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Bioclimatic Characterization Relating to Temperature and Subsequent Future Scenarios of Vine Growing across the Apulia Region in Southern Italy

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Abstract: The progressive climate change has an impact on the quantity and quality of grapes. Among meteorological parameters, air temperature is believed to have a direct influence on grape yield and composition, as well as on the organoleptic characteristics of wines. Therefore, in this work three bioclimatic indices based on temperature have been considered, with the aim of classifying the climate in the winegrowing region of Apulia (southern Italy) based on historical periods of thirty years (1961–1990 and 1991–2022) and verifying its evolution in the future in relation to global warming under two different Shared Socioeconomic Pathways, SSP2–4.5 and SSP5–8.5, by combining four global climate models. The results showed that the period 2021–2040 was almost unchanged compared to the last historical period of 1991–2022. The differences between the two SSPs became more pronounced as time progressed until the end of this century. By 2081–2100, SSP2–4.5, considered the most likely and mildest future scenario, demonstrated the existence of areas still suitable for quality viticulture, mainly in the higher altitudes of the Murgia plateau, the Gargano promontory and the Pre–Apennine area. In contrast, SSP5–8.5, described as “highly unlikely”, showed a dramatic shift of more than 90% of Apulia region to “too hot” classes to ensure the survival of viticulture for all the bioclimatic indices considered. These results suggest the winegrowers should consider short– and long–term solutions and adaptations in order to preserve the regional tradition and wine quality and to plan the Apulian viticulture for future scenarios.

Keywords: bioclimatic indices; Shared Socioeconomic Pathways; spatialization; Apulia; viticulture

Citation: Gentilesco, G.; Coletta, A.; Tarricone, L.; Alba, V. Bioclimatic Characterization Relating to Temperature and Subsequent Future Scenarios of Vine Growing across the Apulia Region in Southern Italy. *Agriculture* **2023**, *13*, 644. https://doi.org/10.3390/agriculture13030644

Academic Editor: Manuel Ângelo Rosa Rodrigues

Received: 13 February 2023
Revised: 2 March 2023
Accepted: 8 March 2023
Published: 9 March 2023

1. Introduction

In recent decades, climate change has become a topic of global and transversal interest, because of its enormous impact on various production systems, including the wine sector. It is well known that viticulture is strongly affected by climate variability [1,2], mainly due to temperature increase, which directly affects grape yield and composition, wine organoleptic characteristics [3], shift or shortening of entire growing seasons or the duration of single phenological phases [4]. Certainly, precipitation or other weather/climate factors also have their effects on grapevines, but temperature is the most influential factor in overall grape growth and productivity [5]. Temperature is expected to increase by 0.3 °C to 1.7 °C over the next 20 years and reach even higher values in the following decades [6]. As a result, several areas of the Mediterranean basin, which are historically considered as III and IV centers of the domestication of grapevines [7,8], are affected by a dramatic process of desertification [9]. In fact, the Mediterranean area is considered a hotspot of climate change [10,11], where the increase of soluble solids in berries, the decrease of anthocyanins and titratable acidity content, and incomplete or slow fermentative processes will occur as a consequence of the temperature increase [12]. Therefore, in some areas traditionally dedicated to viticulture, the suitability of the environment is decreasing due to climate change. In contrast, other areas are gaining suitability for the production of quality wines based on the concept of vineyard relocation in terms of higher latitudes or elevations [13].

Apulia region in southern Italy exhibits the typical Mediterranean climate with quite hot summers and mild winters and has an ancient winemaking tradition with 4 Controlled and Guaranteed Denomination of Origin (DOCG) wines, 28 Controlled Denomination of Origin (DOC) wines and 6 Typical Geographic Denomination of Origin (IGT) wines currently in production and regulated by disciplinary productions [14]. The regional territory is administratively divided into three different homogeneous winegrowing districts: Capitanata (Foggia province); Central Murgia (BAT and Bari provinces) and Salento–Jonic Arc (Taranto and Lecce provinces) [15]. In total, more than 87,000 ha of vineyards are currently cultivated for wine production in Apulia, which represents about 13% of the total Italian winegrowing area [16].

The use of bioclimatic indices based on temperature is an efficient and synthetic tool to represent the climatic evolution of an area in relation to grape production. These indices include Growing Season Temperature (GST) [17], Huglin Index (HI) [18] and Winkler Index (WI) [19] (Table 1), which have been widely considered in studies of historical characterization and future climate projections for different viticultural areas around the world [1–4,6,20]. GST represents the mean temperature of the growing season, is closely related to the ripening potential of a wine grape variety in terms of sugar accumulation and is calculated on an annual basis; HI helps characterize areas based on their potential for viticulture, is based on a six–month period from April to September that overlaps with the grapevine growing season, takes into account maximum temperatures and a coefficient of day length based on latitude and, similar to GST, shows a good correlation with the potential of sugar content of the grape variety [21]; WI, also known as Growing Degree–Days (GDD), refers to the period from April to October and takes into account a base temperature of 10 °C, below which the vines are unlikely to grow, and can be taken into account in the prediction of phenological phases. The bioclimatic indices are easy to calculate, and the data on temperatures are available and can be effectively geo–spatialized, providing a comprehensive context of the variability and suitability of different areas for viticulture.

Table 1. Bioclimatic indices considered and class partitioning.

Bioclimatic Index	Formula	Classes
Growing Season Temperature (GST)	$GST = \sum_{01st\ Apr.}^{31st\ Oct.} \frac{[(Tmax+Tmin)]}{2} / n$	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)	$HI = \sum_{01st\ Apr.}^{30th\ Sept.} \frac{[(Tmean-10)+(Tmax-10)]}{2} d$ d: adjustment for latitude/day length 1.02 for latitude comprised between 40° and 42° 1.00 for latitude below 39°	Too cool < 1200 Very cool = 1200–1500 Cool = 1500–1800 Temperate = 1800–2100 Warm temperate = 2100–2400 Warm = 2400–2700 Very warm = 2700–3000 Too hot > 3000
Winkler Index (WI)	$WI = \sum_{01st\ Apr.}^{31st\ Oct.} \left[\frac{(Tmax+Tmin)}{2} - 10\right]$	Too cool < 850 (Region I) 850–1389 (Region II) 1389–1667 (Region III) 1667–1944 (Region IV) 1944–2222 (Region V) 2222–2700 Too hot > 2700

In 2021, the Intergovernmental Panel on Climate Change [22], based on the Coupled Model Intercomparison Project Phase 6 (CMIP6) [23], produced the Sixth Assessment Report (AR6), which identified the imminent risk of a 1.5–degree rise in the near future and predicted future climate trends using a range of emission scenarios driven by different socioeconomic assumptions called Shared Socioeconomic Pathways (SSPs). In other words, the SSPs proposed by AR6 integrate and complement the "Representative Con–centration Pathways" (RCPs) previously used to generate emissions pathways in the 2014 AR5 [24]. Specifically, five future scenarios resulting from the combination of the previous RCPs with SSPs were proposed with different greenhouse gas (GHG) emissions between now and 2100: SSP1–1.9 (very low GHG emissions); SSP1–2.6 (low GHG emissions); SSP2–4.5 (intermediate GHG emissions); SSP3–7.0 (high GHG emissions); and SSP5–8.5 (very high GHG emissions). SSPs represent a link between socioeconomics, culture, industry, ecosystems and tourism in an area [25]. Specifically, Hausfather and Peters [26] reported emission pathways leading to SSP5–8.5 as largely unlikely, as fossil fuel use would increase fivefold, while SSP2–4.5 is considered the most plausible, with a warming of 3 °C above pre–industrial levels by the end of the century, instead of the feared 5 °C in the worst–case scenario. In this context, different international institutions have provided several global circulation models (GCM) simulations, summarized in CMIP6 [27], to hypothesize future climate scenarios, with a higher average resolution compared to the previous CMIP5 [28]. Nevertheless, Di Virgilio et al. [29] proposed criteria to select more than one GCM for climate projections and to consider ensemble data.

The aim of this work was to characterize and describe the climatic evolution of the Apulia region using bioclimatic indices calculated on the basis of historical time series (1961–2022) and to project future scenarios according to SSP2–4.5 and SSP5–8.5 up to the year 2100, in order to understand and predict the suitability of the area for the production of quality wines in the coming decades.

2. Materials and Methods

2.1. Study Area, Climate Historical Data, Future Scenarios, and Bioclimatic Indices

The study was conducted in the Apulia region, southern Italy (Figure 1), which lies between 39°44′–41°56′ N and 14°56′–18°32′ E. The average annual temperatures are 15–16 °C with 500–800 mm of precipitation per year [30]. The area is flat and hilly (average elevation of 184 m a.s.l.), with a range of 0–1070 m a.s.l., as shown by the Digital Elevation Model considered in this study. Historical series of monthly Tmax and Tmin for the period 1961–2022 were retrieved from the Apulian Civil Protection site (https://protezionecivile.puglia.it/annaliedatiidrologicielaborati. Accessed on 12 October 2022). Of the total 157 available weather stations, 66 were selected based on the completeness of the data to calculate the bioclimatic indices for the period 1961–1990, while for the period 1991–2022 another 14 stations were added, for a total of 80 (Figure 1). For the same stations, data on monthly Tmax and Tmin were retrieved from https://www.worldclim.org (accessed on 14 October 2022) to calculate bioclimatic indices for the Future Scenarios. The site provides data downscaled according to CMIP6 using WorldClim v2.1 as the baseline climate [31] in the form of GeoTiff maps, from which the data were sampled by QGIS version 3.16.11 for the coordinates of interest with a spatial resolution of 30 s, corresponding approximately to a 1 km^2 grid. A combination of four GCMs from the list at https://www.worldclim.org was considered: CNRM–CM6–1 (France), CMCC–ESM2 (Italy); HadGEM3–GC31– LL (UK); and MPI–ESM1–2– LR (Germany). Data were downloaded for SSP2–4.5 and SSP5–8.5 for the next four 20–year periods (2021–2040, 2041–2060, 2061–2080, 2081–2100).

The Bioclimatic indices considered were Growing Season Temperature (GST), Huglin Index (HI) and Winkler Index (WI), all based on temperatures (Table 1).

2.2. Geostatistical Interpolation Techniques

Regression–kriging (RK) [32] was performed for spatial interpolation of the bioclimatic indices using a Digital Elevation Model (DEM) raster by means of the QGIS plugin SRTM

Downloader with a resolution of 10 m in the UTM WGS 84 zone 33N. RK accuracy was checked using the Normalized Root–Mean–Square Error (NRMSE) between the calculated and interpolated bioclimatic indices and by the R^2 of the model (Table 2). The interpolation procedure was performed using the software SAGA GIS (System for Automated Geoscientific Analyses) version 2.3.2, while the spatialization figures were obtained using QGIS version 3.16.11.

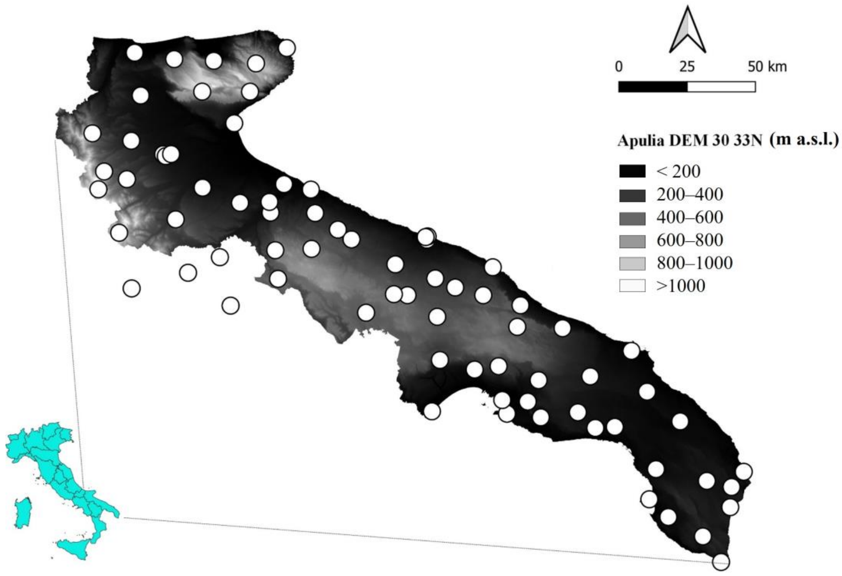

Figure 1. Map of Apulia. Digital elevation models and weather stations.

Table 2. Average Tmax and Tmin, Normalized Root–Mean–Square Error (NRMSE) between calculated and interpolated bioclimatic indices, R^2 of the model, average of the period and coefficient of variation (%) of bioclimatic indices GST, HI and WI calculated for historical (1961–1990 and 1991–2022) and future scenarios SSP2–4.5 and SSP5–8.5 (2021–2040, 2041–2060, 2061–2080 and 2081–2100).

				GST				HI				WI			
Scenario	Period	Avg Tmax	Avg Tmin	NRSME	R^2	Mean	CV%	NRSME	R^2	Mean	CV%	NRSME	R^2	Mean	CV%
Historical	1961–1990	19.4	11.1	10.51	0.83	19.8	5.2	9.19	0.85	2397.3	8.5%	10.49	0.83	2106.3	10.0%
	1991–2022	20.4	12.0	11.33	0.83	21.0	4.9	10.20	0.86	2638.3	7.7%	10.79	0.84	2368.1	9.1%
SSP 245	2021–2040	20.8	12.4	5.15	0.96	21.2	5.4	9.09	0.90	2662.4	8.6%	4.95	0.97	2409.0	10.3%
	2041–2060	21.7	13.3	4.34	0.97	21.8	5.1	8.45	0.91	2861.1	7.8%	4.58	0.97	2531.7	9.3%
	2061–2080	22.4	14.0	5.45	0.96	22.9	5.0	9.36	0.90	2980.2	7.6%	5.86	0.96	2760.0	8.8%
	2081–2100	22.9	14.4	4.96	0.96	23.5	4.9	7.29	0.93	3094.2	7.2%	5.60	0.96	2890.1	8.4%
SSP 585	2021–2040	21.0	12.6	4.37	0.97	21.5	5.4	7.67	0.93	2713.7	8.3%	5.17	0.96	2466.2	10.1%
	2041–2060	22.1	13.7	4.66	0.97	22.7	5.0	7.65	0.93	2953.2	7.6%	5.07	0.97	2725.8	9.0%
	2061–2080	23.6	15.1	5.54	0.96	24.3	4.6	7.55	0.92	3262.0	6.8%	5.14	0.96	3067.8	7.8%
	2081–2100	25.4	16.7	5.39	0.96	26.2	4.1	7.59	0.92	3634.9	6.0%	5.16	0.96	3481.2	6.7%

3. Results

Monthly Tmax and Tmin of 66 and 80 Civil Protection weather stations, respectively, were considered for the calculation of bioclimatic indices for the thirty–year periods 1961–1990 and 1991–2022. The difference in the number of stations considered in the two historical periods depends on the completeness of the available data. Some stations located along the borders of the neighboring Basilicata region (Figure 1) were considered for an accurate estimate of the peripheral areas [2]. As suggested by the World Meteorological Organization (WMO), a period of thirty years was established for the historical analysis, preferably using the period 1961–1990. Recently, the European Centre for Medium–large Weather Forecasts (ECMWF) has established the period 1991–2020 as the main reference period due to the availability of satellite data [33]. Table 2 shows the statistical results of average Tmax and Tmin for all periods. There was already an increase of about 1 °C between the two historical periods. Under the future scenario SSP2–4.5, Tmax and Tmin increased by 2.5 °C and 2.4 °C, respectively, in the period 2081–2100 compared to the historical period

1991–2022. Comparing the Tmax and Tmin of the historical period 1991–2022 with those recorded under SSP5–8.5 in the period 2081–2100, an increase that varies between 5.0 °C and 4.7 °C emerged. The accuracy of the interpolation (RK) for all bioclimatic indices was confirmed by low NRMSE values, indicating a lower residual variance of a model, and a high $R^2 > 0.80$.

3.1. Growing Season Temperature (GST)

Specifically, in 1961–1990, GST (Figure 2, Table 3) classified marginal areas in the Northwest toward the Appennine's dorsal and on the Gargano promontory, i.e., areas with elevations above 800 m a.s.l., as intermediate (2.7%). Some 14.8% (Murgia plateau) were classified as warm, while most of the Apulian regional area (76.7%) was classified as hot. Another 5.7%, mainly located around the Jonic Arc, was classified as very hot. In the following thirty years from 1991 to 2022, the increase of Tmax and Tmin by about 1 °C in the regional area led to a shift in the classification of many areas, resulting in an almost complete loss of the intermediate class, reducing the warm class to 5.1% and the hot class to 33.1%. As expected, the very hot class grew to 61.4% in the entire regional area and was no longer limited to the Jonic Arc, but was spread throughout the region from north to south, encompassing the Capitanata, the entire Adriatic coast and Salento, excluding only internal areas. Regarding future scenarios up to 2100, GST in 2021–2040 in both SSPs achieved similar average values as in the previous historical period, with an increase in GST of a few decimal places and an essentially unchanged percentage distribution of classes (Figure 2, Table 3). More than 60% of the regional territory was classified as very hot, therefore unsuitable for viticulture, and about 30% as hot. The differences between the two SSPs emerged clearly in the next period, 2041–2060, when a GST increase in SSP5–8.5 resulted in 90.8% of Apulia being classified as very hot, with the emergence of a 1.3% too hot zone, still negligible but sounding like a first alarm bell. However, for the next period 2061–2080, SSP2–4.5 itself predicted a 10.9% too hot area, located on the coast of the Jonic Arc and in upper Salento. In the same period, the worst scenario SSP5–8.5 reported a dramatic increase in too hot zones to 66.5% of Apulia region, with almost all of the remaining area on the Murgia plateau and in Gargano classified as hot. In the final period 2080–2100, SSP2–4.5 still provided for an acceptable 49.7% very hot areas, with 47.1% too hot impaired zones for quality viticulture. On the other hand, if we consider SSP5–5.8 in the same period, we obtain a value of 96.3% too hot for the Apulian area, indicating the risk of losing suitability for the cultivation of quality grapes and the production of premium wines.

Table 3. Apulia classification by bioclimatic indices Growing Season Temperature (GST), Huglin Index (HI), Winkler Index (WI) and relative percentage distribution in classes referred to historical periods 1961–1990 and 1991–2022 and to future scenarios under SSP2–4.5 and SSP5–8.5 for the periods 2021–2040, 2041–2060, 2061–2080, 2081–2100.

		Classes					
		GST					
Scenario	Period	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
Historical	1961–1990	0.1%	2.7%	14.8%	76.7%	5.7%	–
Historical	1991–2022	–	0.4%	5.1%	33.1%	61.4%	–
SSP 245	2021–2040	–	0.2%	4.6%	30.7%	64.5%	–
	2041–2060	–	–	1.8%	23.8%	74.4%	–
	2061–2080	–	–	0.4%	5.9%	82.9%	10.9%
	2081–2100	–	–	0.1%	3.2%	49.7%	47.1%
SSP 585	2021–2040	–	0.1%	3.2%	28.2%	68.5%	–
	2041–2060	–	–	0.6%	7.4%	90.8%	1.3%
	2061–2080	–	–	–	1.1%	32.4%	66.5%
	2081–2100	–	–	–	–	3.7%	96.3%

Table 3. *Cont.*

		Classes					
		HI					
		Cool <1800	Temperate 1800–2100	Warm temperate 2100–2400	Warm 2400–2700	Very warm 2700–3000	Too hot >3000
Historical	1961–1990	2.7%	4.4%	33.8%	58.7%	0.4%	–
Historical	1991–2022	0.3%	3.2%	6.0%	44.8%	45.4%	0.3%
SSP 245	2021–2040	0.4%	3.1%	8.6%	30.1%	57.6%	0.2%
	2041–2060	–	0.8%	3.9%	16.4%	45.9%	33.0%
	2061–2080	–	0.3%	2.9%	7.6%	29.6%	59.6%
	2081–2100	–	–	1.4%	4.6%	23.0%	70.9%
SSP 585	2021–2040	0.1%	2.5%	6.1%	28.3%	61.3%	1.6%
	2041–2060	–	0.3%	3.1%	9.0%	32.2%	55.4%
	2061–2080	–	–	0.2%	2.9%	8.6%	88.3%
	2081–2100	–	–	–	–	1.9%	98.1%
		WI					
		Region I <1389	Region II 1389–1667	Region III 1667–1944	Region IV 1944–2222	Region V 2222–2700	Too hot >2700
Historical	1961–1990	1.2%	3.6%	14.2%	46.5%	34.5%	–
Historical	1991–2022	–	1.6%	4.0%	13.2%	80.7%	0.5%
SSP 245	2021–2040	–	1.0%	4.0%	19.4%	73.7%	1.9%
	2041–2060	–	0.2%	1.7%	9.3%	57.3%	31.5%
	2061–2080	–	–	0.5%	2.6%	31.9%	65.1%
	2081–2100	–	–	0.1%	1.5%	22.3%	76.1%
SSP 585	2021–2040	–	0.6%	3.0%	15.1%	66.2%	15.1%
	2041–2060	–	–	0.6%	3.2%	33.9%	62.3%
	2061–2080	–	–	–	0.3%	7.5%	92.2%
	2081–2100	–	–	–	–	0.4%	99.6%

3.2. Huglin Index (HI)

Two HI macro zones were revealed during the 1961–1990 period, the first of which was classified as warm temperate (33.8%) and was mainly related to the central regional wine district "Central Murgia" and marginally to eastern lower Salento; the second one was classified as warm (58.7%) and spread to the other two Apulian wine districts Capitanata and Jonic Arc with Upper Salento (Figure 3, Table 3). This general division into two HI macrozones persisted over the 1991–2022 period, with a significant shift toward the upper classes due to an increase in HI of about 300 HI. The zones formerly classified as warm temperate were reduced to 6.0% as they moved to warm and, consequently, as a domino effect, the formerly warm areas shifted to very warm, representing 45.4% of the Apulian territory. In fact, therefore, no Apulian territory has yet reached the upper limit of suitability for viticulture of 3000 HI, that is, the class too warm. This configuration remains almost unchanged until the following twenty–year period, 2021–2040, in both SSPs considered. On the other hand, a greater impact of the temperature increase on the values of HI was observed in the period 2041–2060, when a dramatic 33.0% and 55.4% of the Apulian territory was classified as too hot for viticulture in SSP2–4.5 and SSP5–8.5, respectively. Larger differences between the two SSPs occurred during the period 2061–2080. SSP2–4.5 reported zones preserved from excessive warming, with a total of 40.2% of areas still below the 3000 threshold. This percentage decreased in SSP5–8.5 to 11.5% in the inner zones of the Murgia plateau and Gargano, while the rest of the region exceeded the threshold and became unsuitable for viticulture. Finally, the projections of HI showed that Puglia was almost completely unsuitable for viticulture in the last period of the century 2080–2100 under SSP5–8.5, while SSP2–4.5 reported 29% of Apulia still suitable for viticulture.

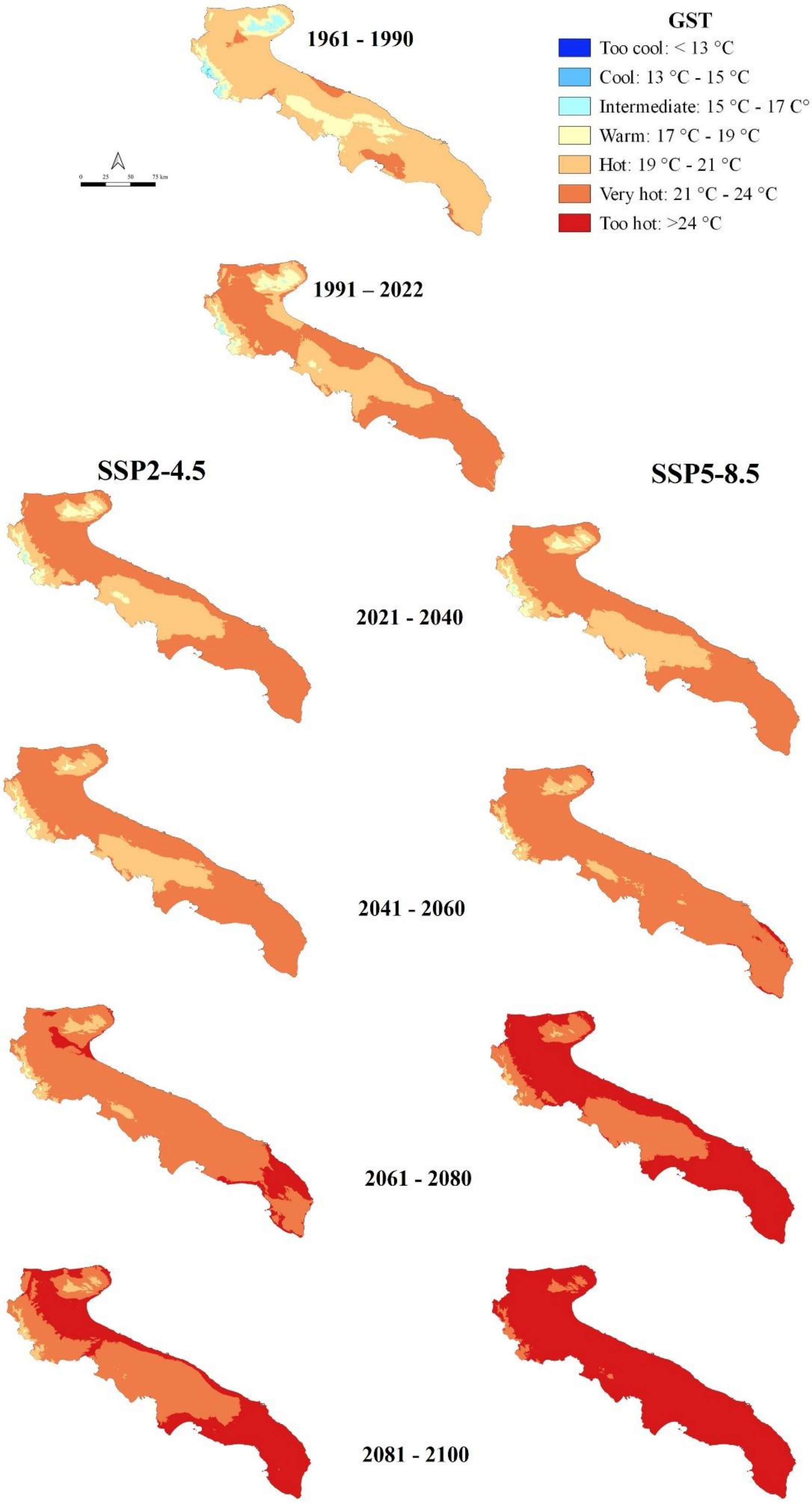

Figure 2. Spatial distributions of GST in Apulia during the historical periods 1961–1990 and 1991–2022 and future scenarios under SSP2–4.5 and SSP5–8.5 in four periods (2021–2040; 2041–2060; 2061–2080; 2081–2100).

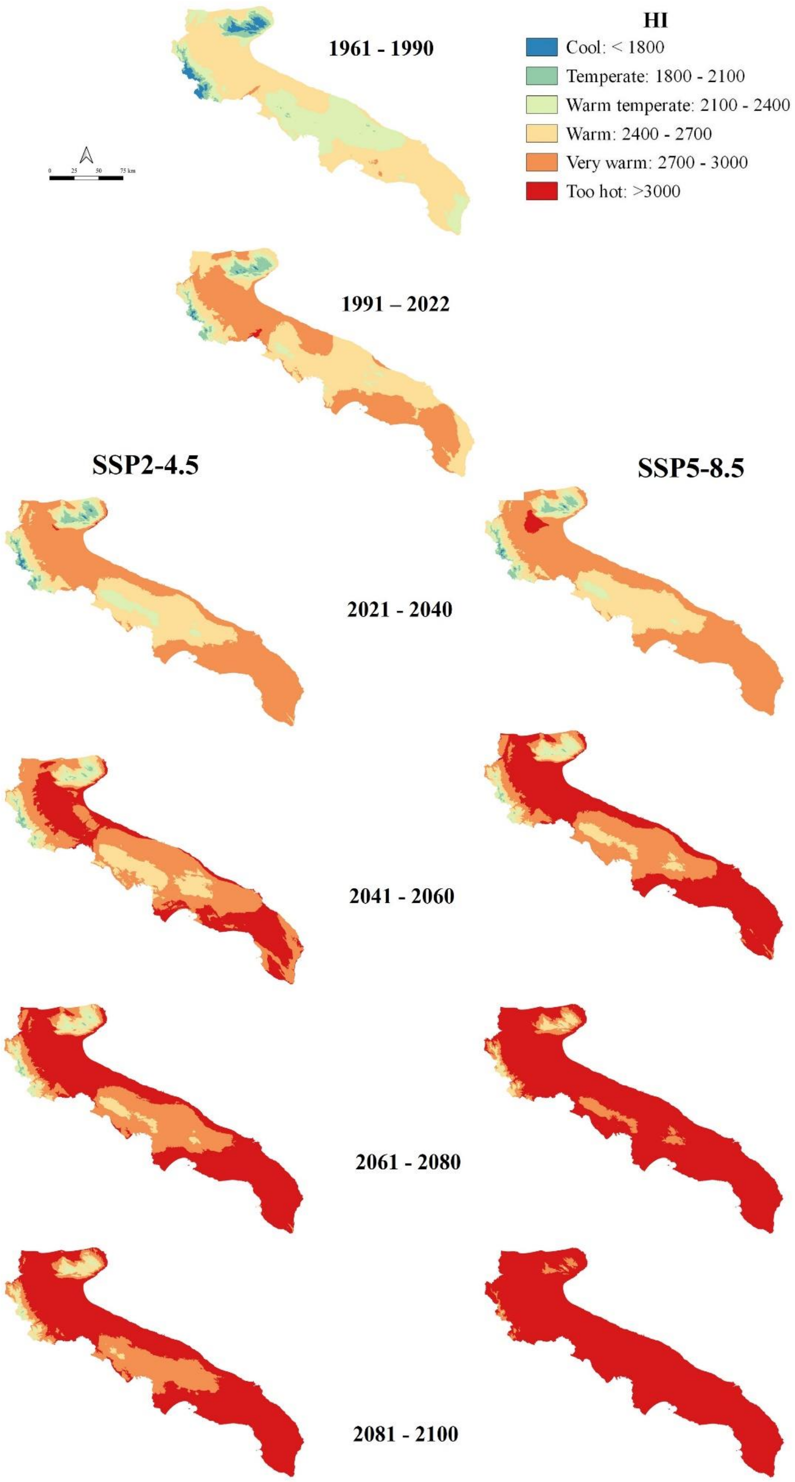

Figure 3. Spatial distributions of HI in Apulia during the historical periods 1961–1990 and 1991–2022 and future scenarios under SSP2–4.5 and SSP5–8.5 in four periods (2021–2040; 2041–2060; 2061–2080; 2081–2100).

3.3. Winkler Index (WI)

Data referring to historical periods 1961–1990 and 1991–2022 showed that the values of WI were almost completely suitable for viticulture in the whole Apulia region. However, the comparison between these two historical periods showed an increase in Region V from 46.5% to 80.7% in the last thirty years (Figure 4, Table 3); the onset of a too hot region, although marginal; and a general shift of the area towards higher WI values. The positive trend toward increasing WI index was more evident in the future scenarios as the decades progressed. In the 2021–2040 period, SSP2–4.5 revealed an Apulian WI classification similar to the previous historical 1991–2022, while SSP5–8.5 described a 15.1% too hot zone located mainly in the Salento Peninsula and the coastal strip of the Jonic Arc. This value increased to 62.3% in the subsequent period 2041–2060, indicating only the highest regional altitudes classified as Region V and therefore still eligible for viticulture, in particular the Murgia plateau, the Gargano promontory and the northwestern Pre–Apennine. Unfortunately, almost all of Apulia (92%) was classified as too hot for viticulture by 2061–2080 under SSP5–8.5. SSP2–4.5, on the other hand, showed how the WI classification saved some areas from being classified too hot until the last period considered, 2081–2100, and also altitude played a crucial role in this case in limiting the impact of global warming on viticulture.

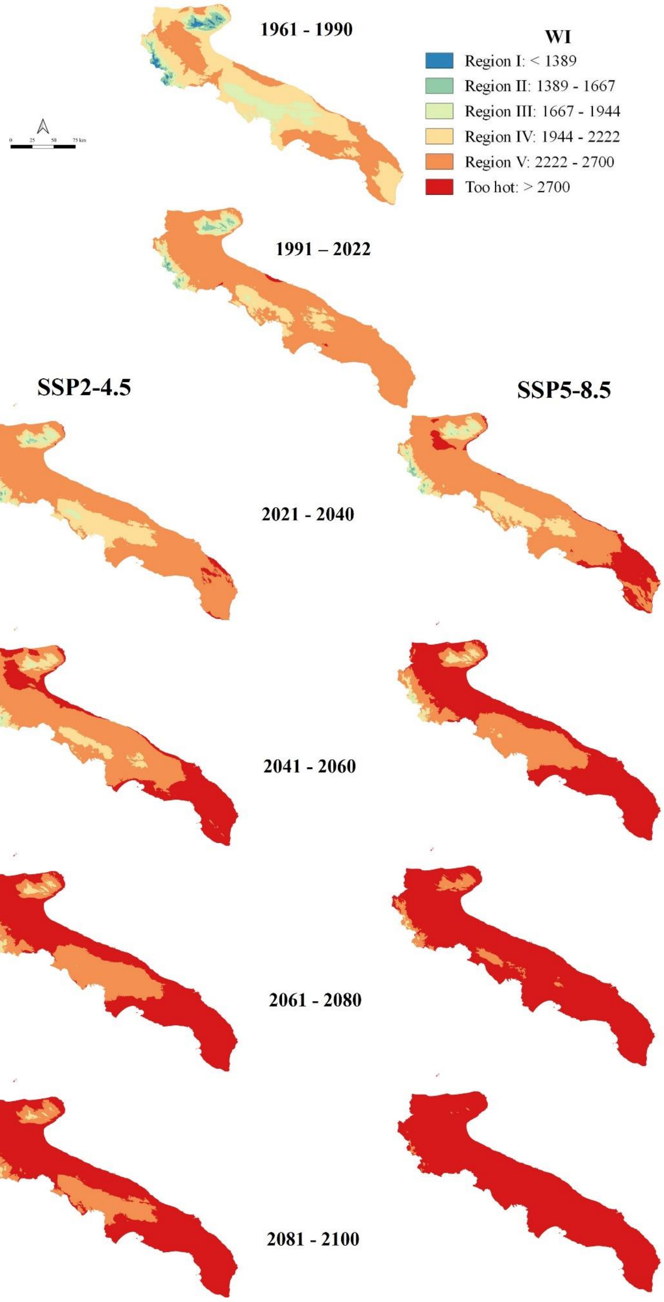

Figure 4. Spatial distributions of WI in Apulia during the historical periods 1961–1990 and 1991–2022 and future scenarios under SSP2–4.5 and SSP5–8.5 in four periods (2021–2040; 2041–2060; 2061–2080; 2081–2100).

4. Discussion

A Tmax and Tmin increase for all the periods emerged between the two historical periods and the future scenarios. These results are consistent with the expected temperature increase given in the IPCC Climate Change Report [22] for the period 2081–2100, with values ranging from 2.1 °C to 3.5 °C in scenario SSP2–4.5 and 3.3 °C to 5.7 °C under scenario SSP5–8.5, calculated on 20–year averages. Consequently, all bioclimatic indices showed a positive trend reflecting the shift of most of the regional area to warmer classes. The historical GST values confirmed other studies [2,34] that showed similar ranges at analogous latitudes related to the climate context of the Mediterranean basin. Moreover, the entire Apulian area was within the limits of a climate suitable for viticulture, which is normally 12 °C < GST < 22 °C [17]. This corresponds to the heat requirement of the Primitivo (Zinfandel) variety, currently one of the best–known Apulian wine grapes, which is present in two regional PDOs: Gioia DOC and Primitivo of Manduria DOC. In any case, the warmer GST classes already started to dominate from 1990 until now. Concerning future scenarios, SSP2–4.5 still provided acceptable GST values for viticulture until 2081–2100, while SSP5–5 revealed the Apulian regional territory to become too hot. In other words, a GST > of 24 °C will require a series of strategies starting with the selection of the most tolerant grape varieties for warmer conditions, with the serious risk of reducing Apulian viticulture to very few grape varieties [35], leading to a loss of biodiversity. Moreover, the increase in temperature will affect the phenological shift of vines, shortening the duration of the entire vegetative cycle and advancing the ripening of the grapes by up to 45 days [36,37], leading to the production of unbalanced wines with undesirably high alcohol content and low acidity [38] and low commercial value [25].

HI has been widely used as an effective bioclimatic index for viticultural zoning [39], and it has often indicated the loss of suitability for viticulture in certain zones of the Mediterranean basin such as southern Iberia and Italy [40]. However, Schultz et al. [41] reported that in some cases assumptions based on HI values may be based on incorrect or incomplete criteria, both because of varietal plasticity of grape varieties, i.e., different varieties respond differently to warming, and because the upper HI limit of a variety is often not well defined. For this reason, the dramatic results under SSP5–8.5, especially by the end of the century, for which almost all Apulia could become unsuitable for viticulture, must be considered cum grano salis, also in light of the "high unlikeliness" of the scenario [26]. In contrast, the milder and "likely" scenario SSP2–4.5 reported that Apulian areas with altitudes above 300–400 m a.s.l. will still be suitable for viticulture until the end of the century. These results are in agreement with other studies [2,34,42] that found general unsuitability of the studied Mediterranean areas for viticulture in the worst SSP5–8.5 scenario until the end of the 21st century, while in the milder SSP2–4.5 scenario certain areas could be classified as very warm and thus still suitable for the production of quality wine.

Similar to HI, regional classification accuracy based on WI may have some limitations, such as the base temperature threshold of 10 °C, or the not always positive impact of temperature > 10 °C, i.e., temperature > 35 °C may have a negative impact on grape yield and metabolite accumulation [3]. In addition, the beginning of the period considered by WI (1 April) appears in some cases as too late a date in view of the climate change that is taking place, with frequent anticipation of the budding phase due to warmer winters. This is the case in the Salento Peninsula and, in general, in Mediterranean areas [20], where earlier satisfaction of the chilling requirement related to endodormancy leads to early budbreak in March, increasing the risk of early spring frost damage. In summary, cultivars with different phenology respond differentially to climate change [43]. For example, early–ripening varieties could be exposed to excessive heat stress during ripening, which could affect grape quality, or late–ripening cultivars could become suitable in areas where they could not previously ripen, as they would have the time and heat necessary to complete the entire cycle until ripeness. From this point of view, the creation of databases with accurate long–term phenological characterizations of the cultivars grown in a given area, combined with environmental, yield and quality data, can help to plan future viticulture in areas of global warming [43].

The research focused on bioclimatic indices based on temperature. Indeed, adequate water supply is fundamental for high–quality grapes, especially in Mediterranean regions, where harvesting during hotter summer days under drought stress could lead to lower yield and quality of grapes in the future. In addition, water stress associated with high temperatures could increase evapotranspiration, which negatively affects flower cluster development, berry set and photosynthesis [37]. Piña–Rey et al. [44] showed a negative precipitation trend in Spain in their future projections, with consequences for grape phenology and quality. In particular, the Iberian Peninsula and Italy are expected to experience an aggravation of water stress conditions during ripening predicted by climate change projections. However, Cavazos et al. [35] reported that precipitation varies greatly from year to year and is subject to greater uncertainty due to an overestimation of mean annual precipitation.

Beside this, changes in rainfall patterns will not be uniform, and the occurrence of extreme events is hardly predictable. On the basis of these considerations, future scenario analysis based on temperature appears more reliable and accurate, even because ensemble GCM are normally considered to predict climate change, but large inter–model differences in rainfall are reported in the literature [45]

Beyond the accuracy of the conclusions of the various publications on the subject, strategies in viticulture have already been undertaken to face climate change. Among these, vineyard relocation in terms of latitude and altitude appears to be an opportunity. Nesbitt et al. [46] reported a vineyard area increase in the United Kingdom (UK) of 148%, thus over the latitudinal limit for grape–wine production of 50° N, while Cardell et al. [47] stated that Germany, northern France, Belgium, South England and the Czech Republic would become suitable in terms of thermal conditions by the mid–century. Higher altitude regions have become suitable for high–quality winegrowing of traditional varieties principally for lower mean air temperature in a context of climate change in future scenarios [39], although other factors must be considered in vineyard relocation, such as day–night variations, sunshine hours or water availability [41], to assure adequate grape productions. Despite this, some authors [44,48] considered the preservation of current vineyards areas as fundamental, as much, if not more, than relocation, which can be considered a long–term and last–resort measure to global warming. In the short term, instead, the use of later ripening varieties, clones, rootstocks and their combinations are considered efficient solutions to safeguard actual viticultural zones from future warmer conditions [49]. Other strategies are represented by the reduction of leaf area to fruit–weight ratio, late pruning [20,46] or the adoption of vine training systems with higher trunk height such as Tendone (horizontal pergola), a common vine training system widely used in Apulia. In this vine training the canopy is distributed on a continuous horizontal plane approximately 2 m above ground level, in which shoots are trained to create an upper layer of leaves that overlaps and shadows the underside productive band of bunches [50,51], minimizing the increase of canopy temperature and preventing cluster sunburn.

5. Conclusions

The research aimed to assess viticultural climatic classification of the Apulia region, by means of bioclimatic indices. The analysis involved time–series data from both historical and future scenarios until the end of the 21st century. Temperature increase due to climate change, already consistent when comparing the two historical periods of 1961–1990 and 1991–2022, will continue in the future scenarios, with values that oscillate from 2.5 °C to 5 °C depending on the Shared Socioeconomic Pathway considered.

All the bioclimatic indices considered in this paper evidenced that under the milder and most reliable SSP2–4.5 there will still be the possibility of quality viticulture even in smaller regional areas than present. By contrast, SSP5–8.5 evidenced a worrying scenario by the end of the century in Apulia. Our results confirm that a certain suitability for grape–

wine cultivation would be preserved in the next decades in Apulia. Territories historically suited to viticulture such as Apulia must make decisions in the short term to face climate change, modulating technical and agronomical features, in order to remain competitive on the market into the world wine scene, precisely in light of new players coming from territories where vineyard relocation has already started a few years ago.

Author Contributions: Conceptualization, G.G., A.C. and V.A.; methodology, G.G.; formal analysis, V.A; investigation, G.G., A.C., L.T. and V.A.; resources, L.T., data curation, G.G. and V.A.; writing—original draft preparation, G.G. and V.A.; writing—review and editing, A.C. and L.T.; visualization, A.C. and L.T.; supervision, L.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Historical series of monthly Tmax and Tmin regarding 1961–2022 were retrieved from the Apulian Civil Protection site (https://protezionecivile.puglia.it/annaliedatiidrologicielaborati Accessed on 12 October 2022); future scenario series of monthly Tmax and Tmin were retrieved from https://www.worldclim.org/data/cmip6/cmip6climate.html accessed on 14 October 2022.

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

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