horticulturae

Article

Structural and Spatial Shifts in the Viticulture Potential of Main European Wine Regions as an Effect of Climate Change

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Abstract: Climate change modifies the base climate of the wine regions and, with it, the structure of their traditional types of wine production, imposing measures to adapt, mitigate, or capitalize on the newly emerging conditions. In order to assess the impact of climate change and establish the appropriate adaptation measures for each wine region, regional and local studies are needed, which allow knowledge of their current climate profile. The aim of this research was to identify the changes that appeared as an effect of climate change in the initial climate profile and the initial structure of the traditional types of wine production of Bordeaux (France), Loire Valley (France), Rhine-Main-Nahe (Germany), La Rioja (Spain) and Cotnari (Romania) wine regions, and also in climate suitability for wine production of the Sussex area from the UK. The study uses multi-year averages for the 1951–1990 and 1991–2010 time periods of reference bioclimatic indices for viticulture, namely the Average Temperature of the Growing Season (AvGST), the Huglin Index (HI), and the Oenoclimatic Aptitude Index (IAOe). The results of this research reveal significant changes in climate suitability for wine production of the studied wine regions: in the Bordeaux wine region, climate change led to the appearance of conditions for the cultivation of the Mediterranean climate varieties Grenache, Syrah, and Carignan; in the cool climate wine regions Rhine-Main-Nahe and Cotnari, traditional producers of white wines, the climate has also become suitable for the cultivation of Pinot noir and Cabernet franc varieties, and implicitly for the production of red wines; in all studied wine regions, the classes of climate suitability for viticulture shifted higher in altitude, as is the case of the La Rioja region, where, in the recent period, the grapevine can be grown up to 922.9 m asl, higher by 206.2 m compared to the 1951–1990 time period; in the low area of each wine region, one or even two new climate suitability classes for wine grape growing appeared. The shifts revealed by this research generate solid conclusions regarding the effect of climatic change on the viticultural potential of geographical areas, namely: in the context of climate change, the altitude of the wine region has a major influence on the evolution of the local viticulture potential; a higher topography allows a better adaptation of the wine region to climate change; low-elevation wine regions are more vulnerable to climate changes, especially the further south they are located; as an effect of climate change, conditions appear in the wine regions for the cultivation of new grapevine varieties and the production of new types of wine.

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Citation: Irimia, L.M.; Patriche, C.V.; Petitjean, T.; Tissot, C.; Santesteban, L.G.; Neethling, E.; Foss, C.; Le Roux, R.; Quénol, H. Structural and Spatial Shifts in the Viticulture Potential of Main European Wine Regions as an Effect of Climate Change. *Horticulturae* **2024**, *10*, 413. https://doi.org/10.3390/horticulturae10040413

Academic Editors: Arif Atak, Andreia Figueiredo, Inmaculada Pascual and Fermin Morales

Received: 21 February 2024
Revised: 7 April 2024
Accepted: 11 April 2024
Published: 19 April 2024

Keywords: viticulture; wine regions; climate change; wine

1. Introduction

With a wine-growing area of 3.3 million hectares, a number of 2.2 million vineyard holdings, and an annual production of about 165 million hl, the EU is, at the level of 2020, the world-leading producer of wine [1]. The EU holds 45% of global wine-growing areas, 64% of world production, and 48% of global consumption. Additionally, viticulture is the largest EU agrifood sector in terms of exports, with 7.6% of the agrifood value exported in 2020. Most of the EU's wine production is supplied by Italy, France and Spain, which jointly own 2439 million ha (75.6% of the EU's wine-growing area), but also countries such as: Romania, which has 0.844 million vineyard holdings (37.8% of the EU's wine-growing holdings) and 0.190 million ha of wine-growing plantations (5th place at the European level in terms of wine-growing area and 10 place worldwide); Portugal (0.195 million ha), or Germany (0.103 million ha) [1,2]. Given the high share of European viticulture in the global wine industry, the quantitative and qualitative yields variations that occur in European viticulture have the potential to influence the wine market at the global level. For this reason, the influence of climate change, considered a factor with a major impact on viticulture and the wine industry globally, is studied in Europe under all its aspects, the research results constituting the foundation of strategies for adapting to the new conditions, reducing their possible impact, capitalizing on newly emerging opportunities and forecasting the outlook for decades to come.

Research carried out over time confirms the key factor of climate for wine production [3–9]. Worldwide, the grapevine is grown exclusively in areas with an average annual temperature above 9 °C [10,11]. Moreover, the climate has a decisive effect on yield, especially using precipitation volume [12–14], and equally on the quality of the grapes, through a balance of climatic factors suitable to ripening grapes and the accumulation of sugars, polyphenols and aroma compounds in the berries [8]. In different climates and different regions of the world, the same values of average growing season temperature ensure the cultivation of the same wine grape varieties and obtaining the same type of wine [15]. These factors include, equally, the temperature of the warmest month [16], the average temperature of the growing season [15], values of solar radiation and insolation [17], length of the growing season [18], or effective temperatures [11]. Their action is manifested at the plant level via a certain intensity of photosynthesis and implicitly a certain amount of synthesized organic compounds; a certain intensity of malic acid degradation, resulting in a balanced or, on the contrary, deficient/excessive level of titratable acidity of the must; different intensities of the coloring of the grapes and implicitly of the wine. For the different wine-growing regions of the world, over time, against the background of the stability of the climate and the edaphic and topographical suitability of the area, these ranges of values have remained constant and have led to the production of wines with a distinct sensory profile, constant over time, which made them representative of the wine regions and, in many cases, brought them fame (Bordeaux, Rhône, Chianti, Barolo, Jerez, La Rioja, Rhine Valley, Tokay, Cotnari wine regions, etc.).

This stability of the climatic profile of the wine regions and of the sensory profile of the wines they produce has been influenced in recent decades by climate change [19]. The research carried out in the last 20 years shows that the increase in the average global temperature correlates in the case of Mediterranean and northern wine growing regions, with the increase in the accumulation of sugars in the grapes and the decrease in the titratable acidity [6], the modification of the aromatic and anthocyanin profile of the grapes and implicitly of the wines [20,21], which leads to new sensory profiles [22], which deviate, in a positive or negative sense, from the established sensory profile of wines representative of the wine regions. In the case of the European wine regions, the effects are generally positive for wine regions with cooler climates, located at higher altitudes and more northern latitudes and negative for those located in Mediterranean climates [23]. The increase in the average air temperature, coupled with the variability of the vertical thermal gradient for temperate and Mediterranean climate wine regions, leads, at the continental level, to a shift of the viticulture potential to the N in the Northern Hemisphere and to the S in the Southern Hemisphere, and also to higher elevations, simultaneously with the emergence of new areas with viticulture potential [23–26]. This evolution is also identified at the regional and even local level of the wine regions, the spatial shifts of the viticulture suitability being quantifiable [27–29] and confirmed by the appearance, in recent decades, of grapevine plantations in areas without tradition, unsuitable in the past for grape growing [30,31]. Moreover, these changes are part of broad trends whose evolution and perspectives have been thoroughly studied [24–26,32] and which indicate profound changes in the spatial distribution of viticulture potential in the coming decades.

Given the economic importance of wine production for EU countries and taking into account the possible consequences of the influence of climate change, between 2014 and 2020, an extensive study was carried out at the European level [33], looking at the impact of climate change on the Bordeaux and Loire Valley (France), La Rioja (Spain), Rhine-Main-Nahe (Germany) and Cotnari (Romania) wine regions, as well as on the Sussex area in the south-east of Great Britain, which has acquired climate suitability in recent decades for wine grape growing. One of the objectives of the research was to establish the differences in climatic suitability for wine production between an earlier reference period (1951–1990) unaffected by climate change and a more recent period (1991–2010) affected by climate change. For all these wine regions, located at different latitudes and in relatively different climatic zones, research in recent years has highlighted changes in the composition of the grapes and the typicality of the wines, the accentuation of drought, the change in climate suitability for wine grape growing, phenomena associated with the impact of climate change on viticulture [27,34–38]. Climate suitability was evaluated by using some relevant bioclimatic indices for viticulture, namely the Average Temperature of the Growing Season [15], the Huglin Index [3], and the Oenoclimatic Aptitude Index [39].

Our research aimed at identifying the changes in viticultural potential that appeared as a consequence of climate change within the six viticultural areas, their mapping for the two time periods, and the analysis of their particularities in order to obtain the necessary information for establishing viticulture adaptation strategies, in relation to the climatic zone, varieties and environmental characteristics of each wine region.

2. Materials and Methods

The research concerns areas from the Bordeaux and Loire Valley wine regions (France), Rhine-Main-Nahe wine regions (Germany), Cotnari wine region (Romania), La Rioja wine region (Spain) and the Sussex area in the south-east UK (Figure 1). The changes in climate profile of the studied wine regions and their suitability for wine grape growing were established using climate data from the 1951–1990 and 1991–2010 time periods, taken from nearby weather stations: Bordeaux Mérignac (Bordeaux), Angers (Loire Valley), Geisenheim (Rhine-Main-Nahe), Cotnari (Cotnari), Logrono (La Rioja) and Eastbourne (Sussex).

The studied wine-growing regions are located at different latitudes, in relatively different climatic conditions, and have distinct topography, which allows the identification of the specific impact of climate change in relation to latitude, ranges of elevation, and dominant climate type (Table 1). We used reference areas surrounding the wine regions for mapping the climate variables and assessing the altitudinal shifts induced by climate warming. The sizes of these areas were established so that the spatial variation of the ecological factors is well captured and the potential altitudinal and latitudinal shifts can be identified.

Figure 1. Location of studied European wine regions.

Table 1. Main data of the studied wine regions.

Wine Region	Reference Area	Latitude (°N lat)	Longitude (°)	Reference Area Size (km^2)	Reference Area Elevation Range (m, asl)	Climate Type *
La Rioja	Ausejo-Carbonera	42.45	−2.12	5210	251–1924	Cfb/subtropical maritime
Bordeaux	Bordeaux	44.89	−0.16	5600	0–199	Cfb/temperate maritime
Loire Valley	Saumur-Champigny	47.26	−0.05	223	17–119	Cfb/temperate maritime
Cotnari	Cotnari	47.34	26.95	120	90–396	Dfb/temperate continental
Rhine-Main-Nahe	Rhine-Main-Nahe	49.98	7.90	6440	60–889	Cfb/temperate transitional
Sussex	Rock Lodge	50.99	−0.04	299	0–280	Cfb/temperate maritime

* according to Köppen-Geiger climate classification [40]/European Environment Agency classification [41].

The climate variables, including the mean, minimum, and maximum monthly temperatures, and the mean monthly precipitations, were mapped based on the mean monthly altitudinal gradients of temperature and precipitation, using 30 m × 30 m resolution digital elevation models (DEM) of the study regions:

$$C_H = C_{station} + g \times (H - H_{station}), \quad (1)$$

where C_H is the estimated value of the climate variable at altitude H, $C_{station}$ is the recorded value of the climate variable at weather station altitude ($H_{station}$), and g is the altitudinal gradient (per meter change of climate variable).

Therefore, our study performs an elevation-based analysis of climate suitability for vine in the test areas. The DEMs were extracted from the global Shuttle Radar Topography Mission (SRTM, https://doi.org/10.5066/F7F76B1X). In the applied in GIS environment, the H parameter in Equation (1) is the digital elevation model (DEM). The gradient values (g) of temperature and precipitation were computed in NewLocCLim v 1.1 software [42] based on the available meteorological station data surrounding the wine regions. In our study, the spatial analysis was carried out mostly in ArcGIS v 10.8 software [43]. We also used the SAGA-GIS v 9.3.0 software [44] to derive the potential (clear sky) sunshine duration, and then the mean sunshine fraction values, obtained from NewLocClim software, were used to achieve the actual sunshine duration:

$$ASD = PSD \times f, \quad (2)$$

where ASD is the actual sunshine duration (hours), PSD is the potential sunshine duration (hours), and f is the sunshine fraction.

These basic climate variables (temperature, precipitations, sunshine duration) were further used to derive bioclimatic indices: Average Growing Season Temperature [3,15]; Hugin Index; Oenoclimatic Aptitude Index [39,45]; Average Annual Temperature; Growing Season Precipitations (Table 2).

Table 2. Climate variables were used to study the climate profile of the six wine regions and their suitability for wine grape growing during the 1951–1990 and 1991–2010 time periods.

Variable	Equation	Months	Class Limits		
Average Growing Season Temperature (AvGST, °C) [15]	$\frac{\sum_{Apr1}^{Oct31}\left(\frac{Tmax+Tmin}{2}\right)}{n}$ where Tmin is minimum daily temperature (°C); Tmax is maximum daily temperature (°C); n is the number of days in the growing season (1 April–31 October).	April–October	Too cool		<13 °C
			Cool		13–15 °C
			Intermediate		15–17 °C
			Warm		17–19 °C
			Hot		19–21 °C
			Very hot		21–24 °C
			Too hot		>24 °C
Huglin Index (HI, °C units) [3]	$K\sum_{Apr1}^{Sep30}\frac{(Tmean-10)+(Tmax-10)}{2}$ where Tmean is mean daily temperature (°C); Tmax is maximum daily temperature (°C); K is the latitude coefficient depending on daylength (latitude).	April–September	HI-3	Very cool	<1500
			HI-2	Cool	1500–1800
			HI-1	Temperate	1800–2100
			HI+1	Temperate warm	2100–2400
			HI+2	Warm	2400–3000
			HI+3	Very warm	>3000
Oenoclimatic Aptitude Index (IAOe, units) [39,45]	IAOe = ASD + Σta − (P − 250) where ASD is the actual sunshine duration (hours), Σta is the sum of active temperatures (sum of daily temperatures >10 °C in the growing season, P are precipitations (mm), 250 is minimum precipitation needed for unirrigated vines (mm), if precipitations are <250 mm, the difference (P − 250) is set to zero.	April–September	restrictive for grape growing		<3793
			white table wines, sparkling wines, wines for distillates		3793–4300
			quality white wines, red table wines		4301–4600
			quality red and white wines		>4600
Average Annual Temperature (AAT, °C) [45]	AAT = $(\Sigma t_m)/12$ where t_m are the mean monthly temperatures	January–December	restrictive for grape growing		<8.5
			white table wines, sparkling wines, wines for distillates		8.5–9.3
			quality white wines, red table wines		9.4–10.0
			quality red and white wines		10.1–11.2
Growing Season Precipitation (GSP, mm) [45]	GSP = ΣP_m where P_m are the mean monthly precipitations from April to September	April–September	white table wines, sparkling wines, wines for distillates		>390
			quality white wines, red table wines		<250
			quality red and white wines		251–390

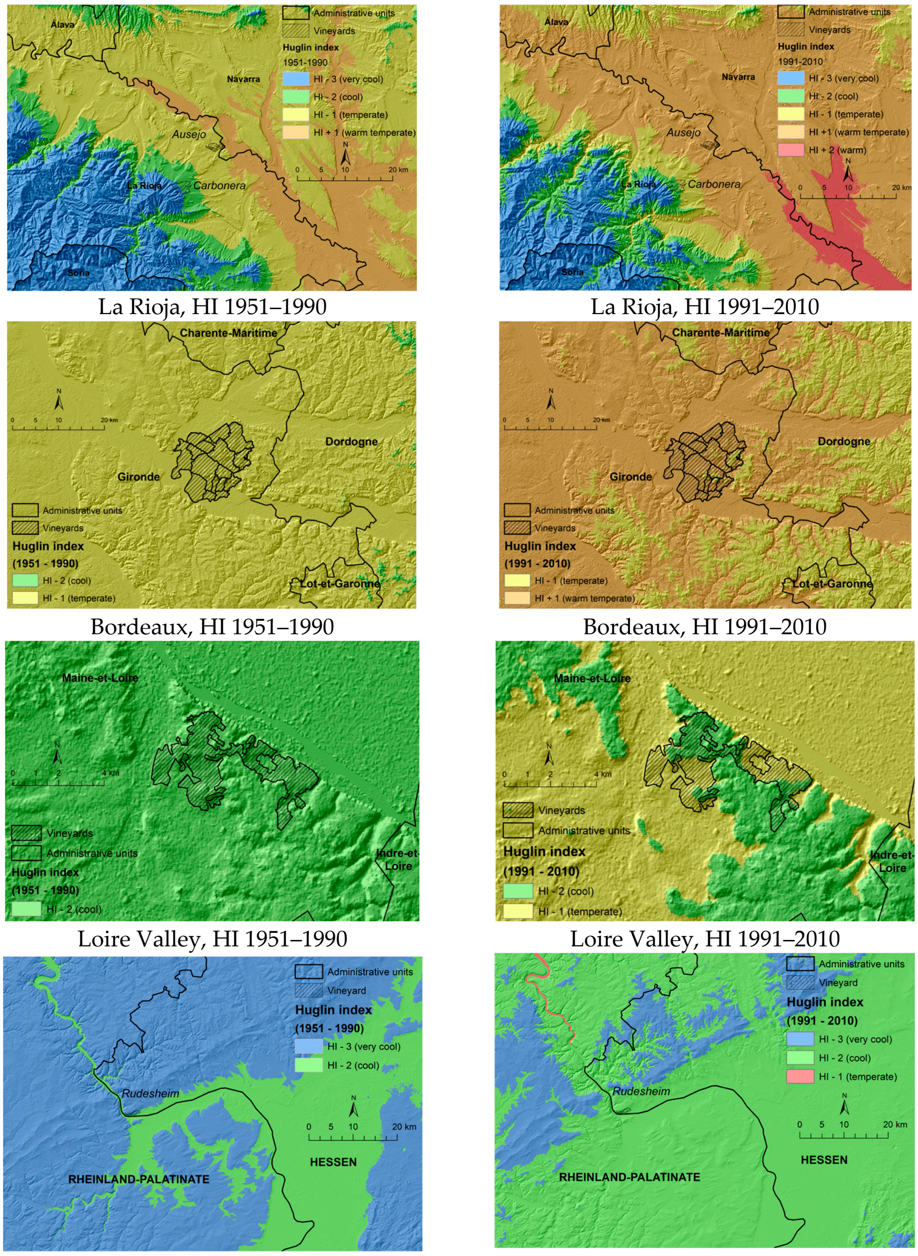
Note: AvGST, Huglin index, and IAOe are computed based on monthly values.

The climate suitability for grapevine growing and wine production of the six wine growing areas was assessed based on average multiannual values for the 1951–1990 and 1991–2010 time periods of the above presented bioclimatic indices AvGST, HI, IAOe, and AAT. The values of these parameters were extracted within the limits of the mapped wine regions, classified according to their specific methodologies, and compared for the two time periods.

3. Results

3.1. Variations of Parameters and Bioclimatic Indices Representative of the Climate of the Studied Wine Regions

The comparative analysis of the multi-year averages of the climate parameters and bioclimatic indices for the 1951–1990 and 1991–2010 time periods indicates their modification and, implicitly, the modification of the initial climate profile of all the studied wine-growing areas, regardless of the latitude at which they are located (Table 3).



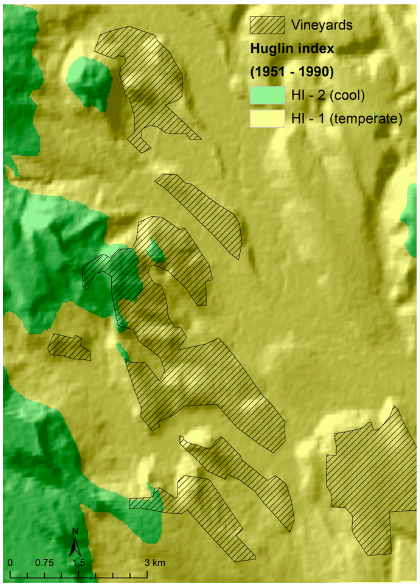
La Rioja, HI 1951–1990 La Rioja, HI 1991–2010

Bordeaux, HI 1951–1990 Bordeaux, HI 1991–2010

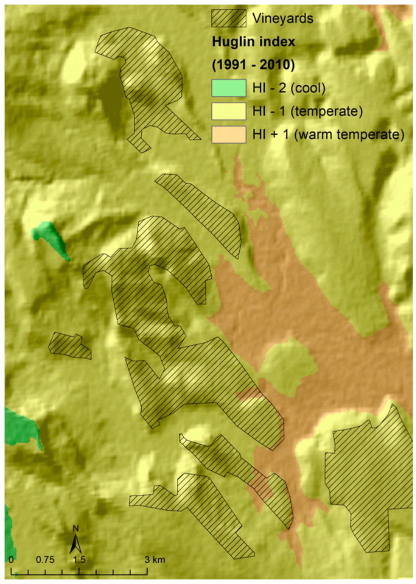
Loire Valley, HI 1951–1990 Loire Valley, HI 1991–2010

Rhine-Main-Nahe, HI 1951–1990 Rhine-Main-Nahe, HI 1991–2010

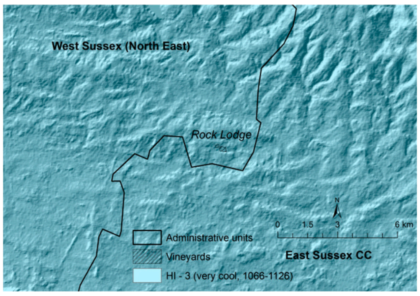
Figure 2. *Cont.*



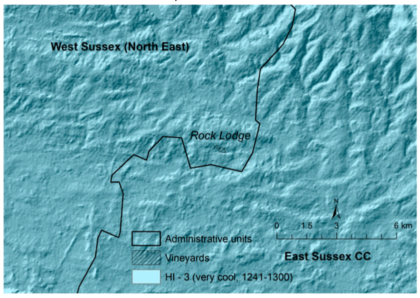
Cotnari, HI 1951–1990



Cotnari, HI 1991–2010



Sussex, HI 1951–1990



Sussex, HI 1991–2010

Figure 2. Shifts in the spatial distribution of the Huglin Index (HI) for the 1951–1990 and 1991–2010 time periods in studied wine regions.

Table 3. Mean values (avg.) and differences (diff.) for some climate parameters and bioclimatic indices for the 1951–1990 and 1991–2010 time periods.

Wine Region	N Latitude (°)	Time Period	AAT (°C)		GSP (mm)		AvGST (°C)		HI (Units)		IAOe (Units)	
			Avg. *	Diff. **	Avg.	Diff.	Avg.	Diff.	Avg.	Diff.	Avg.	Diff.
La Rioja	42.45	1951–1990	10.6	+0.6	243.9	+16.7	15.2	+0.9	1534.8	226.2	4206.9	154.6
		1991–2010	11.2		260.6		16.1		1761.0		4361.5	
Bordeaux	44.89	1951–1990	12.7	+1.3	387.1	+40.0	16.9	+1.6	1830.1	286.4	4302.6	254.8
		1991–2010	14.0		427.1		18.5		2116.5		4557.4	
Loire Valley	47.26	1951–1990	11.3	+0.9	270.8	+49.3	15.6	+1.0	1597.9	201.7	4097.7	133.6
		1991–2010	12.2		320.1		16.6		1799.6		4231.3	
Cotnari	47.34	1951–1990	9.6	+0.8	342.7	+12.1	16.3	+0.5	1860.2	164.0	4228.6	307.4
		1991–2010	10.4		354.8		16.8		2024.2		4534.2	
Rhine-Main-Nahe	49.98	1951–1990	9.4	+0.9	310.9	−16.8	14.8	+1.1	1472.2	232.8	3662.1	218.1
		1991–2010	10.3		294.1		15.9		1705.0		3880.2	
Sussex	50.99	1951–1990	10.5	+0.8	328.3	+3.4	13.8	+0.8	1078.5	174.6	3696.8	143.0
		1991–2010	11.3		331.7		14.6		1253.1		3839.8	
Averages/Differences		1951–1990	10.8	+0.8	313.9	+17.4	15.4	+0.9	1564.7	+214.3	4032.4	+201.6
		1991–2010	11.5		331.4		16.4		1779.0		4234.0	

* Average; ** Differences. Note: the means were computed for the areas denoted as "vineyards" in the maps from Figure 2.

The average annual temperature (AAT) of the 1991–2010 time period recorded higher values by 0.6 to 1.3 °C compared to 1951–1990, with an absolute average for all six areas of +0.8 °C. If, in the case of the Cotnari wine region, the increase in AAT by 0.8 °C leads during the 1991–2010 period to the acquisition of the potential for quality wine production [46], in the case of the Bordeaux wine region, the increase of 1.3 °C leads the AAT to an average of 14.0 °C for the 1991–2010 time period, the highest of all studied wine regions and in the range of average annual temperatures that assure the production of great wines [47].

Precipitation during the growing season (GSP) records, in the more recent 1991–2010 time period, compared to 1951–1990, variations between −16.8 mm in the case of the Rhine-Main-Nahe wine regions and +49.3 mm in the Loire Valley (Table 3). The rainfall requirement of the vine during the growing season is 300–350 mm [10]. In relation to this value, the research data indicate the maintenance of the precipitation deficit in the La Rioja wine region, with a GSP value in the recent time period at 260.6 mm, a decrease below the minimum threshold of 300 mm in the Rhine-Main-Nahe wine regions, from 310.9 mm previously to 294.1 mm in the recent period; exceeding the minimum threshold of 300 mm of GSP and implicitly a better water supply to the grapevine in the Loire Valley, by increasing the GSP from 270.8 mm to 320.1 mm in the more recent time period. For Bordeaux, Cotnari, and Sussex wine regions, the GSP values are maintained in the range considered optimal for grape growing and wine production. However, the increase in temperature in the context of climate change [48] determines a corresponding increase in the potential evapotranspiration, which may, in turn, negatively affect the soil water content, exposing the vines in these areas to water stress, especially in Cotnari area, a situation already anticipated in previous research [35,49].

The average temperature of the growing season (AvGST) registers increases in all six wine regions, with values between +0.5 °C in the Cotnari wine region and +1.6 °C in the Bordeaux wine region, with an average of 16.41 °C for all six areas, 0.98 °C higher than between 1951 and 1990. At the level of the wine regions, however, the AvGST developments are different, as follows: the La Rioja, Loire Valley, and Cotnari wine regions remain in the *intermediate* class, suitable to the Riesling, Pinot noir, Chardonnay, Sauvignon, Sémillon, and Cabernet franc varieties [15]; the Bordeaux wine region, after an increase of 1.6 °C in AvGST, passes from the *intermediate* climate class between 1951 and 1990 to the *warm* climate class during the 1991–2010 time period, suitable including for the Mediterranean climate varieties Grenache, Syrah and Carignan [15]; the Rhine-Main-Nahe wine regions go from the *cool* climate, suitable to varieties for white wines Muller-Thurgau, Pinot Gris, and Gewurztraminer to the *intermediate* climate class, suitable also for the production of red wines from Pinot noir and Cabernet franc wine grape varieties; the AvGST for the Sussex wine region maintains in the *cool* climate class suitable for very early varieties such as Muller-Thurgau (Table 3).

The Huglin Index (HI) recorded higher values between 1991 and 2010, 164.1 to 286.4 units, compared to the period from 1951 to 1990 (Table 1). The HI increases marks the transition of the wine regions climate to higher classes of suitability for wine production, as follows: the Bordeaux wine region shifts from the temperate climate class (HI-1), suitable for Cabernet franc, Cabernet Sauvignon, Merlot and Ugni blanc to the temperate warm class (HI+1), suitable also for the Mediterranean varieties Grenache, Mourvedre, Carignan [50]; in the Rhine-Main-Nahe wine regions, HI goes from the very cool class (HI-3) suitable for very early varieties such as Muller-Thurgau, to the cool class (HI-2) suitable also for Pinot noir, Merlot, Cabernet franc [50]; the Loire Valley wine region maintains in the cool class (HI-2), but with a higher average of 201.7 units than between 1951 and 1990, which places it on the threshold of transition to HI-1 [50]; the viticulture potential of the Cotnari and La Rioja wine regions, placed between 1951 and 1990 at the lower limit of the temperate (HI-1) and cool (HI-2) classes, respectively, increased to the upper limit of the same classes; in the Sussex wine area HI maintains in the very cool class (HI-3), but with a higher average of 174.6 units than between 1951 and 1990 (Table 3).

The Oenoclimatic Aptitude Index (IAOe) records significant increases in all wine-growing regions, interpreted as an increase in suitability for the diversification of wine grape varieties and types of wine production. The most significant developments are recorded in (Table 3): Cotnari wine region which goes from climatic suitability for white wine production to suitability for red wine production; and Sussex, where the value of IAOe during 1991–2010 exceeds 3793 units, indicating the acquisition of climate suitability for white table wines and sparkling wines production. The highest increase in IAOe for the Cotnari wine region, located most to the east, could be explained by the increase in the duration of the insolation towards the east of the continent as a result of the aridification of the climate [51].

3.2. Spatial Shifts of Climate Suitability Classes during the 1991–2010 Compared to 1951–1990 Time Period

Mapping the averages of climatic parameters and bioclimatic indices from the two time periods revealed significant differences in their spatial distribution in the studied areas (Figure 2). These differences are represented by the appearance in the wine regions during the 1991–2010 time period of new classes of climate suitability, which radically changed the structure and weight of the types of wine production specific to the 1951–1990 time period. Such shifts of suitability classes have been highlighted and described at large in our previous research [28,29,52].

The spatial distribution of the Huglin index reveals that, in all studied areas, the new suitability classes appear in the low area, while the classes of the old, traditional climate of the wine region move higher up in altitude, narrowing spatially towards the top of the hills and disappear, one by one, at the altitude at which the temperature becomes unsuitable for grape growing (Table 4).

Table 4. Shifts on altitude of the HI classes in the studied areas, as an effect of climate changes, for the 1951–1990 and 1991–2010 time periods.

	Classes of the Huglin Index (HI)	Saint-Émilion (Bordeaux)		Ausejo-Carbonera (La Rioja)		Rhine-Main-Nahe (Rhine Valley)		Cotnari (Cotnari)		Rock Lodge (Sussex)		Saumur Champigny (Loire Valley)	
		1951–1990	1991–2010	1951–1990	1991–2010	1951–1990	1991–2010	1951–1990	1991–2010	1951–1990	1991–2010	1951–1990	1991–2010
Highest altitude	HI-3 (very cool)	-	-	1160.3	1266.1	309.2	471.3	-	-	57	57	-	-
↑	HI-2 (cool)	150.9	-	716.7	922.9	107.1	209.6	280	360	-	-	48.6	81.1
	HI-1 (temperate)	54.4	99.8	448.6	641.2	-	68.1	149	180	-	-	-	34.8
	HI+1 (temp. warm)	-	39.3	313.0	406.3	-	-	-	106	-	-	-	-
	HI+2 (warm)	-	-	-	277.1	-	-	-	-	-	-	-	-
Lowest altitude	HI+3 (very warm)	-	-	-	-	-	-	-	-	-	-	-	-

The average altitude (m, asl) at which the Huglin Index classes are found during the two time periods (m, asl)

The research results indicate that, in the Bordeaux wine growing region, during the 1991–2010 period, the temperate class (HI-1) was located at 99.8 m asl, compared to 54.4 m asl in the 1951–1990 period (Table 4). At the same time, in the low area of the wine region, at 39.3 m asl, we find the newly appeared climate class, not specific to the area, temperate-warm class (HI+1), which is specific to wine regions in Mediterranean climate, such as Montpellier or Napa Valley [3,50]. Also, the cool class (HI-2) disappeared from the area, while between 1951 and 1990, it was located at an average altitude of 150.9 m asl (Figure 2).

In the La Rioja wine region, between the 1991 and 2010 time periods, all the old climate classes are found, but each of them at a higher altitude of about 200 m than during the 1951–1990 time period (Table 4). In the low area of this wine region, at an average altitude of 277.1 m asl, one can find that during the more recent time period, the newly appeared warm climate class (HI+2). It is noted that, in the La Rioja wine region, the high topography allowed the climate suitability for grape growing to move up to 1266.1 m asl between 1991 and 2010, higher by 105.8 m as compared with 1160.3 m asl during the 1951–1990 period.

Similar developments can be found in all the other wine regions: in the low area of the Rhine-Main-Nahe wine regions, at 68.1 m asl, we find between 1991 and 2010, the temperate climate class (HI-1), newly appeared in the area and allowed production of red wines from Cabernet Sauvignon and Merlot, while climate suitability for the wine varieties extended in altitude up to 471.3 m asl, compared to 309.2 m asl between 1951 and 1990. In the Cotnari wine region, the cool HI-2 class and implicitly the suitable conditions for wine grape growing extended higher in altitude by 120 m, up to 360 m asl, while a new climate suitability class (HI+1) appeared in the low area at 106 m asl, increasing the potential for red wines production of this region. In the Sussex area, the very cool climate class (HI-3) maintains on the entire region, while in the low area of the Loire Valley, at an average altitude of 34.8 m asl, under the old HI-2 climate class, which shifted 32.5 m to higher altitude, the temperate climate class (HI+1) appeared.

The analysis of the spatial distribution by altitude reveals the fact that the types of climate suitability, and implicitly the potential types of wine production, are all the more diverse and numerous the further south the wine region is located and the higher the altitude in its area (Table 4). The developments observed in the altitudinal distribution suggest that continuing on the same trend of increasing climate change and implicitly climate warming would lead to the appearance in the studied wine regions and, subsequently, the extension towards high altitude of the very warm climate class (HI+3), the last of those that allow the economically efficient cultivation of the grapevine.

4. Discussion

The analysis of climate parameters, bioclimatic indices, and spatial shifts of their suitability classes during the 1951–1990 and 1991–2010 time periods revealed the changes of the base climate profile and implicitly of the climate suitability for wine grape growing in the Bordeaux, Loire Valley, Rhine-Main-Nahe, La Rioja, Cotnari and Sussex regions. The changes are in the category of those recorded so far in viticulture globally or expected to occur as an effect of climate change [18,23,24,53–56] and which is embodied in the modification of the climate suitability structure for the wine production of traditional wine regions; the expansion of wine grape growing conditions to higher altitudes and more northern latitudes; the appearance of new suitable areas for grape growing; the possible degradation of climatic conditions for viticulture in the current Mediterranean wine growing regions.

The generating factor of these changes is the increase in temperatures, expressed in our research mainly by the Average Annual Temperature (AAT), the Average Temperature of the Growing Season (AvGST), the Huglin Index, and secondarily, by the Oenoclimatic Aptitude Index (IAOe).

The increase in the multiannual average value of the thermal parameters in the studied areas during the 1951–2010 time period is subsumed to the general increase in the global average temperature of 0.74 °C for the 1906–2005 time period [19]. The annual growth rate of AAT varies between 0.01 °C/year for the La Rioja wine region and 0.02 °C/year for the Bordeaux wine region, values lower than those reported in previous research for European wine regions and comparable periods, respectively, of 0.06 °C/year for Herault in southern France [57], or 0.036–0.051 °C/year for southern Poland [58]. Even if AAT is not a widespread indicator in the evaluation of the viticultural climate because it can mask extreme weather events, harmful to the vine and to wine quality [59], its values are relevant because they show the limits that allow the grapevine culture in an area (>9.0 °C) or the possibility of obtaining quality wines (>10.0 °C) [46].

The average growing season temperature (AvGST), which increased globally by 1.3 °C between 1950 and 1999 and by 1.7 °C in Europe between 1950 and 2004 [23], records at the level of the studied wine regions an average increase of 0.98 °C for the 1951–2010 time period, with a maximum of +1.6 °C in Bordeaux and a minimum of +0.50 °C in Cotnari wine region. The values revealed in this research are comparable to values reported by previous research: +1.76 °C for Bordeaux between 1950 and 1999 [23]; +0.7 °C for the Rhine Valley between 1950 and 2000 [49]; +1.3 to +1.8 °C for the Loire Valley between 1960 and 2010 [60]; +2.3 °C for Veneto between 1964 and 2009 [61]. In the case of the Rhine-Main-Nahe wine regions, the AvGST shows for the 1951–2010 time period an increase of 1.1 °C, which aligns this wine region to the general evolution of climate suitability recorded in the last decades in European wine regions. The average of 14.6 °C for AvGST in Sussex during 1991–2010 is in the range of 13–15 °C found for this region by [62], which is acceptable for cool climate viticulture in the area.

Our research shows that all these increases in AvGST are accompanied by major changes in climate suitability for wine production, revealing in several cases the transition of local climate to a different class of suitability than that specific to the base climate of the wine region.

A similar type of evolution reveals the change in the multi-year averages of the Huglin index for the studied wine regions, which agrees with the results of other research: for the Rhine-Main-Nahe, our findings similarly correspond with trends of the HI shown by [63] for the Palatinate and by [48] for the 1972–2002 in Colmar (southern Alsace, France); for Bordeaux, the transition of HI to a new suitability class, temperate-warm, is supported by recent results provided by [64] for the 1977–2002 time period and [65] for 1956–2017; HI evolutions for La Rioja, are supported by similar results for 1950–2015 provided by [66]; for Cotnari, we find similar results for the period 1961–2013, indicating the transition of HI to the temperate class [28].

All these evolutions of the temperature-based indices reveal the modification of the climate of wine regions in the sense of increasing suitability for wine production. On the other hand, taking into account the existing close correlation between the growing season temperature and the phenological development of vines [4], AvGST increases are also accompanied by changes in the rhythm of the phenophases and in the chemical composition of grapes [48,60]. Moreover, among the information provided by viticultural research, data from Romania indicate that an increase of 0.2–0.4 °C in the average annual temperature is accompanied by increases in the sugar content of 12 to 20 g/L, decreases in the total acidity at ripening of 0.75 to 1.8 g/L tartaric acid, increases of 100 mg/kg of anthocyanins in the grapes [67], favorable developments that confirm the increase in viticulture potential for quality red wines production in the southern Romania found in previous research [27].

Our research shows that climate change causes significant spatial shifts in the viticulture potential in wine-growing regions, a fact expected or demonstrated by numerous previous research papers [24,25,28,52,54]. Along with these spatial shifts, in the wine regions, there is the need to relocate the traditional varieties on the sites with their corresponding viticulture potential in order to adapt the local viticulture to the new conditions of climate suitability by introducing new varieties [68] and, implicitly, technological adaptation, through decisions such as changing vine management systems or using new rootstocks [69]. As our study demonstrates, while northern wine-growing regions such as Rhine-Main-Nahe, Sussex, and Cotnari are experiencing significant increases in the potential to produce quality wines on old sites and altitudes, in the wine regions located at more southern latitudes (La Rioja, Bordeaux) the old classes of climate suitability shifts higher in the area, the lower area gradually becoming warmer. As a consequence, in the southern wine regions, the need to move the grapevine culture to higher altitudes with a more suitable climate for grape growing could appear in the future, as predicted in previous research: possible need to relocate wine plantations in the warm south of Italy to altitudes higher than 600–800 m [70], or relocating wine plantations from the island and coastal regions of Greece to the higher mountain areas [71].

According to our research, the altitudinal shifts involve the movement of the old, cooler climate classes to higher altitudes and the appearance in the low area of the new, warmer suitability classes, which leads to the diversification of the wine type production of the wine regions, if the topography is high and allows this kind of development. As an example, in the La Rioja wine region, the cool suitability class (HI-2) shifted from 716.7 m asl in the past to 922.9 m asl between 1991 and 2010, while a new suitability class appeared in the lowland, respectively, the warm class (HI+2). This result is in perfect agreement with similar developments expected for Serbia [72], Austria [73], Hungary [74], Romania [52], Germany [75], or for the high-altitude regions of northwestern Spain [26,76]. For lowland wine regions, such as Sussex (57 m asl), with no available altitude for climate class expansion or shift, the old suitability class or classes are only gradually replaced by new, increasingly warm suitability classes generated by rising temperatures due to climate change.

Our analysis of the evolution of climate conditions in several large European wine regions highlights the fact that climate change has significantly influenced their base climate and the traditional types of wine production. The follow-up of these developments must be carried out further, at the fine scale, of the wine region in relation to the influence of local topography [77], the impact on the vines, the characteristics of the yield, and the sensory profile of the wines produced in order to adapt the local viticulture to climate change, to reduce its unwanted effects on viticulture or capitalize on the opportunities that arise.

5. Conclusions

The results of our research, in full agreement with those of global research on the same subject, reveal the fact that climate change has the potential to reconfigure European viticulture by changing the traditional structure of the types of wine production of wine regions, changing their surface, the appearance of new suitable areas for viticulture and the expansion of the suitable area for grape growing towards higher altitudes and more northern latitudes. The change in the structure of production types is closely related to the ranges of elevation of the wine regions, with areas with new viticulture potential appearing in the lowest zone of wine regions, while the classes of initial climate suitability move higher in altitude. The greater the topography and the more southerly the wine region, the greater the variability of climate suitability classes on altitude in the wine region area. A greater range of topography allows a better adaptation of the wine region to climate changes by maintaining specific climate suitability, which moves to a higher altitude. Low-elevation wine regions are more vulnerable to climate change, especially the further south they are located. In their case, with the increase in temperatures, the suitability classes for viticulture should be successively replaced until the entire viticulture potential of the area disappears and the dominance of high temperatures exceeds the climate suitability for wine-growing. At the same time, the climate suitability for viticulture is gradually expanding northwards towards cold regions, which were previously climatically restrictive for viticulture.

Our research provides information that winegrowers and policymakers from each studied wine region can use to establish effective measures of viticulture adaptation to climate change. Although, at a general level, the developments are converging towards the warming of the climate, the environmental situation of each wine region in particular, requiring approaches adapted to the local grapevine varieties, the specific production technologies, and the types of wines that represent them, in order to preserve their specificity.

Author Contributions: Conceptualization, L.M.I.; methodology, L.M.I. and C.V.P.; software, C.V.P.; validation, L.M.I. and C.V.P.; formal analysis, C.V.P. and H.Q.; investigation, C.V.P., L.M.I., T.P., C.T., R.L.R., L.G.S., E.N. and C.F.; resources, C.V.P., T.P., C.T., L.G.S., E.N., C.F., R.L.R. and H.Q.; data curation, L.M.I. C.V.P. and R.L.R.; writing—original draft preparation, L.M.I.; writing—review and editing, L.M.I. and C.V.P.; visualization, H.Q.; supervision, L.M.I.; project administration, H.Q. and C.V.P.; funding acquisition, L.M.I., C.V.P. and H.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was carried out in the frame of the LIFE13 ENV/FR/001512 project Adaptation of viticulture to climate change: high resolution observations of adaptation scenario for viticulture, and benefited by the financial and logistic support of the LIFE13 ENV/FR/001512 project and the support of the PN-III-P4-PCE-2021-1350 project: Modeling current and future land suitability for crops in Romania under climate change scenarios (RO-CROP), funded by the Ministry of Research, Innovation and Digitization, CNCS—UEFISCDI, Romania, within PNCDI III.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank to Laure de Rességuier (Bordeaux Sciences Agro, France) and Marco Hofmann (Hochschule Geisenheim University, Germany), for their valuable suggestions which helped improve our research.

Conflicts of Interest: The authors declare no conflicts of interest.

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