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Climate Change Impacts on Viticulture in Italy: Insights from Historical and Future Scenarios Across Administrative Areas, Latitudes, and Elevations

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Abstract: (1) Background: The aim of the work was to characterize the climatic evolution and change based on the Multi Criteria Classification through the dynamics of bioclimatic indices in viticulture across Italy and its regional administrative boundaries, focusing on latitudes and elevations. (2) Methods: The impact of climate change on viticulture in Italy was analysed and spatialized with reference to historical data from 1991 to 2021 and to the Future Scenarios up to 2080 assumed by SSP2-4.5 and SSP5-8.5, taking into account 13 GCMs. (3) Results: The bioclimatic indices have all shown a significant trend in the historical period, with an increase in temperature and a decrease in precipitation, reflecting their effects on the entire Italian territory with respect to HI, up to 44°N for CI and up to 46°N for DI, regardless of altitude. The Future Scenarios highlighted a shift towards the warmer classes of the two temperature-based indices (HI and CI) for both SSPs, especially for altitudes up to 900 m a.s.l.. The DI-based classification based on DI remained relatively stable in Italy over time, although DI values will become increasingly negative in the near future. (4) Conclusions: The climate in Italy is warming, especially in the south and in the coastal regions. By 2080, more areas will be "Very Hot" with "Warm Nights." Drought will also increase and have a negative impact on viticulture. The importance of higher latitudes and altitudes in mitigating the effects of climate change justifies the continuing trend towards the relocation of vineyards as a medium-term solution and as an alternative to targeted cultivation methods that must be adopted in the short-term to safeguard the suitability of an area to quality viticulture.

Keywords: bioclimatic characterization; viticulture suitability assessment; latitude and elevation; future scenarios

1. Introduction

Climate plays a fundamental role in shaping ecosystems and influencing human activities. Understanding climate variability and its possible future changes is fundamental to assess the potential impacts on different sectors such as agriculture, forestry and water management. Viticulture is an important sector in the Italian agricultural landscape and contributes significantly to the country's economy and cultural heritage [1,2]. However, Italian wine-growing regions are increasingly facing the challenges of climate change, which directly affects the physiology of the vine [3,4], the composition of the grapes [5] and ultimately the quality of the wine [6].

In this context, the classification of climatic zones based on bioclimatic indices provides valuable information on the spatial distribution of climatic conditions and their changes over time [7–10], describing in particular the suitability characteristics of an area for future quality viticulture.

Italy, known for its rich cultural heritage and diverse landscapes, can look back on a winegrowing tradition that goes back thousands of years. The country's viticultural heritage is closely intertwined with its climate, which varies greatly from region to region due to the complexity of the territory, with a rich palette of climatic models ranging from the Alpine climate in the north to the Mediterranean climate in the south [11]. Italian wine regions are therefore characterized by different regional features that contribute to the diversity and quality of the wines. In the north, regions such

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as Piedmont and Trentino-Alto Adige are known for their cooler climate and hilly landscape [12]. In these regions, there are often significant diurnal temperature fluctuations, which contribute to the development of complex flavors and aromas in the grapes [13]. In the south, Tuscany stands out with its rolling hills, Mediterranean climate and iconic vineyards that thrive in this warm, sunny climate, producing classic and renowned wines such as Chianti and Brunello di Montalcino [14]. Further south, in regions such as Sicily and Puglia, the climate becomes more Mediterranean, with hot, dry summers and mild winters. Here, international grape varieties such as Nero d'Avola and Primitivo thrive alongside indigenous varieties, producing powerful, fruit-driven wines with a unique sense of terroir [15].

Currently, several bioclimatic indices are used to study and analyze the suitability of a region for viticulture, focusing on important climatic variables such as temperature, precipitation, evapotranspiration and solar radiation [16]. In particular, Tonietto and Carbonneau [17] introduced a MultiCriteria Climate Classification (MCC) that uses three bioclimatic indices simultaneously to assess the viticultural potential of a region. These indices are the Huglin Index (HI) [18], the Cool night index (CI) [19] and the Dryness Index (DI) [20]. The first two indices are based on temperature and are linked to the needs of the vines, the quality of the grapes (including sugar, color and aroma) and the typicity of the wines. The DI, on the other hand, provides a water balance that takes into account precipitation and evapotranspiration and thus indicates the presence or absence of drought. So far, the bioclimatic characterization of Italy as a whole has been based on historical data on production and climate, but spatialization of bioclimatic data and future projections have been lacking [2]. Other studies focused on areas of local interest [21], on a regional scale [22] or on specific parts of the Italian territory in the broader context of the Mediterranean basin [23] or in continental Europe [24].

The imminent risk of reaching a temperature increase of 1.5°C in the near future, as reported by the Intergovernmental Panel on Climate Change [25], highlights the far-reaching and worsening impacts of climate change based on climate-based emissions scenarios. Background Shared Socioeconomic Pathways (SSPs), which formulate five future climate projections: SSP1-1.9 (very low greenhouse gas emissions), SSP1-2.6 (low greenhouse gas emissions), SSP2-4.5 (intermediate greenhouse gas emissions), SSP3- 7.0 (high greenhouse gas emissions) and SSP5 -8.5 (very high greenhouse gas emissions). Specifically, the IPCC reports that the 1.5°C target will be reached or exceeded between 2021 and 2040, and in the case of a high emissions scenario, this threshold could be reached earlier, i.e. today. Even worse would be very high greenhouse gas emissions under a carbon-intensive pathway (SSP5-8.5), in which global warming could rise to 3.3-5.7°C by the end of the century. The effects of this temperature rise could, for example, lead to a loss of 29% of biodiversity.

The effects of this temperature rise could, for example, lead to a loss of 29% of biodiversity, which could be catastrophic in the case of Italian wine regions, as they are historically tertiary centers of vine domestication [26]. This biodiversity represents a real reservoir of genes useful to face the new challenges of climate change. These challenges range from the selection of genotypes that are predominantly resistant to water and heat stress to those that exhibit late maturation to mitigate the excessive shortening of phenological phases and the advance of ripening [27].

Predicting future precipitation patterns, especially in the Mediterranean regions known as climate change hotspots, is a greater challenge than temperature [28]. The precipitation diplomacy observed at the end of the 20th century [29] is expected to continue due to future warming in the high emissions scenario, especially in summer over land areas, with the exception of the northern Mediterranean in winter [30]. In any case, there will be an increase in extreme drought events alternating with abundant rainfall, which will lead to water scarcity or, conversely, floods in spring, resulting in an increase in parasite and disease infestations and influencing the quality of the wine [31]. However, especially in areas subject to desertification [32], such as most of southern Italy, the precipitation rate does not always compensate for the increasing negative effects of temperature on the evapotranspiration demand of the vine [33], leading to an increasingly negative soil water balance [34], which directly influences the calculation of the DI and its temporal and spatial variation.

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In this study, we investigate the dynamics of bioclimatic indices in viticulture, focusing on key indices such as HI, CI and DI across Italy. These indices provide valuable information on the suitability of wine regions and the ripening potential of grape varieties. Furthermore, we evaluate the expected impact of climate change impacts on viticulture in Italy by analyzing the SSPs, in particular SSP2-4.5 and SSP5-8.5, up to the year 2080.

2. Materials and Methods

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

The study was conducted on all national territory of Italy. Data were retrieved for a 5 km x 5 km points grid covering all the national Italian territory, for a total of 12931 points. Historical (1991-2021) and Future Scenarios (2021-2080) series of monthly Tmax, Tmin and Precipitation were retrieved from https://www.worldclim.org with a resolution of 2.5 min. The site provides data downscaled according to CMIP6 using WorldClim v2.1 as the baseline climate (Frick et al., 2017) Historical Potential EvapoTranspiration (Penman-Monteith) (PET-PM) was retrieved from https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php (E-OBSv25.0e), while PET-PM for Future Scenarios was calculated by CROPWAT 8.0 [35] on the base of retrieved temperatures. For Future Scenarios, two Shared Socioeconomic Pathways were considered: SSP2-4.5 and SSP5-8.5 and an Ensemble of climatic data was provided based on a total of 13 General Circulation Models (GCM): ACCESS-CM2, BCC-CSM2-MR, CMCC-ESM2, EC-Earth3-Veg, FIO-ESM-2-0, GISS-E2-1-G, HadGEM3-GC31, INM-CM5-0, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL. Future Scenarios data were averaged with an interval of time windows of 20 years: 2021-2040, 2041-2060 and 2061-2080. Tmin, Tmax, Precipitations and PET-PM were utilized to calculate Huglin index (HI), Night Cold index (CI) and Dryness index (DI) (Table 1).

2.2. Historical Trends of Bioclimatic Indices in Italy

Historical trends for HI, CI and DI were analysed by Mann-Kendall test and the trend significance calculated with Sen's Slope after having subdivided the whole Italian area per latitude (<40.00°; 40.01-42.00°; 42.01°-44.00°; 44.01°-46.00°; >46.00°) and elevation (<300 m; 301-600 m; 601-900 m; >900 m a.s.l.).

Table 1. Bioclimatic indices considered and class partitioning.

Bioclimatic index	Formula	Classes
Huglin index (HI)	$\boldsymbol{HI} = \sum_{\boldsymbol{01st\ Apr.}}^{\boldsymbol{30th\ Sept.}} \frac{[(\boldsymbol{Tmean}-\boldsymbol{10})+(\boldsymbol{Tmax}-\boldsymbol{10})]}{\boldsymbol{2}}\boldsymbol{d}$ d: adjustment for latitude/day length 1.02 for latitude comprised between 40° and 42° 1.00 for latitude below 39°	Very cool < 1500 Cool = 1500 — 1800 Temperate = 1800 — 2100 Warm temperate = 2100 — 2400 Warm = 2400 — 3000 Very warm > 3000
Cool night index (CI)	*CI* = Tmin Semptember	Very cool nights ≤12°C Cool nights 12°C — 14°C Temperate nights 14°C — 18°C Warm nights > 18°C
Dryness index (DI)	*DI* = Wo + P – Tv – Es	Very dry < -100 mm

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	Wo: soil water reserve at the end of the growing season (mm) P: Precipitation (mm) Tv: ETPk potential grapevine evapotranspiration (mm) where: ETP potential evapotranspiration (mm) k coefficient of radiation absorption by vineyard (in the Northern hemisphere: 0.1 for April, 0.3 for May, 0.5 from June to September) Es: ETP⁄N(1 − k) JPm where: N: number of days in the month JPm: monthly precipitations in mm/5 (number of days of effective evaporation from the soil per month).	Moderately dry -100mm — 50 mm Sub-humid 50 mm — 150 mm Humid > 150 mm

2.3. Geostatistical Interpolation Techniques

Regression–kriging (RK) [36] was performed for spatial interpolation of the bioclimatic indices. The interpolation utilizes linear or multiple regression analysis of auxiliary information, in this case the elevation was considered by means of a Digital Elevation Model (DEM) raster, downloaded from https://www.worldclim.org at a resolution of 30 s. Leave-one-out cross validation (LOOCV) (Stone 1974) was performed for each grid point for the validation of the predicted bioclimatic indices in both the historical and future scenarios. The reliability/accuracy of the kriging model was verified by the normalized root-mean-square error (NRMSE) between calculated and interpolated bioclimatic indices and by the R2 of the model (Table S1). The interpolation procedure by means of kriging and the cartographic rendering were conducted with SAGA GIS software (System for Automated Geoscientific Analyses) version 2.3.2 and QGIS version 3.16.11, respectively.

3. Results

3.1. Historical data

Figure 1 shows the MultiCriteria Climate Classification (MCC) based on three indices: Huglin Index (HI), Cool Night Index (CI) and Dryness Index (DI) for the Italian territory using historical data from 1991-2021, Figure 2, 3 and 4 show the average MCC of the three indices for the Italian territory based on elevation and latitude, while Table S2 presents the MCC on a regional basis. The results regarding the spatial distribution of HI (Figure 1) classified Italy predominantly as “Temperate warm” (28%) and “Warm” (34%). The regions most frequently classified on average as “Temperate Warm” were Marche, Piedmont and Umbria, with a 45% or more of the regional territory, while the areas classified as “Warm” were mainly located along the Italian coasts and in large parts of Apulia, Calabria, Sicily and Sardinia in the south and in Emilia Romagna, Friuli Venezia Giulia and Veneto in the north, with percentages around 50% of the territory and even of 70% in Apulia (Table S2). In terms of latitude and elevation, all the areas up to 300 m a.s.l. and up to 46° N were classified as “Warm”, while this class was not recorded further north than 46° N. The “Temperate Warm” class mainly covered the foothill regions of the Alps and the Apennines, including the major islands such as Sardinia and Sicily, with elevations between 300 and 600 m a.s.l. below the 44° N. and between 0 and 300 m a.s.l. beyond the 46° N (Figure 2).

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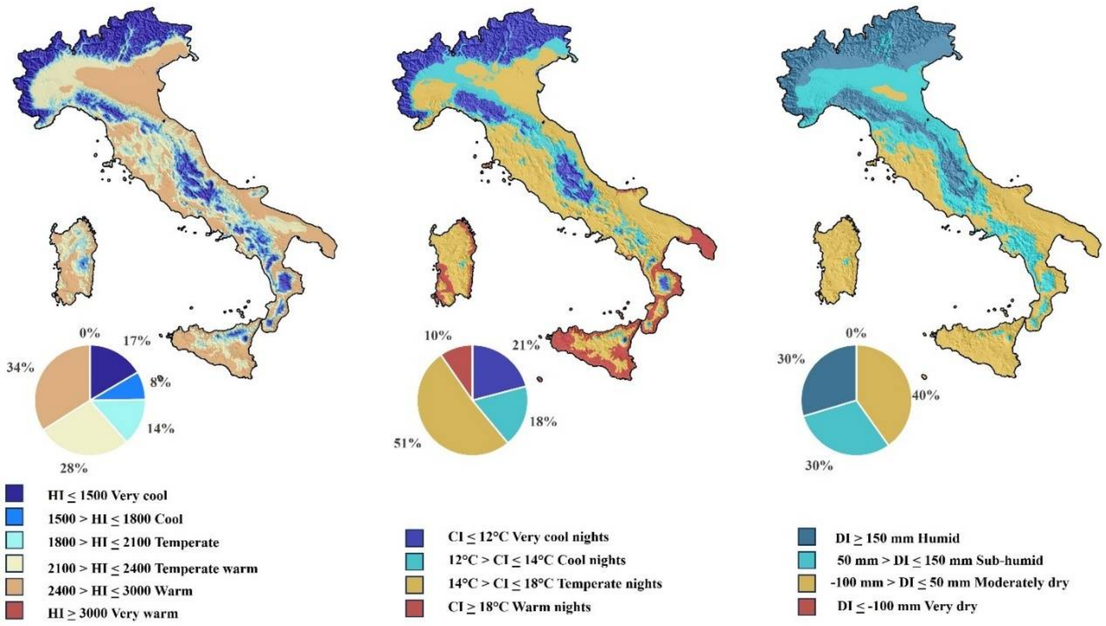

Figure 1. Spatial distributions of Huglin index (HI), Cool night index (CI) and Dryness index (DI in Italy during the Historical period (1991-2021).

As for the CI (Figure 1), the predominant class on the Italian territory was “Temperate nights” class (51%), with Basilicata, Campania, Lazio, Puglia, Sardegna and Toscana the most representative with at least 60% of the regional area (Table S2). A further 10%, of Italia, mostly concentrated in southern Italy, was classified as “Warm nights”. South of 40° N the areas with elevation up to 300 m a.sl. were classified as “Warm nights” (Figure 3) and were mainly found in southern Apulia (25% of the regional territory), Calabria (43%), Sicily (56%) and Sardinia (23%). Beyond 40°N no altitudinal or longitudinal band was found to be "Warm nights", while the class “Temperate nights” was found up to 900 m a.s.l. and up to 42°N, 600 m a.s.l. between 42°N and 44° N and 300 m a.sl. between 44° and 46°N. Further north than 46°N only "Cool nights" and "Very cool nights" were observed.

Table 2. Mann-Kendall and Sen’s Slope of Historical trends (1991-2021) of Huglin index, Cool night index and Dryness index by latitude and elevation in Italy.

Lat	Elevation	%	HI		CI		DI	
	(m a.s.l.)	Area	ZMK	β	ZMK	β	ZMK	β
< 40° 00'	0-300	49.8%	3.03^{**}	7.43	3.43^{***}	0.05	-3.40^{***}	-1.51
	301-600	26.7%	3.03^{**}	7.28	3.64^{***}	0.05	-2.72^{**}	-1.44
	601-900	13.6%	3.13^{**}	7.39	3.86^{***}	0.05	-3.13^{**}	-1.62
	> 900	9.9%	3.03^{**}	6.86	3.71^{***}	0.06	-2.18^{*}	-1.72
40° 01'-42° 00'	0-300	49.7%	3.50^{***}	8.31	2.89^{**}	0.06	-2.45^{*}	-1.88
	301-600	27.1%	3.43^{***}	8.22	2.79^{**}	0.06	-2.14^{*}	-1.81
	601-900	14.9%	3.40^{***}	7.78	2.65^{**}	0.06	-2.01^{*}	-1.67
	> 900	8.3%	3.20^{***}	6.71	2.52^{*}	0.05	-1.97^{*}	-2.33
42° 01' - 44° 00'	0-300	46.7%	3.84^{***}	9.29	2.07^{*}	0.05	-2.62^{**}	-2.81
	301-600	29.4%	3.81^{***}	9.37	2.12^{*}	0.05	-2.31^{*}	-3.16
	601-900	12.8%	3.67^{***}	8.92	2.12^{*}	0.05	-2.41^{*}	-3.23

	> 900	11.1%	3.40^{***}	7.46	2.14^{*}	0.05	$–2.24^{*}$	-3.39
44° 01' - 46° 00'	0-300	54.6%	3.50^{***}	8.53	$1.63^{n.s.}$	0.04	$–2.52^{*}$	-2.56
	301-600	15.4%	3.84^{***}	9.07	$1.73^{n.s.}$	0.05	$–3.16^{**}$	-4.38
	601-900	9.3%	3.81^{***}	8.75	$1.87^{n.s.}$	0.05	$–2.89^{**}$	-3.88
	> 900	20.7%	3.03^{**}	5.64	$1.70^{n.s.}$	0.05	$–2.11^{*}$	-2.98
> 46° 00'	0-300	5.5%	2.82^{**}	8.73	$1.12^{n.s.}$	0.04	$0.54^{n.s.}$	1.31
	301-600	6.8%	3.09^{**}	9.16	$1.31^{n.s.}$	0.03	$0.17^{n.s.}$	0.35
	601-900	9.2%	3.13^{**}	8.72	$1.17^{n.s.}$	0.03	$0.20^{n.s.}$	0.36
	> 900	78.5%	2.79^{**}	5.16	$1.29^{n.s.}$	0.03	$0.27^{n.s.}$	0.32

Regarding the average DI in the period 1991-2021 (Figure 1), Italy had not yet experienced extreme drought conditions (“Very dry” class), but was mostly classified as “Moderately dry” (40%). The entire foothills of the Apennines and the Po Valley were classified as “Sub-humid” (30%), the remaining 30% as “Humid”, especially in the Alpine region. The regions most frequently classified as “Moderately dry” were once again Apulia, Sicily and Sardinia Apulia, Sicily and Sardinia, for most, if not all, of the region (Table S2). Figure 4 shows how the altitudinal bands up to 900 m a.s.l. and below 42°N were classified as "Moderately dry" on average, while between 42° and 44°N the elevation was reduced to 300 m a.s.l.. However, the "Sub-humid" strips were found above 900 m a.s.l. up to 42°N, an elevation that drops to 300 m a.s.l. between 42° and 44°N and even reached sea level between 44°N and 46°N. Above 46°N, however, the area was classified as "Humid" on average at all elevations.

The analysis of historical trends (Table 2) shows a clear and significative increase in HI at all latitudes and elevations. The increase occurred significantly also beyond 46°N even at elevations higher than 900 m a.sl., accounting for 78.5% of the territory. The CI trends increased significantly up to a latitude below 44° N, while no significant increase was recorded at higher latitudes. Similarly, the DI trends were statistically significant below 46° N, while further north, due to greater water availability and less solar radiation at higher latitudes resulting in lower Et0 values, a substantially stable situation occurred over the years without any significant trend.

		Huglin Index (HI)						
		Historic	SSP2-4.5			SSP5-8.5		
Lat	elev (m a.s.l)	1991-2021	2021-2040	2041-2060	2061-2080	2021-2040	2041-2060	2061-2080
< 40° 00'	0-300	2621 Warm	2778 Warm	2903 Warm	3012 Very warm	2796 Warm	3006 Very warm	3247 Very warm
	301-600	2350 Temperate warm	2510 Warm	2636 Warm	2746 Warm	2528 Warm	2741 Warm	2984 Warm
	601-900	1996 Temperate	2193 Temperate warm	2322 Temperate warm	2433 Warm	2213 Temperate warm	2429 Warm	2675 Warm
	> 900	1466 Very cool	1692 Cool	1820 Temperate	1931 Temperate	1712 Cool	1928 Temperate	2176 Temperate warm
40° 01'- 42° 00'	0-300	2538 Warm	2733 Warm	2878 Warm	3004 Very warm	2760 Warm	3001 Very warm	3279 Very warm
	301-600	2200 Temperate warm	2408 Warm	2556 Warm	2685 Warm	2435 Warm	2684 Warm	2970 Warm
	601-900	1856 Temperate	2100 Temperate	2249 Temperate warm	2379 Temperate warm	2127 Temperate warm	2378 Temperate warm	2667 Warm
	> 900	1362 Very cool	1638 Cool	1783 Cool	1910 Temperate	1664 Cool	1911 Temperate	2199 Temperate warm
42° 01' - 44° 00'	0-300	2441 Warm	2637 Warm	2786 Warm	2919 Warm	2662 Warm	2919 Warm	3215 Very warm
	301-600	2177 Temperate warm	2385 Warm	2538 Warm	2675 Warm	2412 Warm	2676 Warm	2983 Warm
	601-900	1835 Temperate	2066 Temperate	2219 Temperate warm	2356 Temperate warm	2092 Temperate	2357 Temperate warm	2665 Warm
	> 900	1298 Very cool	1568 Cool	1714 Cool	1845 Temperate	1593 Cool	1847 Temperate	2144 Temperate warm
44° 01' - 46° 00'	0-300	2446 Warm	2663 Warm	2810 Warm	2954 Warm	2686 Warm	2956 Warm	3267 Very warm
	301-600	2087 Temperate	2275 Temperate warm	2421 Warm	2564 Warm	2296 Temperate warm	2563 Warm	2874 Warm
	601-900	1723 Cool	1934 Temperate	2081 Temperate	2223 Temperate warm	1956 Temperate	2223 Temperate warm	2532 Warm
	> 900	803 Very cool	996 Very cool	1116 Very cool	1236 Very cool	1013 Very cool	1237 Very cool	1503 Cool
> 46° 00'	0-300	2323 Temperate warm	2427 Warm	2570 Warm	2715 Warm	2448 Warm	2719 Warm	3025 Very warm
	301-600	1969 Temperate	1988 Temperate	2130 Temperate warm	2275 Temperate warm	2008 Temperate	2278 Temperate warm	2583 Warm
	601-900	1618 Cool	1641 Cool	1780 Cool	1921 Temperate	1660 Cool	1925 Temperate	2224 Temperate warm
	> 900	575 Very cool	716 Very cool	824 Very cool	935 Very cool	730 Very cool	941 Very cool	1184 Very cool

Figure 2. Huglin index classification of Italy during the Historical period 1991–2022 and Future Scenarios SSP2–4.5 and SSP5–8.5 in 2021–2040, 2041–2060 and 2061–2080 by latitude and elevation.

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		Cool night Index (CI)						
		Historic	SSP2-4.5			SSP5-8.5		
Lat	elev (m a.s.l.)	1991-2021	2021-2040	2041-2060	2061-2080	2021-2040	2041-2060	2061-2080
< 40° 00'	0-300	19.2 Warm nights	20.3 Warm nights	21.0 Warm nights	21.6 Warm nights	20.4 Warm nights	21.7 Warm nights	23.0 Warm nights
	301-600	17.6 Temperate nights	18.7 Warm nights	19.4 Warm nights	20.0 Warm nights	18.8 Warm nights	20.0 Warm nights	21.4 Warm nights
	601-900	16.0 Temperate nights	17.2 Temperate nights	18.0 Temperate nights	18.5 Warm nights	17.3 Temperate nights	18.6 Warm nights	20.0 Warm nights
	> 900	13.3 Cool nights	14.7 Temperate nights	15.5 Temperate nights	16.1 Temperate nights	14.8 Temperate nights	16.1 Temperate nights	17.5 Temperate nights
40° 01'- 42° 00'	0-300	17.1 Temperate nights	18.4 Warm nights	19.2 Warm nights	19.9 Warm nights	18.5 Warm nights	19.9 Warm nights	21.4 Warm nights
	301-600	15.5 Temperate nights	16.8 Temperate nights	17.6 Temperate nights	18.3 Warm nights	16.9 Temperate nights	18.3 Warm nights	19.8 Warm nights
	601-900	14.4 Temperate nights	15.8 Temperate nights	16.6 Temperate nights	17.3 Temperate nights	15.9 Temperate nights	17.3 Temperate nights	18.9 Warm nights
	> 900	12.0 Very cool nights	13.7 Cool nights	14.5 Temperate nights	15.2 Temperate nights	13.8 Cool nights	15.3 Temperate nights	16.8 Temperate nights
42° 01' - 44° 00'	0-300	15.3 Temperate nights	16.8 Temperate nights	17.6 Temperate nights	18.3 Warm nights	16.9 Temperate nights	18.3 Warm nights	19.8 Warm nights
	301-600	14.2 Temperate nights	15.7 Temperate nights	16.5 Temperate nights	17.2 Temperate nights	15.8 Temperate nights	17.3 Temperate nights	18.8 Warm nights
	601-900	12.9 Cool nights	14.5 Temperate nights	15.3 Temperate nights	16.1 Temperate nights	14.6 Temperate nights	16.1 Temperate nights	17.7 Temperate nights
	> 900	10.8 Very cool nights	12.5 Cool nights	13.3 Cool nights	14.1 Temperate nights	12.6 Cool nights	14.1 Temperate nights	15.7 Temperate nights
44° 01' - 46° 00'	0-300	14.4 Temperate nights	16.0 Temperate nights	16.7 Temperate nights	17.5 Temperate nights	16.1 Temperate nights	17.5 Temperate nights	19.1 Warm nights
	301-600	13.2 Cool nights	14.6 Temperate nights	15.3 Temperate nights	16.1 Temperate nights	14.6 Temperate nights	16.1 Temperate nights	17.6 Temperate nights
	601-900	11.4 Very cool nights	13.1 Cool nights	13.8 Cool nights	14.6 Temperate nights	13.2 Cool nights	14.6 Temperate nights	16.1 Temperate nights
	> 900	7.0 Very cool nights	8.6 Very cool nights	9.2 Very cool nights	10.0 Very cool nights	8.7 Very cool nights	10.0 Very cool nights	11.5 Very cool nights
> 46° 00'	0-300	13.1 Cool nights	14.4 Temperate nights	15.1 Temperate nights	15.8 Temperate nights	14.5 Temperate nights	15.9 Temperate nights	17.3 Temperate nights
	301-600	11.7 Very cool nights	12.5 Cool nights	13.2 Cool nights	13.9 Cool nights	12.6 Cool nights	14.0 Cool nights	15.4 Temperate nights
	601-900	10.1 Very cool nights	10.9 Very cool nights	11.6 Very cool nights	12.3 Cool nights	11.0 Very cool nights	12.4 Cool nights	13.8 Cool nights
	> 900	4.7 Very cool nights	6.4 Very cool nights	7.0 Very cool nights	7.7 Very cool nights	6.4 Very cool nights	7.8 Very cool nights	9.2 Very cool nights

Figure 3. Cool night index classification of Italy during the Historical period 1991–2022 and Future Scenarios SSP2–4.5 and SSP5–8.5 in 2021–2040, 2041–2060 and 2061–2080 by latitude and elevation.

3.2. Future Scenarios

Figures 5, 6 and 7 illustrate the evolution and spatial distribution of the HI, CI and DI indices on the Italian territory, based on two Shared Socioeconomic Pathways (SSP): SSP2-4.5 and SSP5-8.5, for the periods 2021-2040, 2041-2060 and 2061-2080.

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		Dryness Index (DI)						
		Historic	SSP2-4.5			SSP5-8.5		
Lat	elev (m a.s.l.)	1991-2021	2021-2040	2041-2060	2061-2080	2021-2040	2041-2060	2061-2080
< 40° 00'	0-300	-29.4 Moderately dry	-51.7 Moderately dry	-61.4 Moderately dry	-57.9 Moderately dry	-57.4 Moderately dry	-73.1 Moderately dry	-74.5 Moderately dry
	301-600	-10.6 Moderately dry	-34.5 Moderately dry	-44.6 Moderately dry	-40.6 Moderately dry	-40.2 Moderately dry	-56.4 Moderately dry	-57.7 Moderately dry
	601-900	4.8 Moderately dry	-1.2 Moderately dry	-10.8 Moderately dry	-6.9 Moderately dry	-6.5 Moderately dry	-23.7 Moderately dry	-25.5 Moderately dry
	> 900	65.2 Sub-humid	46.2 Moderately dry	37.1 Moderately dry	40.9 Moderately dry	41.2 Moderately dry	22.9 Moderately dry	20.4 Moderately dry
40° 01'-42° 00'	0-300	-14.9 Moderately dry	-12.3 Moderately dry	-27.8 Moderately dry	-22.6 Moderately dry	-20.3 Moderately dry	-40.5 Moderately dry	-46.4 Moderately dry
	301-600	9.0 Moderately dry	14.2 Moderately dry	-1.3 Moderately dry	4.2 Moderately dry	6.4 Moderately dry	-14.6 Moderately dry	-21.2 Moderately dry
	601-900	38.0 Moderately dry	44.5 Moderately dry	29.9 Moderately dry	35.9 Moderately dry	37.6 Moderately dry	15.9 Moderately dry	9.5 Moderately dry
	> 900	102.5 Sub-humid	106.6 Sub-humid	90.3 Sub-humid	98.4 Sub-humid	99.7 Sub-humid	75.4 Sub-humid	68.2 Sub-humid
42° 01'-44° 00'	0-300	27.2 Moderately dry	33.6 Moderately dry	13.0 Moderately dry	19.8 Moderately dry	24.2 Moderately dry	-1.0 Moderately dry	-10.1 Moderately dry
	301-600	70.8 Sub-humid	80.2 Sub-humid	58.2 Sub-humid	65.3 Sub-humid	70.6 Sub-humid	42.8 Moderately dry	31.7 Moderately dry
	601-900	147.5 Sub-humid	148.3 Sub-humid	124.4 Sub-humid	133.4 Sub-humid	138.8 Sub-humid	107.8 Sub-humid	95.5 Sub-humid
	> 900	185.6 Humid	199.6 Humid	175.4 Humid	187.4 Humid	191.3 Humid	159.4 Humid	148.2 Sub-humid
44° 01'-46° 00'	0-300	125.5 Sub-humid	113.7 Sub-humid	88.9 Sub-humid	94.3 Sub-humid	103.0 Sub-humid	73.2 Sub-humid	55.8 Sub-humid
	301-600	182.9 Humid	171.3 Humid	153.8 Humid	146.6 Sub-humid	161.6 Humid	129.7 Sub-humid	111.4 Sub-humid
	601-900	222.2 Humid	220.4 Humid	203.8 Humid	195.4 Humid	211.0 Humid	177.2 Humid	158.4 Humid
	> 900	285.8 Humid	285.2 Humid	274.4 Humid	266.0 Humid	278.7 Humid	248.0 Humid	230.4 Humid
> 46° 00'	0-300	390.9 Humid	315.8 Humid	290.3 Humid	284.6 Humid	301.5 Humid	263.7 Humid	237.0 Humid
	301-600	417.1 Humid	337.6 Humid	315.4 Humid	304.0 Humid	324.8 Humid	287.9 Humid	263.6 Humid
	601-900	416.6 Humid	339.3 Humid	320.7 Humid	307.6 Humid	327.7 Humid	292.9 Humid	271.8 Humid
	> 900	399.6 Humid	359.6 Humid	350.9 Humid	332.6 Humid	353.8 Humid	323.6 Humid	309.1 Humid

Figure 4. Dryness index classification of Italy during the Historical period 1991–2022 and Future Scenarios SSP2–4.5 and SSP5–8.5 in 2021–2040, 2041–2060 and 2061–2080 by latitude and elevation.

Figure 5, referring to the HI index, described an essentially similar situation for the two SSPs considered in the first twenty years 2021-2040, with the percentage of areas classified as "Warm" being the most widespread, while those classified as "Very warm" resulted practically non-existent. For both SSPs, the differences compared to the historical period 1991-2021 remained limited (Figure 2), also in terms of % distribution of the various classes on a regional scale, with the southern regions still leading the ranks of the hottest regions in both SSPs (Table S2). The first differences between the two SSPs appeared in the following period, 2041-2060, with the emergence of areas classified as "Very warm": 7% for SSP2-4.5 and 19% for SSP5-8.5. The areas most affected by this increase in HI were the Ionian-Salentian Arc and the Capitanata in Apulia, the Po Valley and some coastal areas in Lazio, as well as the two largest islands, Sardinia and Sicily. For SSP5-8.5 in particular, areas with elevations below 300 m a.sl. at latitudes below 42°N moved into the "Very warm" class (Figure 2). In particular, in the twenty-year period 2041-2060 in SSP2-4.5, 9 out of 20 regions began to see areas classified as "Very warm", with a percentage of 34% in Puglia, followed by Emilia Romagna (21%) and Calabria (14%). In the worst-case scenario SSP5-8.5, areas were classified as "Very dry" in 15 out of 20 regions, from 2% in Friuli Venezia Giulia to 61% in Puglia. The regions immune to the occurrence of the hottest class according to HI remained Liguria, Marche, Piedmont, Trentino Alto Adige and Valle d'Aosta with a predominantly mountainous area (Table S2). In 2061-2080 a shift towards warmer classes appeared more intense, reaching "Very warm" class for 18% for SSP2-4.5 and even 52% for SSP5-8.5 of the national territory (Figure 5). In the latter case, the entire Italian territory with elevations below 300 m a.s.l. was classified as "Very warm" (Figure 2).

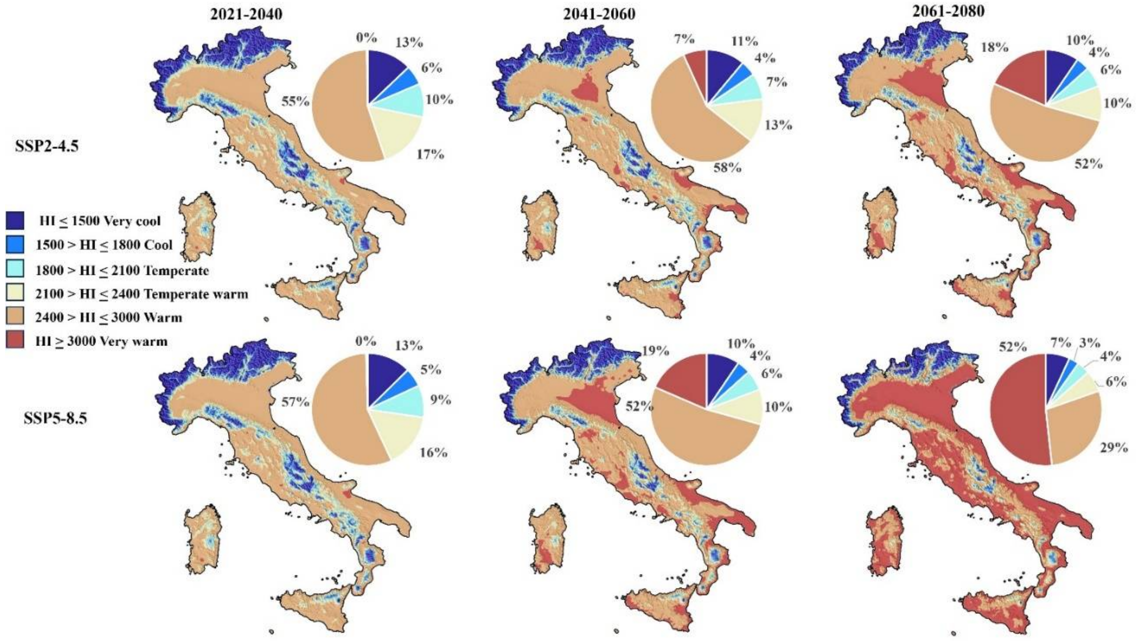

Figure 5. Spatial distributions of Huglin index (HI) in Italy in Future Scenarios SSP2–4.5 and SSP5–8.5 in 2021–2040, 2041–2060 and 2061–2080 and percentage classification.

A shift towards warmer classes could be observed at all latitudes and elevations, with the exception of the Alpine region (>46°N and 900 m a.s.l.), where the HI value almost doubled but the classification remained "Very cool". Furthermore, in SSP5-8.5, 15 out of a total of 20 regions had an area classified as "Very warm" (Suppl 2), while the regions where the mountain component predominates remained quite well preserved, in particular in Val d'Aosta, Trentino Alto Adige and part of Piedmont. Figure 6 shows the spatialization of CI for both SSPs under consideration and for the same twenty-year windows. The period 2021-2040 showed differences compared to the historical reference 1991-2021 (Figure 1) for SSP2-4.5, which practically doubled the percentage of the area that shifted to the "Warm nights" class, from an average of 10% in the historical period to 19% in the period 2021-2040, with CI values > 18°C in the same areas defined as warmer by the previous HI index, i.e. in most coastal areas of southern Italy as well as in Calabria, Apulia, Sardinia and Sicily, with 59%, 50%, 56% and 77% of the territory classified as "Warm nights", respectively (Table S2).

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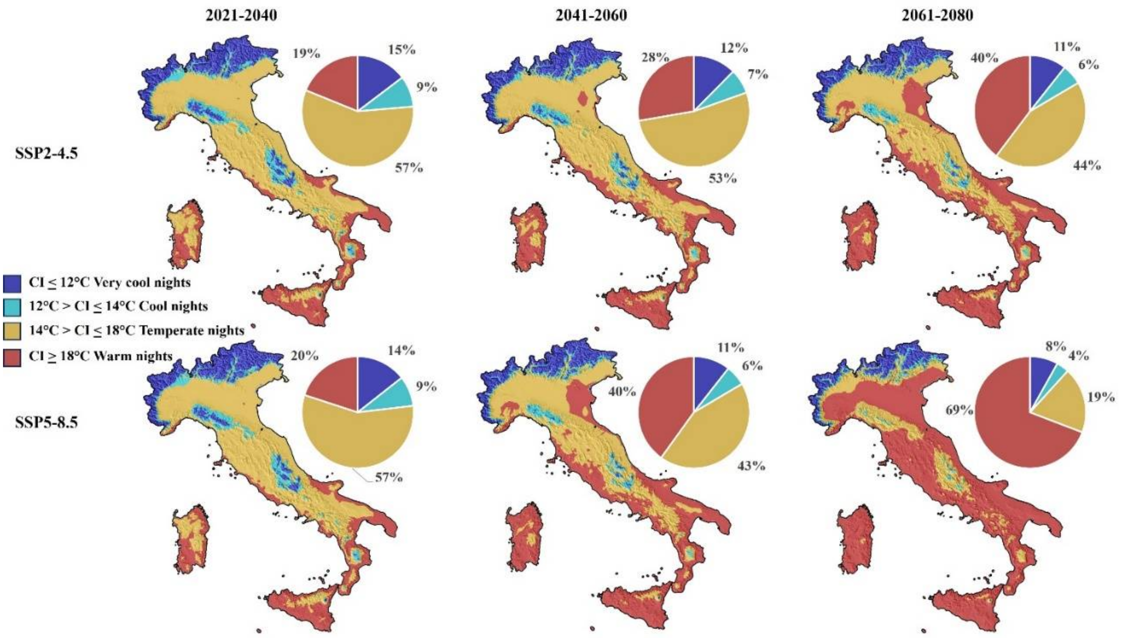

Figure 6. Spatial distributions of Cool night index (CI) in Italy in Future Scenarios SSP2–4.5 and SSP5–8.5 in 2021–2040, 2041–2060 and 2061–2080 and percentage classification.

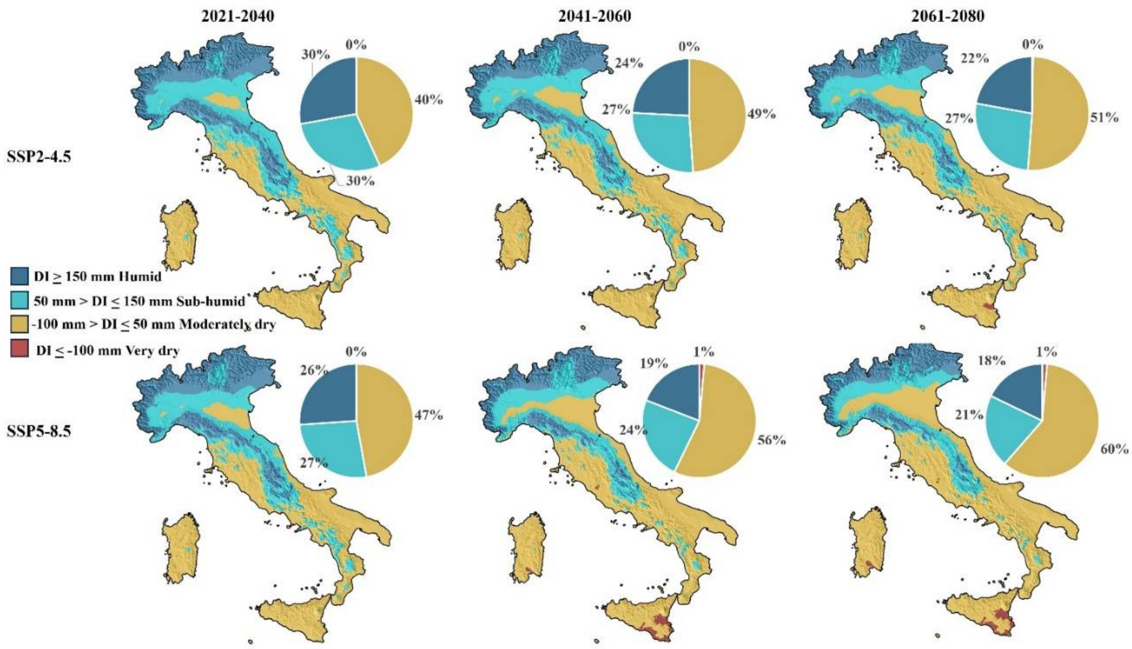

Figure 7. Spatial distributions of Dryness index (CI) in Italy in Future Scenarios SSP2–4.5 and SSP5–8.5 in 2021–2040, 2041–2060 and 2061–2080 and percentage classification.

SSP5-8.5 behaved similarly with 20% of the territory classified as "Warm nights", with the same regions taking the lead. In both scenarios, below 40°N, the areas at an elevation up to 600 m a.s.l. were on average classified as "Warm nights", while the "Very cool nights" class disappeared below 44°N (Figure 3). The situation got worse when analyzing the following twenty years 2041-2060, in which the areas classified as "Warm nights" rose to 28% (SSP2-4.5) and 40% (SSP5-8.5), with the warmest areas increasing in the north of the peninsula. In the milder SSP2-4.5 scenario, some regions reached percentages of "Warm nights" areas of over 70% in Apulia, 68% in Calabria and even 86% of the territory of Sicily and 78% in Sardinia (Table S2). In the worst-case scenario SSP5-8.5, 60% of the area classified as "Warm nights" were encountered in almost all regions, if except for Trentino Alto Adige and Val d'Aosta. The areas below 40° N were all classified as "Warm nights" up to 600 m a.s.l.. (Figure 3) and even up to 900 m a.s.l. in SSP5-8.5. Above 40°N, despite a constant increase in CI over the years, the situation remained overall unchanged in the SSP2-4.5 scenario compared to the previous twenty years 2021-2040, while in the SSP5-8.5 scenario there were areas classified as "Warm nights" at least up to 42°N and up to 600 m a.s.l.. In addition, in this scenario there were transitions to the "Warm nights" class in areas between 0-300 m a.s.l. at 42°N - 44°N and to the "Temperate nights" class, which extended above 900 m as.l.. For the areas above 44°N, however, there were only a few deviations. The analysis of the following twenty years 2061-2080 showed CI values > 18° on 40% of the area in SSP2-4.5 and 69% in SSP5-8.5. If in the first case the area classified as "Temperate nights" was still 44%, this percentage dropped to 19% in scenario SSP5-8.5, a negligible area if we consider that in both scenarios the percentage of the area that still retained climatic conditions for a good viticulture decreased as soon as the areas with excessive elevation combined with "Cool" or "Very cool nights" classes cannot be considered suitable for viticulture. Also in the case of CI, as for the previous HI, the regions that succeeded in reducing the percentage of areas that switched to "Warm nights" were those with predominantly mountainous areas such as Trentino-Alto Adige and Valle d'Aosta. In the SSP2-4.5, in particular Apulia, Sicily and Sardinia were classified as "Warm nights" for percentage around 90%, while in SSP5-8.5 all the regions if excepted once again for Trentino Alto Adige and Val d'Aosta experienced at least 1/3 of the regional area classified as "Warm nights", with values of 90% and more in Campania, Apulia, Sardinia and Sicily. However, other regions where a dramatic increase of CI occurred towards "Warm nights" were those in central Italy such as Lazio (81%), Tuscany (77%), Marche (81%) and much of the flat areas of the Po Valley in Emilia Romagna, Piedmont, Veneto and Lombardy.

Figure 7 illustrates the situation of DI for which, in relation to 2021-2040, an essentially unchanged situation can be observed compared to the historical period 1991-2021 (Figure 1), in which the percentage of areas classified as "Moderately dry" represented on average 40% of the national territory, reaching values of 43% and 47% in the two SSP2-4.5 and SSP5-8.5, respectively. However, in some regions such as Apulia, Sardinia and Sicily, almost the entire area was classified as "Moderately dry" (Table S2). Moreover, the area below 40° N was uniformly "Moderately dry" for both SSPs, even at elevations above 900 m above sea level. (Figure 4), although this represents only 9.9 % of the area in question (Table 2). In the areas north of 40° N, the situation was instead rather stable, with small decreases in DI values but no changes in classification. In the following twenty years 2041-2060, the number of areas classified as "Moderately dry" increased slightly, while on the other hand in Sicily "Very dry" areas started to appear on 4% and 22% of the territory in SSP2-4.5 and SSP5-8.5, respectively (Figure 7). Furthermore, all regions increased the percentage of areas shifted to the drier classes, and in SSP2-4.5 Emilia Romagna (+30%), Marche (+23%), Tuscany and Veneto (+14) were the most affected. In scenario SSP5-8.5 scenario, Emilia Romagna was still 66% "Moderately dry" (+26%), followed by Liguria (+21%) and Marche (+25%) (Table S2). With regard to the latitude and elevation bands (Figure 4), there have been few changes compared to the previous twenty years, if we exclude the areas with elevations up to 600 m a.s.l., which in SSP5-8.5 between 42° N and 44° N changed from "Sub-humid" to "Moderately dry" and between 44° N and 46° N from "Humid" to "Sub-humid" in both SSPs. Finally, as far as the last twenty-year forecast period 2061-2080 is concerned, Figure 4 for SSP2-4.5 showed a situation broadly comparable to that of the previous twenty-year period for SSP2-4.5, while in SSP5-8.5 the increase in "Moderately dry" areas reached 60% of Italy and at the same time the "Very dry" areas remained limited to a total of 1% of the country, concentrated mainly in lower Sicily (22% of the regional territory - Table S2).

4. Discussion

This work illustrates the spatialization of the bioclimatic indices Huglin index, Cool night index and Dryness index for the purpose of an MCC classification of the Italian territory both for the historical period 1991-2021 and for the future scenarios SSP2-4.5 and SSP5-8.5 for the time windows 2021-2040, 2041-2060 and 2061-2080.

In this paper we wanted to analyze Italy not only from a general point of view and on a regional administrative basis, but also to deepen the analysis based on a subdivision by latitude and elevation, considering their importance in amplifying or mitigating the effects of the increase in temperature and of the decrease of precipitation. In particular, in the twenty-year period 2061-2080, the latitudes are also subject to the force of the increase in temperature, with the entire area below 300 m classified as "Very warm" and "Cold Nights" up to 46°N and above.

A decrease in precipitation in the future seems to have less impact on the classification of areas for DI, mainly because the width of DI classes is quite large, such as the "Moderately Dry" class, which ranges from -100 mm to 50 mm. On the other hand, both the analysis of the historical trends of DI (Table 2) and the future projections (Figure 4) show conditions that appear to be consistent over time for latitudes above 44°N and from 300 m above sea level.

However, it must be taken into account that precipitation, an essential component for the calculation of DI, has greater spatial heterogeneity than temperatures. Therefore, there may be large differences in the interpretation of precipitation changes in precipitation resulting from the choices made when summarizing and presenting the data [37]. Furthermore, projections, with respect to the precipitation from GCM ensembles, can be subject to uncertainties and conclusions should be drawn with caution as there is a large discrepancy between models, although a significant and consistent decrease in precipitation will affect the Mediterranean region in summer by the end of the 21st century [28].

To ensure the reliability of the results and as suggested by several authors [38–41], relying on a single GCM may be misleading or lead to an overestimation of the data. In our case, the 13 GCMs available on worldclim.org were considered simultaneously by creating an Ensemble dataset. In addition, the data from the 13 GCMs were downscaled and calibrated using WorldClim v2.1 as the base climate (bias correction). Furthermore, Scafetta et al. [42], using the Equilibrium Climate Sensitivity (ECS) parameter to define the quality of a GCM, categorised 38 GCMs available in CMIP6 into three classes: low, medium and high ECS based on their accuracy and precision in back-projecting global mean surface warming. In our case and based on this classification, the GCM employed can be categorised as follows: two GCMs could be classified as high ECS (ACCESS-CM2, IPSL-CM6A-LR), five as medium ECS (BCC-CSM2-MR, ECS -Earth3-Veg, HadGEM3-GC31, UKESM1-0-LL, MRI-ESM2-0), four as low ECS (GISS-E2-1-G, INM-CM5-0, MIROC6, MPI-ESM1-2-HR) and two as unclassified (CMCC-ESM2, FIO-ESM-2-0). The IPCC 2021 [25] predicts an increase of 2° in SSP2-4.5 and 2.4°C in SSP5-8.5 for the twenty-year period 2041-2060. However, if the presence of warming bias and therefore the GCM data are inaccurately downscaled, this could lead to an overestimation of warming if instead the predicted warming for 2040-2060 does not reach 2°C even for SSP5 -8.5 [42].

Apart from these considerations, however, it is a well-established fact that the increase in temperatures and the decrease in precipitation over the last 40 years have led to a shortening and shift in the phenological phases of grapes [6]. This trend is also confirmed by several authors for the future as we approach the end of the 21st century [43–45], with uneven values for the shortening of the overall cycle of the vine, especially depending on latitude and elevation and a reference value of about 3 days in advance per 100 m elevation [12].

All this stated, the problem of climate change requires the search for solutions and strategies to mitigate the effects in viticulture. In the short term, single strategies to mitigate the effects of climate change have been pursued with the aim of protecting today's vineyards from future warmer conditions [8,34]. This includes the ratio between leaf surface area and fruit weight through the introduction of training systems with higher trunk height such as the Tendone (horizontal pergola), which is often used in Apulia [46]. Rogiers et al. [47] summarised some other options. These include the use of later cultivars, rootstocks more resistant to stress induced by drought or heat waves, more efficient irrigation, delayed pruning and row orientation.

However, a rise of more than 2°C predicted by the IPCC 2022 [48] for the near future would render the effects of any adaptation measures ineffective, at least in some areas, particularly in the regions of southern Italy [42]. Consequently, the concept of vineyard relocation will become more relevant than ever, often above 50°N and at higher elevations, as in the case of the United Kingdom, Germany, northern France, Belgium and the Czech Republic, which will be or already are suitable for quality viticulture [49,50].

With regard to the Italian territory, it should be noted that various production diciplinaries for DOC and DOCG wines provide for altitude restrictions in addition to administrative territorial limits, as in the case of Brunello di Montalcino DOCG (600 metres a.s.l.), Montepulciano d'Abruzzo DOC (500-600 metres a.s.l.), Nebbiolo d'Alba DOC (650 metres a.s.l.), Chianti Classico DOCG (700 metres a.s.l.), Aglianico del Vulture Superiore DOCG (200 - 700 metres a.s.l.) [51–55]. It would therefore be desirable to be able to modify the disciplinaries of production by increasing the elevations authorised for the production of quality wines in the DOC administrative regions where this is possible due to their geographical characteristics.

5. Conclusions

The results show that during the historical period, Italy was predominantly classified as "Temperate Warm" and "Warm" based on the HI value, with a clear trend towards increasing temperatures, especially in the lower latitudes and elevations. This trend was more evident in the southern regions and coastal areas, while the northern mountain regions showed a less pronounced increase. Future scenarios showed further warming with an increase in the areas classified as "Very Warm" and "Warm nights", especially in the SSP5-8.5 scenario, where a large part of the Italian territory up to 300 m a.s.l. will fall into these classes by 2080. As for the DI, despite a decrease in precipitation, this change seems to have less impact on the classification than the other indices. However, in areas already classified as "Moderately dry", drought will see an increase, which will have an impact on water management and the sustainability of viticulture.

The wine regions will therefore have to adapt to significantly warmer climatic conditions, which could affect the quality and typicity of the wines.

Therefore, short and medium-term adaptation strategies for Italian viticulture are mandatory, both to preserve the current Italian wine-growing areas and to propose investment strategies for viticulture in areas with higher latitude and elevation

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Table S1: Kriging and semivariogram statistics; Table S2: Italian Regional Muti-Criteria Classification in Historical period (1991-2021) and Future Scenarios (2021-2040; 2041-2060 and 2061-2080) on the base of SSP2-4.5 and SSP5-8.5

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Data Availability Statement: TIFF Maps of single regions are available on request to the corresponding author for all bioclimatic indices in relation to Historical period and Future Scenarios. Processed climatic Data on Temperature and Precipitation for Historical and Future Scenarios are available at https://worldclim.org, while data on Historical Et0 are available at https://surfobs.climate.copernicus.eu/dataaccess/access_eobs_indices.php

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

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