine production. By exploring climate-driven scales, the findings are of relevance in the context of adapting viticulture to climate change, offering support to arising questions that increasingly require attention. Apart from discussing climate change impacts and uncertainties, the perspectives brought by this article argue that flexibility and robustness will be two key areas to focus on when framing sustainable policies and responses. While there are many adjustments possible, there is a need and urgency in developing strategies that are adaptable and flexible in time and over space (e.g. accounting for short-term climate variability and long-term changes), while also being planned and implemented to be more resilient to endure various climate outcomes of an inherently unpredictable future. Therefore, from climate change as a global driver to applying context-specific actions, this understanding of the spatial complexity and temporal dynamics in viticulture should provide a good conceptual and theoretical framework that can be used to address viticultural adaptation to climate change.

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