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Etienne Neethling, Gérard Barbeau, Cécile Coulon-Leroy, Hervé Quénol. Spatial complexity and temporal dynamics in viticulture: A review of climate-driven scales. *Agricultural and Forest Meteorology*, 2019, 276-277, pp.107618. 10.1016/j.agrformet.2019.107618 . hal-02156533

**HAL Id: hal-02156533**

**<https://hal.science/hal-02156533v1>**

Submitted on 25 Oct 2021

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

2

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8

## 9 **Abstract**

10

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

24

25 **Key words:** Climate, global change, spatial complexity, temporal dynamics, viticulture

26

## 27 **1. Introduction**

28

29 Cultivated and shaped by human uses for many centuries, the grapevine (*Vitis vinifera* L.) has a rich geographical  
30 spread, covering more than seventy countries today (OIV, 2018). Given the genetic diversity found in grapevine

31 varieties (This et al., 2006), it can be grown in diverse climates, ranging from Mediterranean (e.g. Mediterranean  
32 Basin) to continental (e.g. Hungary), oceanic (e.g. New Zealand), dry subtropical (e.g. Argentina) and humid  
33 subtropical conditions (e.g. Uruguay). Over these geographical areas, long-term climate structures influence  
34 regional grape growing and winemaking potential (Tonietto and Carbonneau, 2004), while seasonally, affects  
35 grape productivity and wine quality (Salinger et al., 2015; Real et al., 2017). Many studies have demonstrated this  
36 central role of climate on vine parameters such as perennial biomass, yield and berry composition (Buttrose et al.,  
37 1971; Coombe, 1987; Jackson and Lombard, 1993; Jones and Davis, 2000; Van Leeuwen et al., 2004). As wine  
38 structure and flavour are much dependent on grape attributes (Cadot et al., 2012; Bindon et al., 2013), any climate  
39 changes impact wine quality and volume produced, resulting in considerable effects on the economic viability of  
40 the wine sector (Haeger and Storchmann, 2006; Ashenfelter and Storchmann, 2016). For example, world wine  
41 production was 8.2% lower in 2017, than compared with 2016, particularly in the European Union following an  
42 extreme frost event in April (OIV, 2017). Viticulture is therefore highly sensitive to changing climate conditions,  
43 both temporally and spatially (Jones and Webb, 2010).

44 Although until the year 2000, few studies about climate change and its impacts on viticulture emerged (Dry,  
45 1988; Smart, 1989; Kenny and Harrison, 1992; Bindi et al., 1996), this topic has received much attention in recent  
46 years. Across wine growing regions, climate change has essentially resulted in regional warming (Jones et al.,  
47 2005; Cook and Wolkovich, 2016), and to some extent, though less spatially coherent and statistically significant,  
48 in greater variability in seasonal rainfall (Laget et al., 2008; Ramos et al., 2015). In response to increasing  
49 temperatures and declining soil water contents (Webb et al., 2012), grapevine phenology has shifted earlier by  
50 several days (Jones and Davis, 2000; Tomasi et al., 2011), while a warmer ripening period has resulted in changes  
51 in berry composition, increased alcohol contents and altered wine sensory profiles (de Orduña, 2010; Neethling et  
52 al., 2012). With climate playing a key role in viticulture, a changing climate raises many questions ranging from  
53 regional wine quality and style to issues such as geographical shifts in suitable grapevine varieties and production  
54 areas over the long term (Schultz and Jones, 2010; Ollat et al., 2016). Vineyards planted over the next decade, and  
55 remaining economically productive for many years, are likely to be exposed to unprecedented climate conditions  
56 (Mora et al., 2013). Adjusting grape growing and winemaking practices and techniques are therefore an immediate  
57 priority to attenuate climate change and to reduce its impacts (Van Leeuwen and Darriet, 2016).

58 When addressing these issues, one of the key challenges is strategically planning mitigation efforts and  
59 adaptation measures across and within different sectors and scales (Tol, 2005). Firstly, they act at different time  
60 periods, where for instance the beneficial effects of mitigation efforts may take many years to emerge (Meehl et

61 al., 2012). Secondly, despite the global extent of climate change (IPCC, 2014), the relevant factors and processes  
62 that contribute to increasing greenhouse gases or the consequences of a changing climate are local and context-  
63 dependent in nature, varying from one location to another (Mimura et al., 2014). Hence, the question of scale is  
64 central to understanding the challenges, or even the opportunities, brought by a changing climate (O'Brien et al.,  
65 2004). For viticulture, the understanding of scale and cross-scale interactions is specifically important as produced  
66 wines are the result of complex interactions between physical, biological and human factors (Van Leeuwen and  
67 Seguin, 2006), taking place at different levels and times, known as the components of terroir (OIV, 2010). The  
68 content of this article aims to provide an overview of climate-driven scales, outlining the spatial complexity and  
69 temporal dynamics in viticulture. In the context of climate change mitigation and adaptation, the article concludes  
70 with a discussion of the implications of this literature review on assessing expected impacts, understanding  
71 uncertainty and framing sustainable policies and responses in viticulture.

72

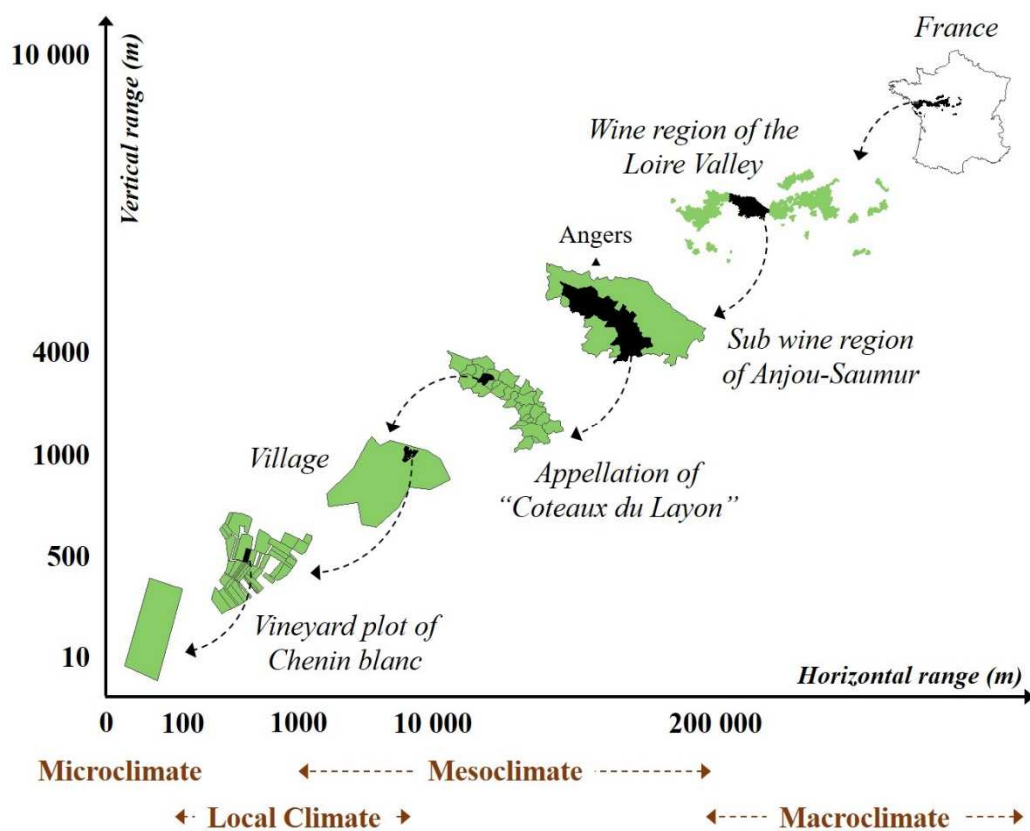
## 73 **2. Spatial complexity in viticulture**

74

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

86 Secondly, the hierarchical organization of climate must be considered, as lower spatial levels (i.e. with a finer  
87 spatial resolution) are embedded or nested within higher levels (Ackerly et al., 2010; QuénoI and Bonnardot, 2014).  
88 The reason for this organization is related to the functioning of the atmosphere, knowing that the same air mass  
89 will generate similar weather patterns for an extended territory, and it is certain that at a smaller spatial entity  
90 within this territory, common climate features will be present (Geiger et al., 1995; Guyot, 1999). The higher level

91 therefore provides a climatic context that imposes conditions and constraints in a top-down approach towards  
 92 lower levels (Wu and David, 2002). Still, local terrain effects (e.g. altitude and aspect) lead to large climate  
 93 variations at smaller scales (Geiger et al., 1995; QuénoI, 2014), which means that lower levels also impose climate  
 94 feedbacks that modify large-scale patterns, by following an upward or bottom-up approach. The individual  
 95 characteristics of the grapevine are therefore dependent on these environmental processes, taking place at different  
 96 spatial levels. As each level has its own attributes, it is important to understand what are the main influencing  
 97 factors that emerge (Willis and Whittaker, 2002), while also knowing that spatial heterogeneity becomes  
 98 increasingly important at finer scales (QuénoI, 2014).  
 99



100

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

103

104 **2.1. Global level**

105

106 Apart from a few exceptions (e.g. Brazil, India), the main wine producing regions are roughly located between  
 107 latitudes 30 to 50 degrees, in both hemispheres. This geographical distribution of wine grape varieties is shaped

108 by the spatial variability of large-scale macroclimatic conditions, which are strongly determined by the latitudinal  
109 differences in solar energy intercepted at the surface of the earth (Geiger et al., 1995; Ricklefs and Miller, 2005).  
110 As the equator receives more incoming radiation during the year, the average annual temperature decreases with  
111 latitude, from the equator to the poles (Guyot, 1999). Consequently, it appears that favourable macroclimate  
112 conditions for cultivating grapevines are found between annual isotherms of 10°C to 20°C (De Blij, 1983;  
113 Spellman, 1999). Schultz and Jones (2010) indicated that the geographical extension of viticulture is best  
114 represented by growing season isotherms of 12°C to 22°C. Regions with seasonal average temperatures below  
115 12°C are unfavourable due to short growing seasons and low amounts of sunshine hours and accumulated heat  
116 (Jones et al., 2012). In these areas, the high frequency and intensity of extreme cold temperatures (e.g. winter or  
117 spring frosts) also makes grapevine growing very difficult. Conversely, in regions with mean seasonal  
118 temperatures above 22°C, grapevines are regularly exposed to very warm summers and extreme heat events. And  
119 depending on the seasonal rainfall rhythm, they may also be subject to either very arid conditions (e.g. North  
120 Africa), or very humid conditions where pest and disease pressures are particularly high (e.g. Thailand). Regarding  
121 the distribution of the most recognized cultivars (e.g. Cabernet Sauvignon), Jones (2006) also showed that the  
122 production of high quality wines from these varieties is located between isotherms 13°C and 21°C. While there  
123 are more than 6 000 wine grape varieties known (This et al., 2006; Myles et al., 2011), 13 cover more than one-  
124 third of the world's vineyard area and 33 varieties cover 50% (OIV, 2017).

125

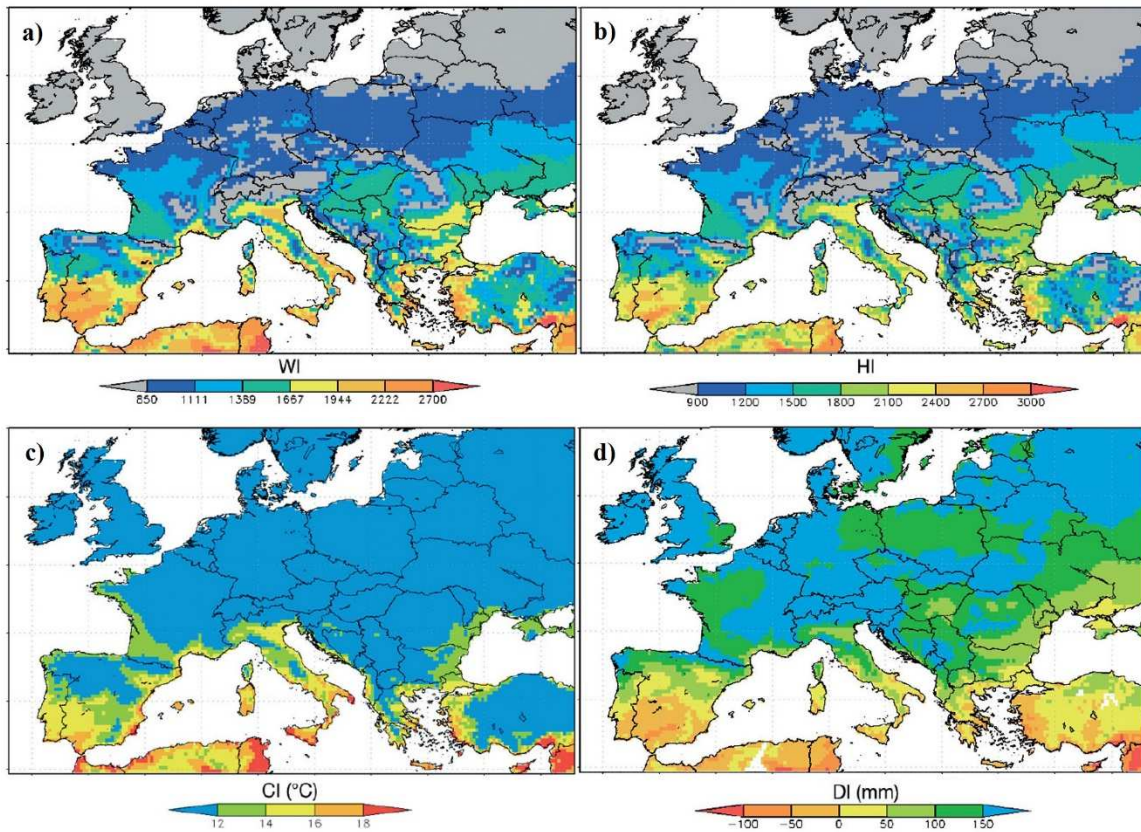
## 126 **2.2. Regional level**

127

128 The wine sector is growing every day with emerging wine regions and markets. In response to an increasingly  
129 competitive global industry, each region seeks to differentiate itself by promoting wines with a strong identity  
130 (Hayward and Lewis, 2008; Easingwood et al., 2011). In order to maintain a premium in the market by ensuring  
131 high quality products, the cultivated grape variety and in particular its ripening period must be in relation with the  
132 surrounding environment (Jackson and Lombard, 1993). When berry maturation is reached too late, grapes remain  
133 unripe, with high acidity, low sugar contents and herbaceous flavours, whereas reached too soon, grapes are rich  
134 in sugars, low in acidity, giving place to unbalanced wines that lack in aromatic complexity (Van Leeuwen and  
135 Seguin, 2006). Since vine phenology and ripening earliness are measurable (Parker et al., 2013), berry maturation  
136 under favourable conditions is usually achieved when varieties are grown at their northern limits in the northern  
137 hemisphere, or southern limits in the southern hemisphere. In European wine regions, extended grape growing

138 through several centuries has allowed the emergence of the most adapted varieties in regional climates that are  
139 representative of their northern limits (Barbeau et al., 2015). For example, Pinot Noir and Chardonnay are the  
140 emblematic varieties of Burgundy wines, Cabernet Sauvignon and Merlot of Bordeaux red wines (France),  
141 Sangiovese of Tuscany red wines (Italy) and Riesling of Rheingau white wines (Germany). Conversely, in new  
142 world wine regions, one of the main challenges in defining their success and competitiveness has been to identify  
143 the most fitted grapevine varieties (Van Leeuwen and Seguin 2006). Varietal suitability is strongly related to the  
144 regional attributes of growing season accumulated heat (Tonietto and Carbonneau, 2004; Jones et al., 2012), i.e.  
145 sum of daily temperatures above a threshold where vine development is active. Still, for a given variety, cultivated  
146 in different regions but under similar heat sums, climatic properties, such as rainfall regime and thermal conditions  
147 during ripening, contribute to the unique traits of produced wines (Shaw, 2012). With this context, several studies  
148 have led to the conception of bioclimatic indices, specific to viticulture. By integrating, in one way or another, the  
149 temperature factor, there are simple or complex indices (i.e. mono- or multi-factorial), which enables to define a  
150 region's ability to produce wine, varietal suitability and vine phenology, possible environmental risks and to some  
151 extent, potential wine styles. Today, the application of these indices allows an understanding of the spatial variation  
152 in viticultural potentialities and limitations, as e.g., in Australia (Hall and Jones, 2010), Chile (Montes et al., 2012),  
153 United States (Jones et al., 2010), New Zealand (Anderson et al., 2012). Figure 2 illustrate the regional climate  
154 differences and their viticultural potentialities encountered over Europe, which are essentially due to latitudinal  
155 position and degree of continentality (e.g. rainfall patterns).

156



157

158 *Figure 2: The average values of a) Winkler Index (WI), b) Huglin Index (HI), c) Cool Night Index (CI) and d)*

159 *Dryness Index (DI), calculated at the European scale for the period from 1950-2009 (adapted from Santos et al.,*

160

*2012).*

161

### 162 **2.3. Local level**

163

164 Within a wine growing region, viticultural potentialities and limitations are described by local terrain features.

165 Indeed, atmospheric boundary layer characteristics are dependent on surface conditions that modify fine-scale

166 environmental conditions (Geiger et al., 1995). Accordingly, each wine region is composed of various local

167 climates depending on its terrain complexity (Figure 3). Through interactions with the atmosphere and different

168 weather patterns, topographical factors (e.g. elevation, aspect) influence heat and moisture exchange at the earth's

169 surface, shaping topoclimates (Jacquet and Morlat, 1997; Orlandini et al., 2006; Bonnefoy et al., 2012). Besides

170 the topographic context, soil parameters (e.g. texture, depth) and other proximity features (e.g. water mass, forest)

171 also have significant effects on local climate or pedoclimate conditions (Guyot, 1999). The latter refers to soil

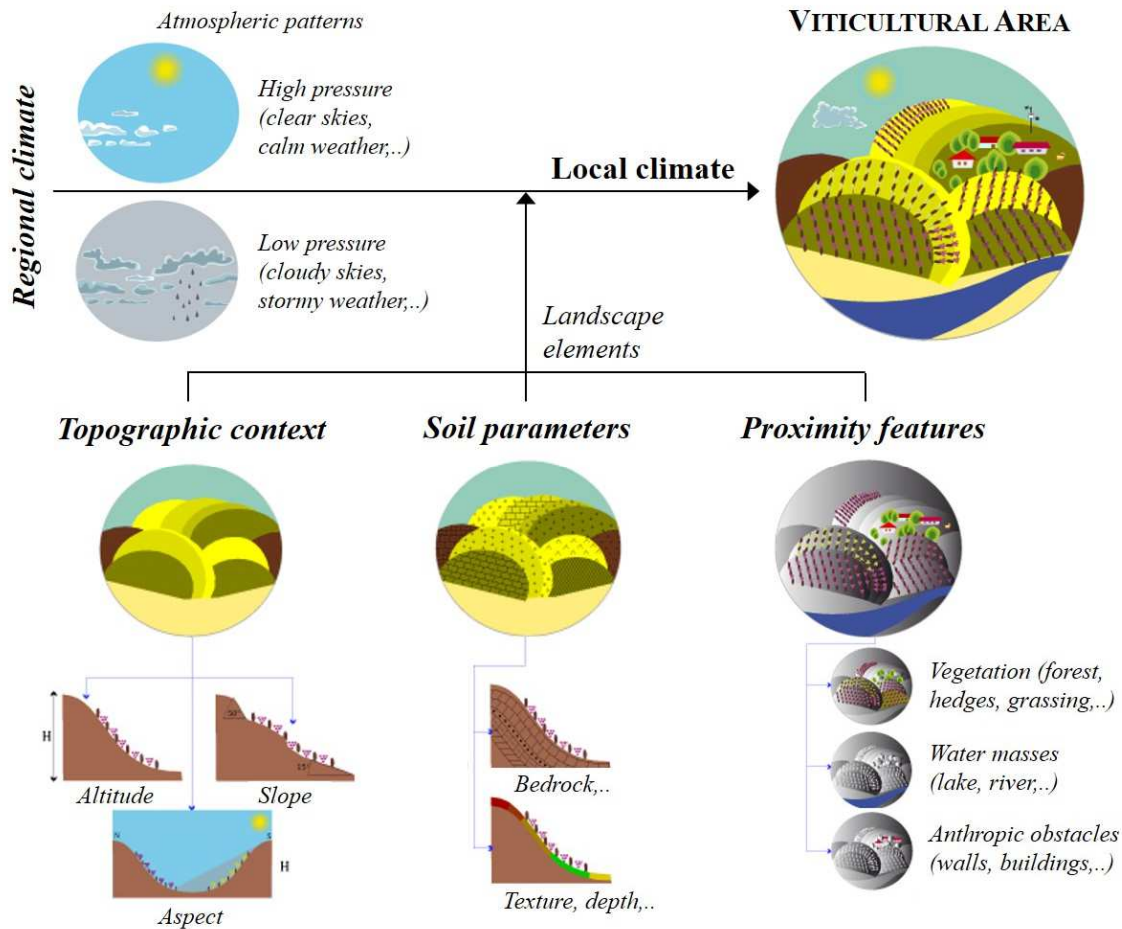
172 moisture and temperature, which is a key factor of the earliness of grapevine growth in spring (Morlat and Jacquet,

173 1993). All the elements of the surrounding landscape generate a strong spatial climate variability, as for example



174 described in the Coteaux du Layon France (Neethling et al., 2014), Saint Emilion France (De Ressaquier et al.,  
175 2016), Canelones Uruguay (Fourment et al., 2013), Uco Valley Argentina (Grassin et al., 2014), Douro Valley  
176 Portugal (Jones and Alves 2012) and Stellenbosch South Africa (Bonnardot et al., 2012). This spatial heterogeneity  
177 in local climates is a critical element in viticulture, making it possible for winegrowers to mitigate the conditions  
178 and constraints imposed by the zonal climate (Quénol, 2014). For example, air temperature generally decreases by  
179 1°C per 150m increasing elevation, except during thermal inversions (Guyot, 1999). In areas with very warm  
180 regional climates, the effects brought by ascending in elevation are beneficial for growing wine grapes, as in the  
181 Uco Valley (1000m-1200m, Argentina), or the Central Valley of Tarija (1600m-2150m, Bolivia). At higher  
182 altitudes, vines profit from lower temperatures, allowing slower berry maturation and higher concentrations in  
183 organic acidity (Miguel-Tabares et al., 2002). The light intensity is also higher, favouring phenolic compound  
184 synthesis in red varieties. Conversely, in cool climate regions, it is worth mentioning the importance of slope  
185 orientation and inclination, the latter describing the angle between orientation and incoming sunlight. In high  
186 latitude regions of the northern hemisphere (e.g. Burgundy), south facing slopes allow for a higher amount of solar  
187 radiation reaching the surface, whereas the steeper slopes of esteemed plots (e.g. Burgundy crus) increases light  
188 and heat energy interception (Huggett, 2006; Jackson, 2008). Although steep slopes enlarge erosion risks, they  
189 enable cold air to drain away during radiative frost events, a frequent event in high latitude vineyards. Similarly,  
190 in warm and dry Mediterranean climates (e.g. Western Cape South Africa), vineyards may benefit significantly  
191 from the cooling effect brought by sea breezes (Bonnardot et al., 2005), whereas in Oceanic climates with regular  
192 rainfall patterns (e.g. Loire Valley France), soils with low water holding capacities favour grapevine earliness and  
193 wine production (Barbeau et al., 1998). Each wine growing region therefore consists of unique environmental  
194 contexts, providing winegrowers with a range of local climates and different viticultural potentialities.

195



196

197 *Figure 3: Nested within a specific zonal climate, local climate conditions in viticultural areas are shaped by*  
 198 *different landscape elements, which varies strongly over space (adapted from Qu  nol 2011).*

199

200 **2.4. Field level**

201

202 The grapevine is a perennial crop and requires a few years to reach reproductive maturity, remaining then  
 203 economically productive for many years (Orlandini et al., 2009). As the lifespan of a plot may correspond to two  
 204 generations of winegrowers, management decisions prior to planting are very important. At this level, decision  
 205 making is closely related to winegrowers' production objectives and the physical attributes and constraints of  
 206 planting sites (Coulon-Leroy et al., 2012). To ensure sustainable productivity, winegrowers strive for appropriate  
 207 measures in terms of perennial practices in order to optimise seasonal grapevine growth and fruit development.  
 208 These practices vary considerably, from the choice of plant material to decisions involved in vineyard design and  
 209 layout, each practice affecting microclimate conditions at field levels (Smart, 1988; Matese et al., 2014). For  
 210 example, row orientation greatly affects light interception and wind velocity and as a result, canopy and fruit

211 temperature (Giacosa et al., 2015; Hunter et al., 2016). For vertically positioned shoots with East-West orientated  
212 rows, less direct sunlight is reach in fruits than compared to North-South orientated rows (Hunter et al., 2016).  
213 East-West orientated rows also expresses greater thermal variations between exposed and shaded leaves. These  
214 alterations in light exposure explains the greater suitability of North-South orientated rows in cool growing areas.  
215 Other notable perennial practices are the choice in planting density (Archer and Strauss, 1989, 1990), training  
216 system (Reynolds and Vanden Heuvel, 2009) and trunk height, where these practices are to some extent  
217 interconnected. For example, planting density is likely to determine the fitted training system, whereas the latter  
218 may condition trunk height. Vineyards with higher planting densities generally display improved crop yield and  
219 quality (i.e. per ha), which are mainly due to greater root competition (Jackson, 2008). Increased root competition  
220 leads to lower vegetative growth and an enhanced microclimate, while also allowing for deeper root penetration  
221 and a greater soil volume to be explored. Still, in shallow soils with low water availability, high planting densities  
222 are likely to cause severe vine water deficiencies, or conversely, excessive vegetative growth in fertile soils with  
223 high water and nutrient availability. In this context, the microclimate is strongly dependent on human decisions,  
224 which makes the spatial variability in viticulture even more complex. Winegrowers are therefore able to influence  
225 plant exposure to different climate conditions (e.g. sunlight and air temperature) and resources (e.g. soil water and  
226 nutrition). They accordingly intervene at field levels and further modify the viticultural potential of their vineyard  
227 sites, by implementing practices that attenuate the undesirable impacts of the natural environment.

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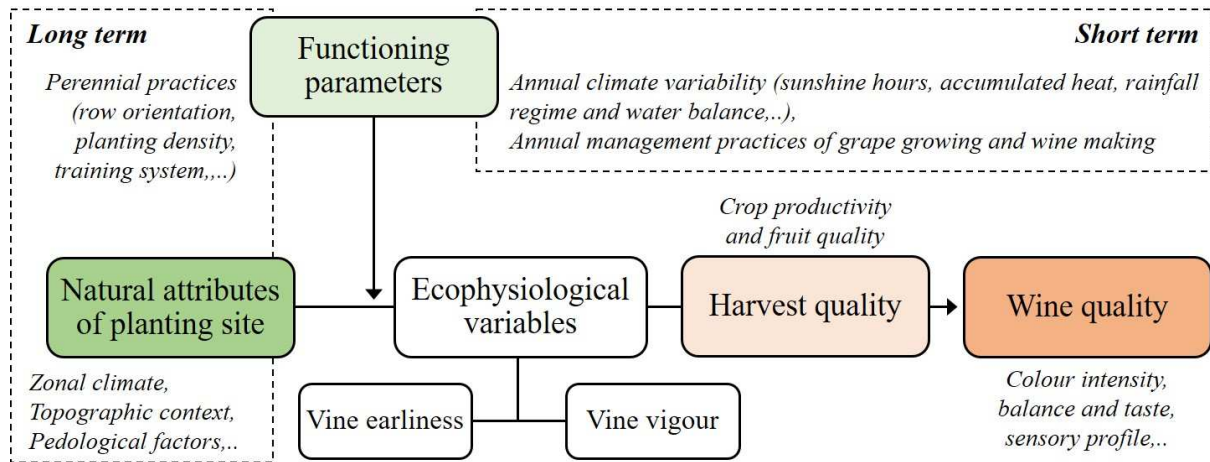
### 229 **3. Temporal dynamics in viticulture**

230

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

241 time, these two ecophysiological variables are used by winegrowers to monitor achieved harvest and wine quality  
 242 (Coulon-Leroy et al., 2012), depending on annual functioning parameters, namely climate variability and  
 243 management practices (Neethling et al., 2017).

244



245

246 *Figure 4: Temporal representation of long- and short-term factors affecting vine ecophysiological variables and*  
 247 *subsequently, harvest and wine quality.*

248

### 249 3.1. Annual climate variability

250

251 Annual climate variability, known as the vintage effect, refers to the natural variation of climate conditions  
 252 between adjacent years. Given its strong temporality, i.e. between and within growing seasons, short-term climate  
 253 variations are key influencing factors of seasonal fruit yield and quality (Jackson and Lombard, 1993; Van  
 254 Leeuwen et al., 2004; Ubalde et al., 2007). Climate conditions (e.g. air temperature, rainfall) and associated factors  
 255 (e.g. water supply) influence grapevine behaviour and characterize vine earliness and vine vigour according to  
 256 their means or sums, critical thresholds or distribution during vine growing cycle (Jones et al., 2012). Warmer than  
 257 normal growing season conditions results in higher heat accumulation to which generally vines respond by an  
 258 earlier onset of phenological stages. Depending on the cultivated variety and its geographical position, improved  
 259 vine earliness is likely to favour grape quality, as for example in high latitude vineyards, where vine earliness  
 260 shifts berry ripening to a warmer period of the year (Barbeau et al., 1998). Conversely, cooler than normal growing  
 261 seasons are challenging as accumulated heat is lower than culture requirements, causing delayed vine phenology  
 262 and unripe grapes (e.g. low sugar contents, high acidity levels). For red varieties, insufficient amounts of heat also  
 263 affect fruit phenolic and flavour ripeness (Barbeau et al., 2004). Climate thresholds, especially critical air

264 temperatures (e.g. during spring frosts), may also greatly affect the intended outcome of yield (Neethling et al.,  
265 2017). Other examples are episodes of extreme weather events (e.g. hail, heatwaves) or the seasonal distribution  
266 and timing of rainfall. Seasonal rainfall distribution plays a central role in vine water supply and fungal pathogen  
267 outbreaks, whereas rainfall timing is associated with vine phenology when dry conditions are crucial (e.g. during  
268 bloom). Annual climate variability is therefore a decisive factor of vine productivity (e.g. plant biomass, yield)  
269 and fruit composition. Strongly linked to berry biochemical characteristics (Cadot et al., 2012; Bindon et al., 2013),  
270 the qualitative attributes of wines (e.g. its sensory profile, aging potential) are also much climate dependent  
271 (Grifoni et al., 2006; Sadras et al., 2007; Baciocco et al., 2014). In this perspective, and in relation to its impact on  
272 the amount volume produced, annual climate variability has considerable effects on the economic viability of the  
273 wine sector (Haeger and Storchmann, 2006; Ashenfelter and Storchmann, 2016).

274

### 275 **3.2. Annual management practices**

276

277 In time, winegrowers continually deal with inter- and intra-seasonal climate variability (Neethling et al., 2017).  
278 As climate influence vine growth and development, winegrowers seek to optimize its behaviour by selecting a  
279 fitting technical itinerary for each plot (Jackson and Lombard, 1993; Hunter et al., 2010). This itinerary involves  
280 all annual practices, from winter pruning to harvest date, including the different techniques of soil, vigour and  
281 disease management. Depending on seasonal climate conditions, a vineyard plot may follow various technical  
282 itineraries, which will consequently cause different grape qualities at harvest (Coulon-Leroy et al., 2012).  
283 Likewise, the same attributes in berry qualities can be achieved through different combinations of practices and  
284 techniques. In this context, the long-term viticultural potential of a plot can be mitigated by farming strategies. For  
285 example, winegrowers are able to manage temporal variations in vine water supply through different vine inter-  
286 row soil management techniques (Wheeler and Pickering, 2003). Within a growing season, most adaptive  
287 responses generally occur at harvest or in the cellar (Neethling et al., 2017). During fruit development,  
288 winegrowers will closely follow the berry ripening process in order to adjust their harvest management decisions  
289 and pick grapes at the most adequate period (Coulon-Leroy et al., 2012). From here, winegrowers will use an array  
290 of winemaking techniques to produce a wine with a distinct structure, style, and sensory profile (Cadot et al.,  
291 2012). Still, the impacts of climate variations are not new and adapting to those conditions has always been a  
292 constant challenge faced by winegrowers. Through constant learning experiences, decision making in viticulture  
293 is an ongoing process, where winegrowers perform various forms and types of adjustments to their existing

294 management practices and techniques (Nicholas and Durham, 2012; Lereboullet et al., 2013; Neethling et al.,  
295 2017). To that end, the term practice describes the action exercised, while technique refers to the knowledge of  
296 exercising the activity (Landais et al., 1988). Adaptation in viticulture is an iterative process, involving many  
297 factors that assist or constrain the process of adjusting practices and techniques, and understanding this dynamic  
298 nature of viticultural and winemaking activities is crucial (Neethling et al., 2017).

299

#### 300 **4. Discussing viticulture in a changing climate**

301

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

323

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

339  
340 In response to global climate change, adjustments made in practices and techniques will need to be place-based  
341 and context-specific, as the relevant factors and processes contributing to increasing greenhouse gases or the  
342 consequences of a changing climate are local in nature (Mimura et al., 2014). To that end, many different strategies  
343 are being discussed with ongoing research projects, for example, changes in the areas of cultural practices related  
344 to vigour or soil management. Still, based on the results of this literature review, flexibility and robustness become  
345 two key elements in framing sustainable policies and responses over space and in time (Hallegatte, 2009; White  
346 et al., 2009). Flexibility refers here to the ability of a viticultural system or itinerary to adjust to changing  
347 circumstances, strengthening its resilience and lessening its vulnerability to climate change. Whereas robust  
348 strategies should allow winegrowers to manage uncertain climate impacts, by developing practices and techniques  
349 that are able to deal with various climate outcomes. Taking the example found in regions like the Douro Valley in  
350 Portugal, robust strategies can imply planting various varieties, and clones of the same variety, each developing  
351 and ripening at different stages, allowing producers to be more responsive to climate impacts. Winegrowers can  
352 also look at implementing no-regret strategies (Hallegatte, 2009), which can benefit grape and wine quality in the  
353 absence of a changing climate. For instance, adjusting rootstock varieties to actual environmental conditions and

354 site-specific soil properties. Goulet and Morlat (2010) illustrated that very few vineyards in the middle Loire Valley  
355 (France) are planted with the most suitable rootstock variety. As in the past with other global drivers of change  
356 (e.g. ramifications caused by Phylloxera), there is a therefore great need for policy and research to assist  
357 winegrowers. They may range from informing and educating stakeholders to providing institutional and  
358 technological support (e.g. varietal creation, flexible regulations). While winegrowers will seek to manage and  
359 adapt to the expected changes in grapevine performance and wine quality, consumers will also have to adjust. The  
360 latter will need to be educated about the issues brought about a changing climate and its impacts on the wine sector.

361

## 362 **5. Conclusion**

363

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

376

## 377 **Acknowledgements**

378

379 This study was carried out with the contribution of the LIFE financial instrument of the European Union, as part  
380 of the LIFE-ADVICLIM project (LIFE13 ENV/FR/001512).

381

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