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VITICULTURE AND CLIMATE: FROM GLOBAL TO LOCAL

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Abstract

Aims: This review aims to (1) present the multiple interests of studying and depicting and climate spatial variability for vitivinicultural terroirs study; (2) explain the factors that affect climate spatial variability according to the spatial scale considered and (3) provide guidelines for climate zoning considering challenges linked to each methodology considered.

Methods and Results: Scientific contributions of the 12 Terroir Conferences proceedings since 1996 have been reviewed together with Vitis-Vea, Oeno One, ASEV, ScienceDirect, SpringerLink and Wiley Online Library data bases with various keywords combination of “Climate”, “Spatial analysis”, “Wine”, “Viticulture”, “Area”, “Scale”, “Terroir” and “Zoning”, including English, Italian and Spanish languages. This literature review led to the classification of climate spatial analysis related studies according to the spatial extent, scale, source of data, spatialization method and indices used to depict the spatial structure of climate. To illustrate the scale issue for climate spatial analysis of wine growing terroirs, a comparison of spatial structure of climate depicted by either large scale data (Worldclim v2.0and CRU4.2TS), point data (weather stations) and spatial interpolation of local weather stations was performed in Bordeaux (2001-2005 period) wine region. It shows the limitations of coarse resolution (macroclimate scale) data to depict mesoscale data.

Conclusions: The climate spatial variability of wine producing regions have been widely documented, yet not exhaustively. However, climate indices and period are not standardized which makes it difficult to compare the climate of terroirs based on the existing literature. Analysing spatial structure might lead to different conclusions according to the source of the data, and thus special care should be provided to the methods, scale and uncertainties associated to spatial data.

Significance and Impact of the Study: This study provides in a nutshell an overview of climate analysis for terroir studies that could be useful for students, winegrowers and researchers interested in climate spatial analysis.

Keywords: Climate**,** spatial analysis, spatial scale, viticulture, terroir

Introduction

The description of climate conditions of the environment has become a consistent contribution to scientific activity and reporting, driven by the intense activity of climate change related research (for example Marx *et al.,* 2017 reported that climate change literature constituted 1.35% of the whole scientific literature published in 2015). In addition, satellite sensing (and more broadly remote sensing technologies) as well as low cost automated data loggers and weather stations and above all climate modelling led to a considerable increase of climate data production (Overpeck *et al.*, 2011). In parallel, multiple initiatives and protocols have been developed to share climate data, such as the Earth System Grid Federation (Cinquini *et al.*, 2014) supporting for example CMIPs (Coupled Model Intercomparison Project) projects simulations data hosting and access. Another example is the WorldClim gridded data set (www.worldclim.org, Fick and Hijmans, 2017) that provides high resolution (down to 1 km approx.) monthly climate data averages for the late 20th century and the 21st century (climate projections). This dataset has been widely used for studying climate of wine producing regions worldwide (e.g. Hannah *et al.*, 2013; Jones and Alves, 2012; Karlik *et al.*, 2018). These recent changes are expected to enhance knowledge in climate and viticulture relationships, making it possible to better depict climate conditions of vineyards and allow for better prediction of the future evolution of wine producing regions and vitivinicultural terroirs.

The current communication reviews the spatial variability of climate conditions for terroir studies and what factors needs to be considered while studying climate conditions at various spatial scales. The variability of climate indices in space in relation to the spatial extent of the analysis is studied through the comparison of a (non-exhaustive) set of scientific papers reporting spatial analysis of wine producing regions. We finally illustrate the impact of data sources and spatialization methods by comparing spatial variability of climate potentialities of two wine producing regions in France.

Depicting Spatial Variability of Climate for Vitiviniculture

The description of climate conditions within and between wine producing regions can be performed for research, production, and marketing purposes. Contrary too many other crops, grapes are often cultivated in challenging terrain areas (specifically for wine production) where diverse topographical features might greatly impact climate diversity at various scale levels (Neethling *et al.,* 2019). This raises an interest in research concerning spatial analysis of climate data that recently led to a considerable production of scientific literature (Neethling *et al.*, 2019; Quénol, 2014). Applications of climate spatial analysis for viticulture are numerous. The OIV resolution 423-2012 (OIV, 2012) and its update proposed by van Leeuwen and Bois (2018) list some concrete applications of climate zoning for viticulture: land suitability for viticulture, territorial management of water resources, grapevine phenological development to better adapt plant material and grapevine products, climate related risks (pest and diseases, frost, extreme heat). Beyond agronomic purposes, climate spatial analysis may provide useful information for delineating appellation areas (Schirmer, 2008), and may also be a support for wine marketing and enhancing the concept of terroir; the connection of a given wine to its geographical origin.

Factors Affecting Climate Diversity at Various Scale Levels

Climate variability in space depends on various factors which relative contribution varies according to the spatial scale that is considered. Various denominations are proposed to refer to scale levels, often defined as fragmentation of the horizontal space according to various ranges of distances. Climatologists and meteorologists have proposed various classes for scale definitions (Orlanski, 1975). Amongst those, four classes are popular and frequently used: macro, meso, local and micro scales (Table 1). Note that confusion between the names of these classes and the adjectives “small” and “large” are common. While “macro” means “large” in ancient Greek, it refers in fact to a small-scale map. Indeed, the ratio of the distance on a map to its corresponding distance on the ground (i.e. the scale) is large at microscale (close to 1 or higher, e.g. 1:100) and small at macro scale (e.g. 1:1 000 000).

Oke (1987) proposed a classification of those four scale levels using overlapping limits between (Table 1). Fixing strict limits between each scale level is not relevant, as climate related phenomena occurring in the atmosphere are indeed continuous in space, rather than discrete.

Table 1: Spatial scales commonly used in climatology and examples of impacts on viticulture of topography driven spatial variability for each scale level.

	Micro	Local (topoclimatology)	Meso	Macro
Spatial extent (from Oke, 1987)	1 cm to 1 km	100 m to 50 km	10 km to 200 km	> 100 km
Example of expected impacts on viticulture of topography -driven climate spatial variations at various scales	Strong changes in phenology and yield cause shading from nearby trees (Castel *et al.*, 2007)	Phenological timing substantial differences due to terrain variations (Bonnefoy *et al.*, 2013) (cold air accumulation and temperature lapse rate)	Grape quality, earliness and thermal stress modified by exposure / sheltering to sea breezes (Conradie *et al.,* 2002)	Changes in grape and wine physical chemical composition and organoleptic features (Amerine and Winkler, 1944) (heat summation modified by distance to Ocean and terrain.

At macroscale (for spaces considering distances larger than 100 km), climate is strongly impacted by differences in latitude, distances to large water bodies (oceans, large lakes, seas) and the presence of mountain ranges. Latitude does not only affect the solar irradiation of the land, it also correlates with air mass origin, winds, and centre of actions (low- and high-pressure areas) over the Planet. For instance, vineyards located at mid-latitude (about 45°) are influenced by large pieces of lands or oceans located to the west, because zonal circulation from west to east is more frequent at theses latitudes. As an example, Fingers Lakes vineyards (New York, USA) are largely affected by continental features due to the westward position of a huge continental body despite the presence of the Atlantic Ocean only 500 km away; while Burgundy vineyards (France), located 500 km away from the same Ocean, are more influenced by oceanic air masses.

At mesoscale (from 10 to 200 km), changes of latitude still affect climate conditions, but other elements affect more consistently climate variations. Distance to water bodies, terrain variations or their interactions drive temperature, humidity, and rainfall variability in space. In the Stellenbosch area (South Africa) for instance, the sea breeze interaction with mountain ranges inland generates considerable variability of climate features within 50 km inland (Bonnardot *et al.,* 2002). Despite moderate variations in elevation, temperature, hence grapevine potential ripening kinetics, is strongly affected by terrain variations such as humps and hollows (small valleys or ridges, Joly *et al.*, 2012).

At local scale, climate analysis is sometimes referred to as topoclimatology. It corresponds to spaces extending over 100 to 50 km. Topography again, plays a key role. Slight changes in terrain can lead to considerable changes, specifically during short duration events such as frost or winter cold (Bois *et al.*, 2011).

Microscale addresses areas of various spatial extensions. Microclimate might refer to the climate conditions of a plant organ, such as a grape as well the climate characteristics within a few hundred metres, such as a vineyard plot. On the later, slight changes of terrain such a hollows or humps of a few metres deep or high or the presence of trees or buildings should be accounted for. As for local climate, slight changes in terrain might strongly affect frost risks (Gavrilescu *et al.*, 2020). Vegetation modifies wind speed (wind breaks) and hence temperature ranges during the day and the night (Guyot, 1987). Shading from nearby trees can affect dramatically crop development, as observed on grapevine phenology (Castel *et al.*, 2007).

Spatial Variability of Climate Conditions for Viticulture

To evaluate the impact of climate spatial variability at various scale levels, a meta-analysis of scientific literature was performed. More than 50 papers from terroir conference proceedings and peer-reviewed journals depicting climate spatial analysis or structure of wine producing regions were analysed. Further, papers that did not provide ranges of climate indices to assess for spatial variability within wine producing regions were discarded from the analysis. Additionally, papers that used data produced by climate modelling (typically Regional Climate Models – RCM) with no substantial bias correction were not considered, to avoid flawed data (Christensen *et al.,* 2008). Finally, 41 papers were considered, reporting information on 38 different locations. Three articles reported studies concerning wine producing regions worldwide (amongst which one considered only cool climate wine producing regions), 1 depicted spatial variability between European wine growing regions, 11 reported climate spatial variability for wine regions within a whole country and 26 papers reported spatial analysis of climate within wine producing regions or between wine regions of a large area (such as Australia or California). The spatial extent of the wine regions within or between the studied climate ranged from 1 km (commercial winery vineyard) to 20000 km (comparison of wine producing regions climates worldwide). Studies used climate data recoded on various time ranges, from one year (local scale studies) to seventy years.

Table 2: List of the 41 references that have been analysed in the current paper, addressing spatial analysis of wine producing regions, with published agroclimatic indices ranges (through tables, maps or plots). The reference format is shortened for the sake of conciseness for the current communication.

Amerine, M. A. et al. Hilgardia 15, 493–673 (1944)
Anderson, J. D. et al. J. Int. Sci. Vigne Vin 46, 149–165 (2012)
Anderson, J. et al. in Proceedings of the 10th International Terroir Congress, (2014)
Avramov, L. et al. J. Agric. Sci. Belgrade 45, 29–35 (2000)
Blanco-Ward, D. et al. VITIS - J. Grapevine Res. 46, 63 (2015)
Bois, B. et al. in Proceedings of the 11th International Terroir Congress, 9–14 (2016)
Bois, B. et al. OENO One 52, (2018)
Bonnefoy, C. et al. Int. J. Climatol. 33, 1849–1862 (2013)
Carey, V. A. et al. OENO One 42, 169–183 (2008)
de Rességuier, L. et al. Front. Plant Sci. 11, (2020)
Fourment, M. et al. Int. J. Biometeorol. 61, 1617–1628 (2017)
Gavrilescu, C. et al. E3S Web Conf. 50, 01003 (2018)
Grassin, M. et al. in Proceedings of the 10th International Terroir Congress (2014)
Hall, A. et al. Aust. J. Grape Wine Res. 16, 389–404 (2010)
Irimia, L. M. et al. Theor. Appl. Climatol. 133, 1–14 (2018)
Jones, G. V. et al. Am. J. Enol. Vitic. 61, 313–326 (2010)
Jones, G. V. et al. Bull. L'OIV 82, 507–517 (2009)
Jones, G. V. et al. in Proceedings of the 9th International Terroirs Congress 3_1-3_4 (2012)
Jones, G. V. et al. Wine Vitic. J. 31, 51 (2016)
Jones, H. E. et al. in Proceedings of the 11th International Terroir Congress 5 (2016)
Karlik, L. et al. OENO One 52, 105–117 (2018)
Koufos, G. C. et al. Int. J. Climatol. 38, 2097–2111 (2018)
Koźmiński, C. et al. Sustainability 12, 5665 (2020)
Montes, C. et al. Aust. J. Grape Wine Res. 18, 20–28 (2012)
Morlat, R. et al. in Proceedings of the 6th International Terroir Congress 1, 485–490 (2006)
Neethling, E. et al. in Proceedings of the 10th International Terroir Congress (2014)
Omazić, B. et al. Int. J. Climatol. n/a, (2020)
Pérez, A. et al. in Proceedings of the 3rd International Terroir Congress (2000)
Pogue, K. et al. in Proceedings of the 7th International Terroir Congress (2008)
Queijeiro, J. et al. in Proceedings of the 6th International Terroir Congress, 34-39 (2006)
Ramos, M. C. et al. in Proceedings of the 10th International Terroir Congress (2014)
Remenyi, T. A. et al. (University of Tasmania, 2019)
Ruml, M. et al. in 47th Croatian and 7th International Symposium on Agriculture 783–786 (2012)
Sánchez, Y. et al. Ecol. Indic. 107, 105646 (2019)
Savić, S. et al. Bull. Univ. Agric. Sci. Vet. Med. Cluj-Napoca Hortic. 75, 73–86 (2018)
Schultze, S. R. et al. Am. J. Enol. Vitic. (2013)
Shaw, T. in Proceedings of the 6th International Terroir Congress 1, 27–32 (2006)
Silvestroni, O. et al. in Proceedings of the 7th International Terroir Congress (2008)
Tonietto, J. (PhD, Ecole Nationale Supérieure Agronomique de Montpellier, 1999)
Vianna, L. F. de N. et al. Remote Sens. Appl. Soc. Environ. 13, 158–170 (2019)
Whitney, H. et al. in Proceedings of the 11th International Terroir Congress 176–181 (2016)

Amongst the 36 reported indices used to characterize the climate conditions of wine producing regions, most of them (26) are based on air temperature only. Heat summation indices during the growing seasons were the most used. More specifically Winkler's growing degree days (WI; Amerine and Winkler, 1944) and Huglin's heliothermal index (HI; Huglin, 1978) were found in 27 and 26 studies respectively (out of 41 papers). Jones' growing season temperature (GST, Jones *et al.*, 2005) was found in 19 papers. The Cool Nights Index (CI, Tonietto and Carbonneau, 2004) was used in 18 studies. The Dryness Index (DI, found in 10 of the 40 studied papers) and the growing season precipitation (GSP, used 8 times) are the most used indices to study the spatial characteristics of water-related climate potentialities of wine regions in the current literature subset.

Not surprisingly, a good relationship was found between the range of variation in space of agroclimatic indices and the spatial extent of the area for which the agroclimatic indices spatial variation have been reported. Figure 1 illustrates the link between spatial range of variation for Huglin's index in comparison to the spatial extent of the studied area, reported in 26 studies over 24 wine producing regions, considering either macro or larger scale levels (local and meso). At mesoscale level, spatial variation of Huglin's index can be almost as large as at macroscale level, with a maximum difference of 1038°C.d and 1050°C.d recorded by weather stations respectively located in Galicia and in Mino River Valley, Spain. Both areas extend over approximately 200 km. Within small areas, HI spatial variability tends to decrease in correlation with the spatial extent the wine producing region(s).

No such clear relationship was found in studies reporting WI or GST spatial variations at meso and local scale levels (results not shown); with small and large variations observed over short distances. For example, the Columbia Gorge wine region located over the border of Washington and Oregon states (USA) extends over 80 km and presents a range of 4°C in GST over the 1981-2010 period (Whitney and Burns, 2016). In contrast, GST varies only 0.2°C between 5 weather stations located at a maximum distance of 80 km, in the Ribera Del Duero for a period of similar duration (1980-2012; Ramos *et al.,* 2014). For the later, elevation is very homogenous between locations of weather stations (from 735 to 790 m asl) while the Columbia Gorge wine region exhibits differences of up to 529 metres (from 29 to 548 m asl). At local scale level, temperature variation, yet lower than at smaller scale, can still be considerable. In Abacela winery (Southern Oregon), average differences of 375°C.d in WI and of 1.8°C in GST during the 2011-2015 have been measured over an area less than 1 km with a range in elevation of 61 m (Jones and Jones, 2016). Bonnefoy *et al.* (2013) measured similar variations in Coteaux de Layon (France) over a 3 km wide area during vintage 2009 (a range of 296°C.d in WI). Such differences have considerable potential impacts on grapevine physiology, and more specifically phenological timing and harvest date. One could then decide the use of cultivars with different heat requirements to better adapt to these local thermal variations. While the current meta-analysis is far from exhaustive, it clearly shows that precipitation or evapotranspiration spatial analysis are under-represented. However, water related indices (9 of 36 indices analysed) also exhibit a correlation between spatial extent (from local to macro) of the considered region(s) and the spatial range of the index. The number of papers reporting spatial variability of water related indices (DI, GSP) within wine producing regions was too scarce to qualify the relationship between spatial variability of climate and spatial extent of the studied area at mesoscale and larger (i.e. local and micro).

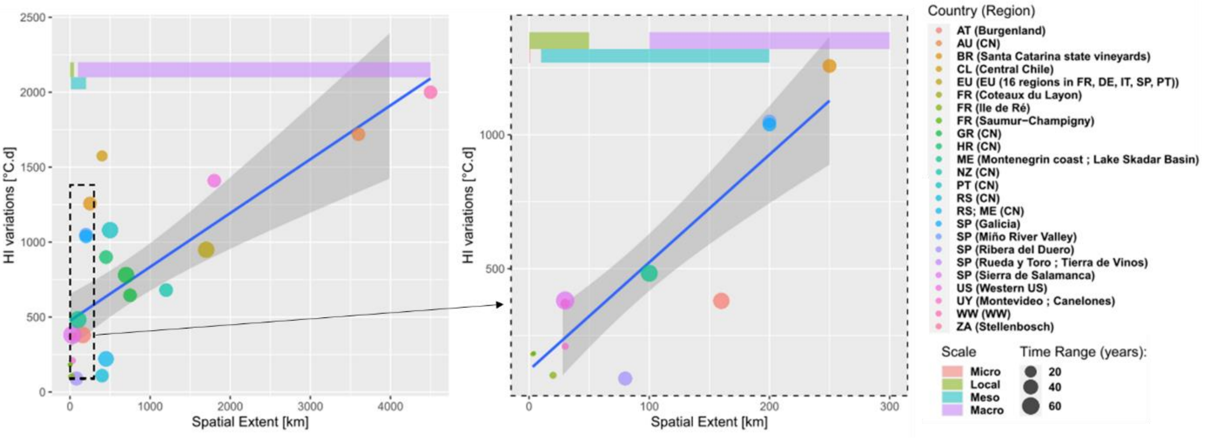

Figure 1: Huglin's Index (HI) ranges of spatial variation (y-axis) reported in the literature as a function of the spatial extent of the studied area. The right-hand plot corresponds to a zoom on the dashed area on the left-hand plot. Each point represents a vineyard, a wine producing region or a set wine producing regions where HI spatial variability has been measured or spatialized (spatial interpolation).

Finally, this meta-analysis highlights the lack of standards in climate indices and periods to study climate conditions. Amongst the 41 references analysed, 6 analysed data averages during the period 1971-2000, 3 during the period 1950-2000, 3 during the period 1980-2012 and 16 during shorter periods, from 1990 or later. In the context of climate change, triggered at the end of the 20th century, it is not relevant to compare climate of wine regions if depicted for very different periods. Besides, the use of different indices between studies prevents any comparison. A standardization for climate indices and period to characterize climate conditions and comparing climate of wine producing regions would be useful for comparing scientific studies, as well as understanding the role of climate in vitivinicultural terroirs.

Climate Zoning for Viticulture

Guidelines to perform the analysis of climate characteristics in wine producing regions can in be found in the OIV resolution 423-2012 (OIV, 2012), with updates provided by van Leeuwen and Bois (2018). Its steps are recalled below:

- *(1) Define the aims of the study*
- *(2) Choose relevant agroclimatic indices*
- *(3) Identify the potential data sources to perform the study*
- *(4) Identify climatically homogenous areas (i.e. perform a zoning)*

Time-period of climate data

The period of observations strongly depends on the relationships of the climate variables that needs to be analysed and other environmental information, more specifically topography (terrain and land cover, see Table 1). When a climate variable is strongly related to topography, the time range to collect data might be shortened to a few months or years, because the odds are that spatial structure might be similar from one year to another. For instance, spatial structures of heat summations to predict potential ripening date exhibit very similar spatial structures from one year to another in Bordeaux (Bois *et al.*, 2018) or in Burgundy (Gavrilescu *et al.*, 2018), so that analysing data for 5 years has been sufficient to provide a zoning of the potential earliness of grape maturity in both regions. On the contrary, much longer precipitation information might be needed to assess spatial structure of rainfall-related issues, because of a strong year-to-year variability of this parameter.

Spatialization

Climate zoning relies usually on climate data that has been spatialised. This means that it has been either measured or estimated in a continuous manner in space. A common way to spatialise climate is the spatial interpolation of climate data measured at weather station locations, but it can be assessed through remote sensing (e.g. radar-derived rainfall) or by means of atmospheric modelling (as recently performed by Remenyi *et al.*, 2019 for Australia wine regions). One issue of spatialisation is the resolution of the output map. Finding the "right" pixel size requires both the spatial extent of the area and the density of the sampling points (Hengl, 2006). However, practically, it is often fixed by the resolution of the digital elevation model (DEM), when terrain features (elevation, slope…) guide the interpolation process. Hence, very high-resolution cartography can be achieved (e.g. down to 5 to 100 metres), even if measurement points (e.g. weather stations) are very distant (several tens or hundreds of kilometres) in space. This might wrongfully suggest that the map is very accurate. To illustrate this issue, the spatial structure of GST maps obtained for Bordeaux wine region either using the WorldClim (version 1.4) 1 km resolution data grids for the 1970-2000 period or using daily temperature grids at 50 m resolution derived from a local network for years 2001 to 2005 has been compared. Temperature recorded by these stations has been interpolated using relationships between air temperature and terrain features, vegetation index and /or distance to water bodies (Bois *et al.,* 2018).

The spatial structure of both (WC and LSN) GST grids are shown in Figure 2. The WorldClim derived GST is mostly elevation driven, while the LSN derived GST maps exhibits some significant changes that are not elevation related. For instance, the northern part of the Pessac-Léognan appellation (PL on Figure 2) exhibit the highest GST values of Bordeaux wine region probably because of the urban heat island offer by the city of Bordeaux (black circle on Figure 2).

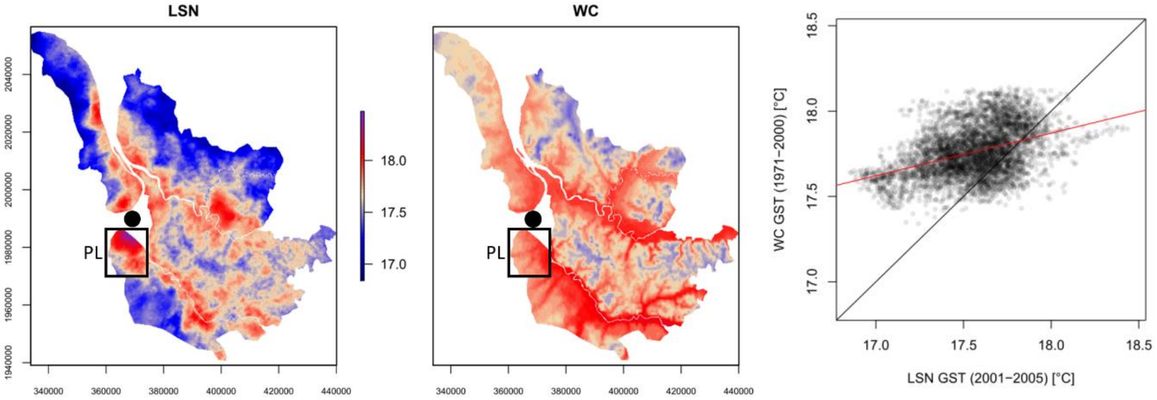

Figure 2: Comparison of Growing Season Temperatures [°C] maps. LSN = map obtained by spatial interpolation of data collected from 2001-2005 by a local network of 32 (2001) to 68 (2005) weather stations (Bois *et al.,* 2018); WC = map obtained with the WorldClim 1.4 database using data collected worldwide from 1970-2000 at 1km resolution (downscaled by bilinear interpolation at 50 m to match LSN map resolution). The black rectangle indicates the location of Pessac-Léognan (PL) appellation. The black circle indicates the location of the city of Bordeaux. The scatterplot of the righthand-side compares GST values of a subsample of 5000 pixels randomly collected on both maps at the same locations. The black and red lines correspond to linear regression and x=y curve, respectively.

Conclusions

An increasing number of publications have addressed the climate spatial variations within wine producing regions. A meta-analysis of 41 of these publications allowed for the link between spatial variability of climate and the spatial extent of the studied area to be quantified. It showed that this relationship is scale dependant but also relies on the variation in terrain features within the studied area. While GIS softwares and environmental information such as elevation offer great opportunities to depict climate variability at high resolution, one should pay attention to the significance of the spatial structure depicted on maps, as the accuracy might not be high enough to provide true representation of the climate conditions of vitivinicultural terroirs.

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