Received: 27 May 2021 | Accepted: 27 August 2021 | Published: 21 September 2021
DOI:10.20870/oeno-one.2021.55.3.4733

OENO One
VINE AND WINE OPEN ACCESS JOURNAL

Climate change in a typical Apulian region for table grape production: spatialisation of bioclimatic indices, classification and Future Scenarios

Vittorio Alba*[1,•], Giovanni Gentilesco[1,•] and Luigi Tarricone[1]

[1] Research Centre for Viticulture and Enology, Council for Agricultural Research and Economics, via Casamassima 148, 70010 Turi (BA), Italy

**corresponding author*: vittorio.alba@crea.gov.it

Associate editor: Vittorino Novello

ABSTRACT

The present research focused on the characterisation of climate evolution in a typical Apulian region for table grape production under the protected geographical indication, "Uva di Puglia I.G.P."
Two thirty-year time window period (TW) were analysed: 1961–1990 and 1991–2020. Georeferenced maps for both TWs were produced to delimit homogeneous zones and to evaluate the climate variability within the investigated area by means of the two bioclimatic indices, Heliothermal Index (HI) and Winkler Index (WI). Spatial analysis of HI and WI was performed using the regression-kriging (RK) interpolation method and the Digital Elevation Model/DEM (10 x 10 m) as a prediction attribute.
An increase in both the minimum and maximum temperatures was observed, and locations above 300 m a.s.l. shifted from HI+1 "temperate warm" to HI+2 "warm" according to the Geoviticulture Multicriteria Climatic Classification System. WI values similarly increased between the periods 1961-1990 and 1991-2020, shifting all the sites grouped in the Elevation Classes defined as being below 300 m a.s.l. from Region IV to Region V of the Winkler Classification.
According to HI and WI, presumed maturity was calculated as being reached 9 to 15 (HI) and 12 to 28 days (WI) earlier in 1991–2020 than in 1961–1990, taking into account the heat requirements of cv. Italia table grape (representative of Apulian table grape production), were set at 2200 for both indices on the basis of literature data.
Moreover, three table grape vineyards, located in the three main producing provinces of Apulia (Bari, Taranto and Barletta-Andria-Trani (BAT)), were considered for future scenarios analysis on the basis of two different Representative Concentration Pathways (RCPs), 4.5 and 8.5, and classified according to the Geoviticulture Multicriteria Climatic Classification System (MCC). Future scenarios scored WI values that exceeded the threshold of 2700 in the BAT and TA provinces in the 2061–2090 time window period for RCP 8.5. In contrast, RCP 4.5 led to a mitigating effect, which was not noticeable until 2040, with a consequent reclassification of the investigated areas on the basis of HI and Cool Night Index (CI).
These findings suggest that in order to prevent or overcome heat stress, it will be necessary to implement strategies, such as vineyard relocation to unexplored elevations or latitudes and/or the exploitation of new table grape varieties able to fulfill the optimal maturity parameters, even when the duration of the phenological phases is shorter.

KEYWORDS

climate change, table grape, spatialization, Representative Concentration Pathways

© 2021 International Viticulture and Enology Society - IVES

INTRODUCTION

The existence of climate change is now incontrovertible, having clear consequences for agriculture and viticulture (Koufos *et al.,* 2018). Bioclimatic indices are an effective tool for the analysis and precise evaluation of climatic conditions in a given grape growing area. Among them, the Heliothermal Index (HI) (Huglin, 1978) and the Winkler Index (WI) (Amerine and Winkler, 1944) (Table 1) are frequently applied in the viticultural sector, as they correlate well with quantitative and qualitative parameters, like yield, chemical composition, sugar and acidity content and accumulation of secondary metabolites (Tonietto and Carbonneau, 2004). Other bioclimatic indices which rely on temperature have been employed in geoviticultural climatic characterisation; for example, Diurnal Thermal Range (DTR) (Koufos *et al.,* 2013), Cool Night Index (CI) (Tonietto, 1999), Biologically Effective degree-day index (BEDD) (Gladstones, 1992) and Growing Season Temperature (GST) (Jones, 2006). The Dryness Index (DI) (Riou *et al.,* 1994) differs from these indices as it is based on rainfall and evapotranspiration with the aim of classifying a geographical area in relation to its hydric components.

In climate research, a sufficiently large and representative dataset needs to be considered — covering at least 30 years — and preferably referred to the specific historic period of 1961–1990, as defined by the World Meteorological Organization (WMO). Recently, the European Centre for Medium-large Weather Forecasts (ECMWF) have started to consider the ten year time window period of 1991–2020 as the main reference period, as previously unavailable satellite data can now be used (C3S Climate Bulletin, 2021).

In macroclimate, mesoclimate and local climate research, data are normally spatially represented and visualised by means of GIS software (Neethling *et al.,* 2019). However, climatic stations that are far apart — which is particularly the case in macroclimate analysis — can result in uncovered

TABLE 1. Classes/Regions of viticultural climate for Winkler Index (WI), Heliothermal Index (HI), Cool Night Index (CI) and Dryness Index (DI) of the grape-growing regions.

Bioclimatic index	Class/Region of viticultural climate	Acronym	Interval
[a] Winkler Index	Too cold		≤ 850
	Region I		> 851 < 1390
	Region II		≥ 1390 < 1668
	Region III		≥ 1668 < 1945
	Region IV		≥ 1945 < 2223
	Region V		≥ 2223 < 2700 °C
	Too hot		≥ 2701
[b] Heliotermal Index	Very cool	HI-3	≤ 1500
	Cool	HI-2	> 1500 ≤ 1800
	Temperate	HI-1	> 1800 ≤ 2100
	Temperate warm	HI+1	> 2100 ≤ 2400
	Warm	HI+2	> 2400 ≤ 3000
	Very warm	HI+3	>3000
[b] Cool Night Index	Very cool nights	CI+2	≤ 12
	Cool nights	CI+1	> 12 ≤ 14
	Temperate nights	CI-1	> 14 ≤ 18
	Warm nights	CI-2	> 18
[b] Dryness Index	Very dry	DI+2	≤ -100
	Moderately dry	DI+1	≤ 50 > -100
	Sub-humid	DI-1	≤ 150 > 50
	Humid	DI-2	> 150

[a] from Amerine and Winkler, 1944; [b] from Tonietto and Carbonneau, 2004.

 © 2021 International Viticulture and Enology Society - IVES

spaces which have to be filled by spatial data products; these are obtained by the interpolation of existing long-term, quality-controlled data sources using numerous techniques (Jones *et al.,* 2010). Universal kriging (UK), kriging with external drift (KED) and regression-kriging (RK) are the most suitable and effective interpolation methods for reducing standard error in the spatialisation of bioclimatic indices in the following cases: when elevation is considered as a single independent variable (Moral *et al.,* 2014; Honorio *et al.,* 2018), in comparative studies (Hengl *et al.,* 2003), and compared to other interpolation methods like localised regression models employed to produce climatic maps (Attorre *et al.,* 2007; Blasi *et al.,* 2007). These interpolations, defined as "hybrid" (McBratney *et al.,* 2000), involve non-static geostatistical methods which use auxiliar predictors with spatially correlated data in order to perform univariate or multivariate regression models, and thus effectively representing a regression analysis method (Wackernagel, 2003).

While recorded climatic data depict what has happened until today, future climate projections (scenarios) are a tool for forecasting climate variables and indices affected by future greenhouse gas concentrations, climate change and global warming. In recent years, a series of studies on future Climate scenarios have been carried out, thanks to the EURO-CORDEX project, which covers a large area of Europe, including the Mediterranean and part of North Africa. Under this project, data like Tmax, Tmin and Precipitation can be retrieved from simulations by various Regional Climate Models (RCMs) driven by Global Climate Models (GCMs). These simulations can be then used to calculate bioclimatic indices in historic scenarios (until 2005) and future ones based on different Representative Concentration Pathways (RCPs). RCPs are trajectories of future greenhouse gas concentrations based on potential radiative forcing. In RCP 4.5, gas emissions, partially curbed by the application of green technologies, will continue to increase until 2040, then they will decline and stabilise by 2100 at 4.5 W/m^2 in comparison to the year 1850 (Thomson *et al.,* 2011). In contrast, in the RCP 8.5 pathway, no gas emission reduction policies for climate mitigation are applied, causing a radiative forcing at 8.5 W/m^2 in comparison to the year 1850 by 2100 (Riahi *et al.,* 2011).

In recent years, much research has dealt with evaluating climate change and its impact on viticulture, mainly with regard to wine grapes (Jones *et al.,* 2010; Li and Zhou, 2014; Sgubin *et al.,* 2019; Koufos *et al.,* 2020; Piña-Rey *et al.,* 2020; Santos *et al.,* 2020).

Little attention has been given to table grape, which represents one of the most important agricultural sectors in the world. However, the climatic characterisation of Apulia has been undertaken from an economic (Sardaro *et al.,* 2021) and environmental (Polemio and Lonigro, 2014) perspective, and the effect of future climate on the reduction of both grape yield and wine production in the first half of the 21st century in Apulia has been investigated (Lionello *et al.,* 2014). Worldwide Table grape production stood at 27 million tons in 2018, with Italy in seventh place with a production of 1.1 million tons, around 4 % of worldwide production, (OIV, 2019). Moreover, in 2020, ISTAT reported that the Apulia region produced 60 % of total Italian table grape, corresponding to 0.63 million tons mostly concentrated in Bari, Taranto and the BAT provinces. Apulian table grape production is therefore protected by the geographical indication, "Uva di Puglia I.G.P." (UE Reg. n.680/2012, 2012), which delimits the production areas at elevations below 330 m a.s.l. and is restricted to Italia, Regina, Victoria, Michele Palieri and Red Globe varieties.

The aim of this study was to characterise and describe the climate evolution of the Apulia region, the most important table grape producing area in Italy, by means of bioclimatic indices based on a historic meteorological series and two time window periods (TW): 1960–1990 (TW_1) and 1991–2020 (TW_2). A spatial analysis of bioclimatic indices was performed to better represent climate changes over the last sixty years. Moreover, three table grape producing vineyards, located in the three main producing provinces of Apulia (Bari, Taranto and BAT), underwent a future scenarios analysis based on RCPs: 4.5 and 8.5, and they were classified according to the Geoviticulture Multicriteria Climatic Classification System (MCC).

MATERIALS AND METHODS

1. Climate data

A historic series of the monthly Tmax and Tmin on 30 Apulian weather stations was downloaded from the Civil Protection site at https://protezionecivile.puglia.it for two thirty-year time window periods (TW): 1961–1990 (TW_1) and 1991–2020 (TW_2).

© 2021 International Viticulture and Enology Society - IVES

In order to evaluate changes in the Heliothermal Index (HI) and Winkler Index (WI) across both TWs (Tables 4 and 5), the 30 sites were grouped into five Elevation Classes (EC) depending on their 100 m range within an elevation of 0 to 500 m a.s.l. Differences in monthly and total HI and WI were evaluated using the non-parametric Kruskal-Wallis test. Moreover, linear regression equations between cumulative HI or WI with Julian Days (JD) were calculated, with the aim of evaluating the number of JD ± SE needed by a representative "Uva di Puglia I.G.P." table grape cultivar, like Italia, to reach 2200 HI or WI for each of the five groups within each of the two TWs. The value 2200 was chosen based on the requirements reported by Fregoni (2005) for late or very late table grape cultivars.

1.1. Bioclimatic Indices

The Bioclimatic Indices and relative classes of viticultural climate are listed in Table 1.

The Winkler Index was calculated as follows:

$$WI = \sum_{01.04}^{31.10} (Tmean - Tbase)$$

where Tbase = 10 °C

For the Multicriteria Climatic Classification (MCC), the Heliothermal Index (HI), Cool Night Index (CI) and Dryness Index (DI) were calculated as follows:

$$HI = \sum_{01.04}^{30.09} \frac{[(Tmean-10)+(Tmax-10)]}{2} d$$

where d = length of day coefficient, set at 1.02 for latitudes of between 40°01' and 42°00'.

CI (°C) = *Tmin* September

DI = $Wo + P - Tv - Es$

where *Wo* = soil water reserve at the end of the growing season (mm)

P = Precipitation (PR) (mm)

Tv = ETP*k* potential grapevine evapotranspiration (mm)

ETP = potential evapotranspiration (mm)

k = coefficient of radiation absorption by the vineyard (in the Northern hemisphere: 0.1 for April, 0.3 for May, 0.5 from June to September)

$$Es = \frac{ETP}{N}(1-k)JPm$$

Where N = number of days in the month; JPm = monthly precipitations (PR) in mm/5 (number of days of effective evaporation from the soil per month).

ETP (Penman, 1948) was calculated by means of CROPWAT 8.0 (FAO, 1992), which provides an Estimated ETP on the base of Tmax and Tmin when other climatic data are missing.

In the occurrence of outliers, medians were taken into account in order to obtain monthly PR (ISPRA, 2013).

The MCC were calculated on the Geoviticulture MCC System web platform available at http://www.cnpuv.embrapa.br/ccm/ccm.en.html# (EMBRAPA UVA E VINHO, 2007).

1.2. Geostatistical interpolation techniques

By applying the geostatistical technique, regression-kriging (RK), it was possible to combine the linear or multiple regression analysis of auxiliary information and subsequently the kriging algorithm for residuals. The independent or predictor auxiliary variable is the digital elevation model (DEM), with a resolution of 10 m in the UTM WGS 84 zone 33N projection system (Tarquini and Nannipieri, 2017). The elevation predictor produces maps with detailed results and high accuracy of the spatial prediction, since its values, which are extracted from a raster format image, are regularly positioned (grid), are available in every point of the regionalised variable and possess a high resolution 10 x 10 m (Hengl *et al.,* 2003; Hengl, 2007).

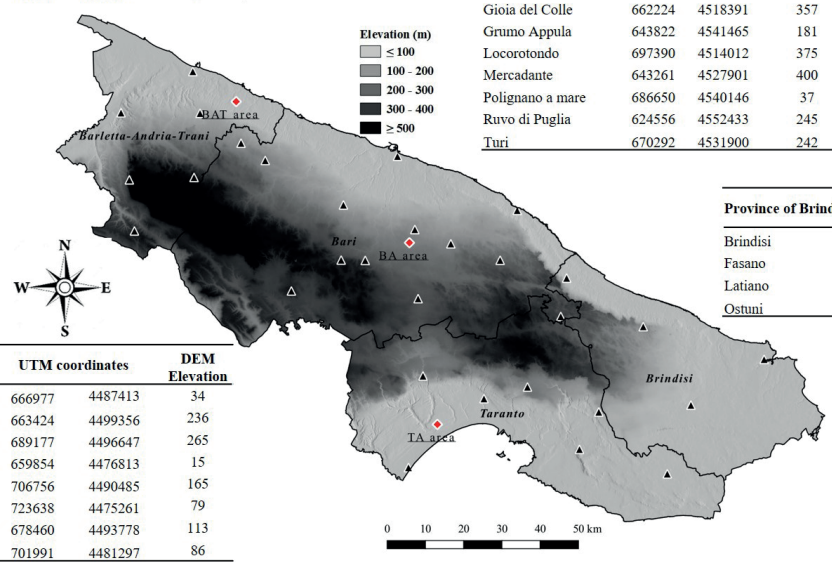
The validation of the predicted bioclimatic indices was processed by Leave-One-Out Cross Validation (LOOCV) in both TW_1 and TW_2 for each weather station, providing an independent comparison of the calculated and interpolated HI and WI indices. The Mean Error (ME) and Root Mean Square Error (RMSE) of the comparison were determined to evaluate the interpolation error, and therefore the reliability/accuracy of the kriging model**.**

The open-source SAGA GIS software (System for Automated Geoscientific Analyses) version 2.3.2 and QGIS version 3.10 were used to perform the interpolation procedure by means of kriging and the cartographic rendering in GRID format with a resolution of 10 x 10 m respectively**.**

 © 2021 International Viticulture and Enology Society - IVES

Province of BAT	UTM coordinates		DEM Elevation
Farm BAT area	617388	4566902	68
Andria	608485	4564040	148
Barletta	606701	4574331	21
Canosa di Puglia	589011	4564170	150
Castel del Monte	607009	4548253	481
Minervino Murge	591064	4547652	496
Spinazzola	592315	4535068	445

Province of Bari	UTM coordinates		DEM Elevation
Farm BA area	660087	4532152	262
Altamura	630998	4520285	467
Bari	657149	4553463	7
Casamassima	661419	4535423	222
Cassano Murge	649193	4527822	339
Castellana Grotte	682446	4527857	310
Corato	618589	4556680	226
Gioia del Colle	662224	4518391	357
Grumo Appula	643822	4541465	181
Locorotondo	697390	4514012	375
Mercadante	643261	4527901	400
Polignano a mare	686650	4540146	37
Ruvo di Puglia	624556	4552433	245
Turi	670292	4531900	242



Province of Brindisi	UTM coordinates		DEM Elevation
Brindisi	747494	4503439	16
Fasano	698832	4523455	110
Latiano	729461	4492174	100
Ostuni	717710	4511508	240

Province of Taranto	UTM coordinates		DEM Elevation
Farm TA area	666977	4487413	34
Castellaneta	663424	4499356	236
Crispiano	689177	4496647	265
Ginosa marina	659854	4476813	15
Grottaglie	706756	4490485	165
Manduria	723638	4475261	79
Massafra	678460	4493778	113
San Giorgio Jonico	701991	4481297	86

FIGURE 1. Digital elevation model (DEM) of 30 sites located in a typical Apulian region for table grape production.

2. Future scenarios

The DEAR-Clima database (http://meteo3.geo.auth.gr:3838/) was employed to retrieve Tmax, Tmin and PR of three representative table grape vineyards: Farm BAT area, Farm BA area and Farm TA area. Geographical and elevation data are given in Figure 1.

The time series were based on high horizontal resolution simulations produced by the Regional Climate Model (RCM) from the Coordinated Regional Downscaling Experiment (CORDEX) research program. RCM data processed in the DEAR-Clima database have a high spatial resolution (0.11° x 0.11°) over the European domain and cover a time period of 1950 to 2100. (Koufos *et al.,* 2020). The RCM LMcom-CCLM4-8-17 driven by the Global Climate Model, CNRM-CERFACS-CNRM-CM5, was used to perform simulations in the following three different scenarios and 30-year time window periods: a historic scenario (1976 to 2005) and two Representative Concentration Pathways (RCPs), RCP 4.5 and RCP 8.5 (both in the time window period 2021 to 2050 and 2061 to 2090).

HI and WI were calculated for the historic and RCP scenarios for each of the three vineyards, together with linear regression equations between cumulative HI or WI with Julian Days (JD) and Multicriteria Climatic Classification (MCC).

Trends in Tmin and Tmax in the historic and RCP scenarios for the three vineyards were graphically plotted using weighted moving averages within a 5-year period.

The predicted JD ± SE required to reach 2200 HI or WI on the three vineyards and in the three different scenarios were also calculated.

RESULTS

Thirty Apulian sites (Figure 1) were studied in two thirty-year time window periods (TWs): 1961–1990 (TW_1) and 1991–2020 (TW_2). The Heliothermal Index (HI) and the Winkler Index (WI) were calculated for each of the two TWs in the Apulian area defined by the Protected Geographical Indication "Uva di Puglia I.G.P.". It comprises all the provinces of Apulia except Lecce province, and limits table grape production to elevations below 330 m a.s.l., which in practice excludes almost the whole province of Foggia.

© 2021 International Viticulture and Enology Society - IVES

Therefore, the research focused on the central part of Apulia dedicated to table grape production in an area that includes the BAT, Bari, Taranto and Brindisi provinces.

Figure 2 represents the spatialisation of bioclimatic indices HI and WI in the two TWs. HI_{TW1} values ranged from 2137.1 for Mercadante (central zone of Murgia) to 2684.7 for San Giorgio Jonico thus, based on the classification of Tonietto and Carbonneau (2004), they can be classified as: HI+1 (temperate warm – 43 %) and HI+2 (warm – 57 %). More generally, the areas with the highest HI were the Jonian coast and the northern border of the BAT province, immediately south of the plain of Tavoliere, from which it is separated by the Ofanto valley.

Similarly to HI_{TW1}, WI_{TW1} spatialisation depicted the warmest territories of Apulia as being the northern boundary of the Murgia Plateau in the BAT province and the Jonian coast of Taranto provinces, with values ranging from 1807.3 for Mercadante to 2480.5 for Massafra, encompassing three Winkler Classification Regions, namely III (13 %), IV (40 %) and V (47 %).

A proportional general increase in the values for both indices for the whole investigated area was to be expected. HI_{TW2} and WI_{TW2} showed a general temperature increase. The annual mean temperature increased from 15.5 °C in TW_1 to 16.6 °C in TW_2. This was reflected in the resulting increase in HI values ranging from 2352.6 for Locorotondo, located in the southern part of the Murgia plateau, to 2956.3 for Canosa di Puglia, located at the border of the BAT province along the Ofanto valley; this shifted the whole Apulian area (except for Locorotondo) to the HI+2 (warm) classification. Likewise, WI_{TW2} increased and, when applying the Winkler Classification, all the sites shifted to Regions IV (13 %) and V (77 %), with values ranging from 2088.1 for Castel del Monte to 2757.6 for Massafra, which, together with San Giorgio Jonico (2701.1) and Canosa di Puglia (2731.9), exceeded the threshold value of 2700 WI for Region V. The subdivision of the 30 Apulian sites into the five Elevation Classes (EC) with ranges of 100 m. a.s.l., based on the Digital Elevation Model-DEM (Figure 1), was highly correlated with the bioclimatic indices. As can be seen in Table 2, HI and WI hare highly correlated;

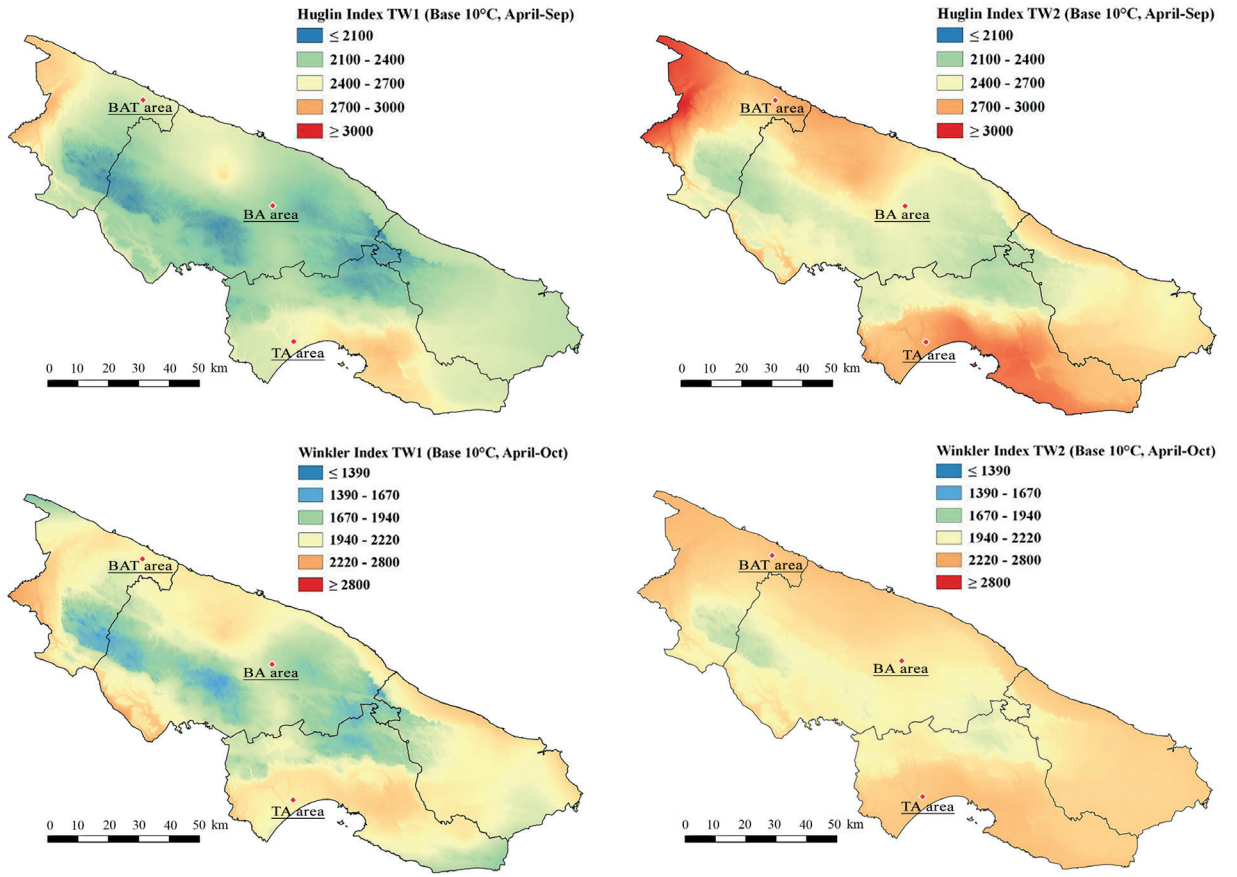


FIGURE 2. Spatialisation of Heliothermal index (HI) and of Winkler index (WI) in a typical Apulian territory for table grape production in two time window periods: 1961–1990 (TW_1) and 1991–2020 (TW_2).

 © 2021 International Viticulture and Enology Society - IVES

this is because they are based on temperature (Moral *et al.,* 2014; Honorio *et al.,* 2018). Table 2 also shows that elevation has a significant negative linear correlation with HI and WI in both Tws, in particular WI_{TW2} (r = -0.79); meanwhile, no significant correlation was found between longitude/latitude and the two bioclimatic indices. The spread of the interpolation error within the study area, and therefore the reliability of the model, was confirmed by the Leave-One-Out Cross Validation (LOOCV) for both TW_1 and TW_2, for each weather station (Table 3). The RK yielded the lowest root-mean-square error (RMSE) with respect to other interpolation methods (data not shown), especially for HI in both TWs, indicating an effective spatial variability representation. The two indices calculated from interpolation (predicted data) based on the 30 Apulian weather stations, were very close to the observed one in both TWs, which was confirmed by the low Mean Error (ME) value and the high Pearson correlation coefficient (Figure 3).

Table 4 and Table 5 report the comparison of HI and WI between TW_1 and TW_2 relative to the five ECs. The number of sites included in each EC ranged from a minimum of 4 in EC V to a maximum of 9 sites in EC I. A total of 21 out of the 30 sites were located between 0 and 300 m. a.s.l., an altitude suitable for table grape cultivation. Given the small number of sites falling into each of the EC, the non-parametric Kruskall-Wallis test was preferred to a parametric ANOVA. Differences in HI between the TWs were found in EC I (0–100), EC III (201–300) and EC IV (300–400), while no significant differences were found in the remaining two ECs, and HI even showed an increase of 196.4 and 178.4 in EC II and V respectively. HI values in TW_1 ranged from 2236.7 in EC IV to 2531.8 in EC II, while in TW_2 it ranged from 2438 in EC V to 2728.2 in EC II. In terms of MCC and compared to TW_1, HI increased in TW_2 in the EC I and EC II, but they remained classified as HI+2 (warm). Meanwhile, all the sites located over 200 m a.sl. showed an increase in HI, thus shifting them from HI+1 (temperate warm) in TW_1 to HI+2 (warm) in TW_2.

In contrast, in terms of WI, significant differences were found for all ECs, with increases of up to 300 WI in EC IV when comparing TW_1 and TW_2. It is worth noting that in TW_1, WI values for EC III, IV and V did not reach the optimum of WI > 2200, while it was reached in TW_2 in all the ECs, including those with an elevation unsuitable for table grape cultivation according to the "Uva di Puglia I.G.P." protocol (i.e., > 330 m. a.s.l.). In TW_1, WI values ranged from 1977.1 for EC IV to 2353.5 for EC I, while in TW_2 the lowest WI value (2207.5) was obtained for EC V and the highest (2600.8) for EC II. In both of the bioclimatic indices HI and WI, EC II obtained higher values than EC I, suggesting that the sea had a mitigation effect. Moreover, in relation to the WI regional classification (Amerine and Winkler, 1944), during TW_1 the sites located within 200 m a.s.l.

TABLE 2. Correlation matrix between Heliothermal Index (HI), Winkler Index (WI), longitude, latitude and elevation in the Apulia region in two time window periods: 1961–1990 (TW_1) and 1991–2020 (TW_2).

	Elevation	Longitude	Latitude	HI_{TW1}	HI_{TW2}	WI_{TW1}	WI_{TW2}
Elevation	1						
Longitude	0.2213	1					
Latitude	-0.4404	-0.7481*	1				
HI_{TW1}	-0.6788*	-0.2120	0.1144	1			
HI_{TW2}	-0.6420*	-0.1337	0.0363	0.8747*	1		
WI_{TW1}	-0.7770*	-0.1870	0.2372	0.9554*	0.8470*	1	
WI_{TW2}	-0.7942*	-0.1210	0.2073	0.8204*	0.9320*	0.8913*	1

** $P < 0.05$*

TABLE 3. Leave-One-Out Cross Validation (LOOCV): Mean Error (ME) and Root Mean Square Error (RMSE) of observed vs predicted Heliothermal Index (HI) and Winkler Index (WI) in two time window periods: 1961–1990 (TW_1) and 1991–2020 (TW_2).

	WI_{TW1}	WI_{TW2}	HI_{TW1}	HI_{TW2}
ME	-0.13	-0.28	-0.015	-0.170
RMSE	48.82	53.94	4.46	18.49

© 2021 International Viticulture and Enology Society - IVES

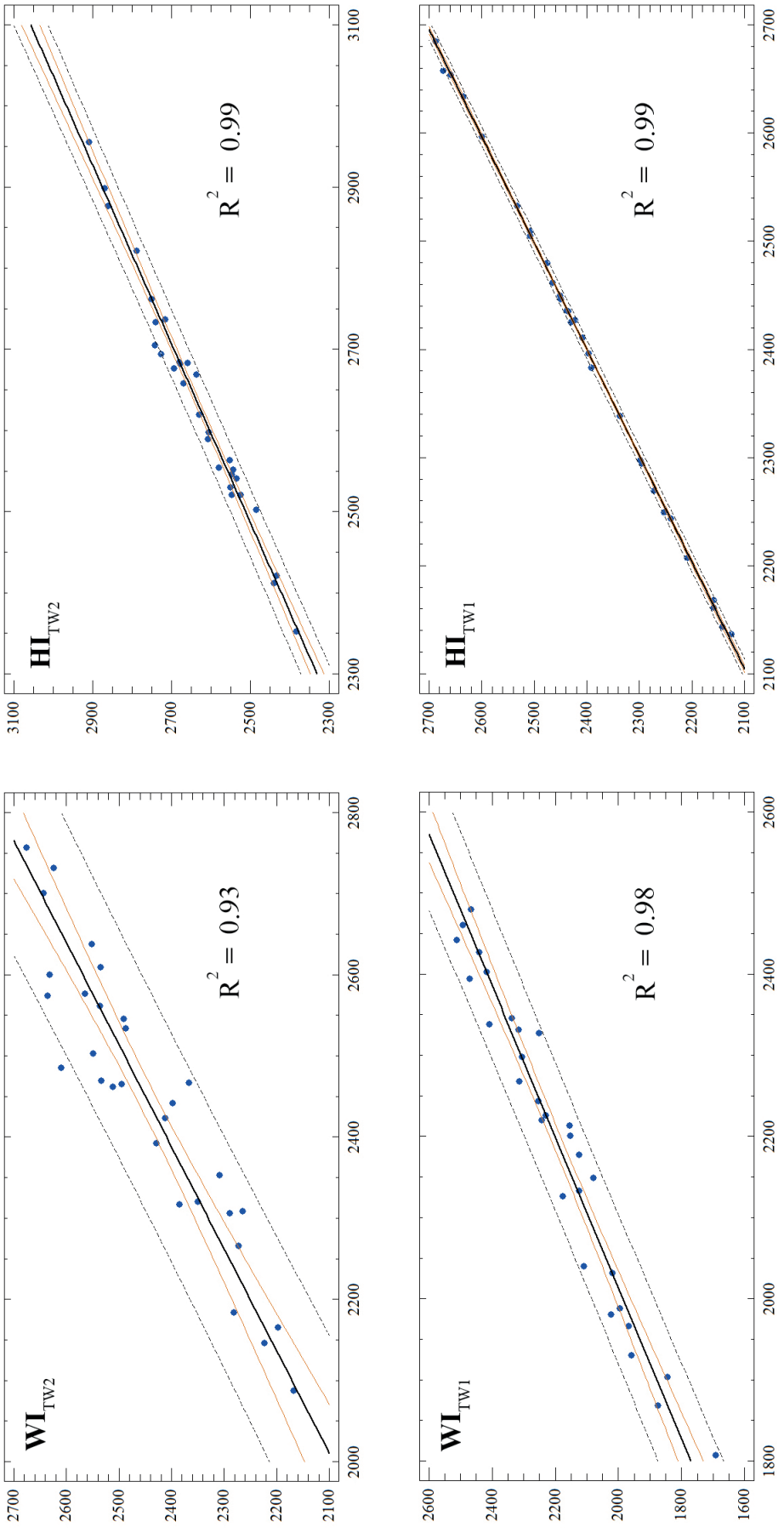


FIGURE 3. Scatterplot and Pearson correlation coefficient of the relations between observed (x axis) and predicted values (y axis) of Heliothermal Index (HI) and Winkler index (WI) in two time window periods: 1961–1990 (TW_1) and 1991–2020 (TW_2). Each point represents a weather station.

TABLE 4. Comparison of thirty-year time window periods (1961–1990 - TW1 *vs*. 1991–2020 - TW2). Huglin Index (HI), Geoviticulture Multicriteria Climatic Classification System (MCC) classes and acronyms, linear regression of HI and Julian Days (JD), JD needed to reach an optimum of 2200 HI based on cv. Italia (a late or very late ripening cultivar) of 30 sites located in a typical Apulian region for table grape production, subdivided into five Elevation Classes (EC) each of 100 m elevation range.

EC (m. a.s.l.)	Nr. Sites	Period	HI	MCC class	MCC acronim	Linear regression JD/cumulative HI	R^2	JD to HI = 2200 +/- SE
EC I (0–100)	9	61-90	2516.2	HI+2	Warm	y = 0.0683x + 104.79	R^2 = 0.9836	255 ± 9.25
		91-20	2665.8	HI+2	Warm	y = 0.0644x + 104.39	R^2 = 0.9843	246 ± 9.06
		Diff	149.5					9
		K-W sign	**					
EC II (101–200)	5	61-90	2531.8	HI+2	Warm	y = 0.0677x + 105.01	R^2 = 0.9833	254 ± 9.36
		91-20	2728.2	HI+2	Warm	y = 0.0628x + 104.28	R^2 = 0.9846	242 ± 8.98
		Diff	196.4					12
		K-W sign	ns					
EC III (201–300)	7	61-90	2359.5	HI+1	Temperate Warm	y = 0.0723x + 106.03	R^2 = 0.9812	265 ± 9.92
		91-20	2561.0	HI+2	Warm	y = 0.0666x + 105.11	R^2 = 0.9829	252 ± 9.46
		Diff	201.5					13
		K-W sign	**					
EC IV (301–400)	5	61-90	2236.7	HI+1	Temperate Warm	y = 0.0756x + 107.24	R^2 = 0.9786	258 ± 10.59
		91-20	2478.7	HI+2	Warm	y = 0.0684x + 105.97	R^2 = 0.9811	243 ± 9.95
		Diff	242.0					15
		K-W sign	**					
EC V (401–500)	4	61-90	2259.6	HI+1	Temperate Warm	y = 0.0746x + 107.94	R^2 = 0.9769	272 ± 10.98
		91-20	2438.0	HI+2	Warm	y = 0.069x + 107.18	R^2 = 0.9782	259 ± 10.68
		Diff	178.4					13
		K-W sign	ns					

Ns: not significant; * $p < 0.05$; ** $p < 0.01$; ***$p < 0.001$ on the base of Non Parametric Kruskall-Wallis analysis

© 2021 International Viticulture and Enology Society - IVES

TABLE 5. Comparison of thirty-year time window periods (1961–1990 - TW_1 *vs.* 1991–2020 - TW_2): Winkler Index (HI), Winkler Region's classification, linear regression of WI and Julian Days (JD), JD needed to reach an optimum of > 2200 WI referred to cv. Italia (late or very late ripening cultivar) of 30 sites located in a typical Apulian territory for table grape production, subdivided in five Elevation Classes (EC) each of 100 m Elevation range.

EC (m. a.s.l.)	Nr. Sites	Period	WI	Winkler Region's classification	Linear regression JD/cumulative WI	R^2	JD to WI = 2200 +/- SE
EC I (0–100)	9	61-90	2353.5	V	y = 0.0815x + 107.87	0.9817	287 ± 10.95
		91-20	2570.8	V	y = 0.0748x + 106.74	0.9833	271 ± 10.47
		Diff	217.3				16
		K-W sign	***				
EC II (101–200)	5	61-90	2333.0	V	y = 0.0816x + 108.25	0.9803	288 ± 11.37
		91-20	2600.8	V	y = 0.0736x + 106.9	0.9823	269 ± 10.78
		Diff	267.8				19
		K-W sign	**				
EC III (201–300)	7	61-90	2146.8	IV	y = 0.0879x + 109.6	0.9777	303 ± 12.09
		91-20	2425.3	V	y = 0.0784x + 107.98	0.9804	280 ± 11.33
		Diff	278.5				23
		K-W sign	**				
EC IV (301–400)	5	61-90	1977.1	IV	y = 0.0937x + 111.78	0.9725	318 ± 13.41
		91-20	2291.8	IV	y = 0.0819x + 109.45	0.9769	290 ± 12.30
		Diff	314.7				28
		K-W sign	**				
EC V (401–500)	4	61-90	1993.4	IV	y = 0.0924x + 112.47	0.971	257 ± 13.79
		91-20	2207.5	IV	y = 0.0838x + 111.29	0.9725	245 ± 13.42
		Diff	214.2				12
		K-W sign	**				

Ns: not significant; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ on the base of Non Parametric Kruskall-Wallis analysis

were all classified in Region V (2223–2700), while those over 200 m a.s.l. belonged to Region IV (1945–2222). In contrast, in TW2, all the sites, except for those located over 400 m a.s.l. were classified in Region V.

Tables 4 and 5 show the linear regression equations calculated between cumulative HI and WI respectively, with JD for each Elevation Class and TW. In all cases, R^2 of the equations was > 0.97; therefore it was necessary to predict the JD required to reach 2200 HI or WI. As stated before, 2200 HI and > 2200 WI were the values reported to be suitable for late or very late table grape cultivars like the Italia variety. All the ECs reached the optimum of 2200 HI earlier when comparing the two TWs, from a minimum of 9 days early in EC I to a maximum of 15 days early in EC IV, with standard error SE suggesting fluctuations of around 9 days. Regarding WI, earlier presumed harvest dates were more consistent when comparing WI_{TW1} to WI_{TW2}, with values ranging from 12 days in EC V to 28 days in EC IV.

In order to analyse the historic (1976–2005) and future (2021–2050 and 2061–2090) climate scenarios (Representative Concentration Pathway – RCP 4.5 and RCP 8.5), monthly Tmin, Tmax and Precipitation (PR) of three table grape vineyards located in three different Apulian provinces (Farm BAT, Farm BA and Farm TA; Figure 1) were retrieved from http://meteo3.geo.auth.gr:3838/. WI, HI, Cool Night Index (CI) and Dryness Index (DI) were calculated for all the scenarios (Table 6).

The differences in terms of Tmax and Tmin between the three vineyards for all the scenarios are shown in Figure 4. In the historic scenario, the recorded temperatures on Farm BA were lower than the other two vineyards by around 1 °C for both Tmax and Tmin and this affected the bioclimatic indices. The lowest WI was calculated for Farm BA, classified as Region IV (2003.2); the other two vineyards were classified as Region V, since they had WI values over 2200. Differences between the vineyards were also found for MCC in terms of HI: Farm BA was classified as temperate warm (HI+1), while according to the Cool Night Index (CI) and the Dryness Index (DI) all the three vineyards were classified as CI-1 (temperate nights) and DI+1 (moderately dry).

In terms of RCPs in 2021-2050, a propotional increase in temperature was observed for all the vineyards, with little differences between RCP 4.5 and 8.5, since each RCP only have an effect after 2040. Farm BAT and Farm TA showed higher temperatures, with Tmax above 20 °C and Tmin above 12 °C in both RCPs, that means that the average annual temperature in 2021-2050 exceeds the range of 15 to 16 °C, which is normally measured in Puglia. In RCP 4.5, the Winkler Classification remained unaltered for all the vineyards, while in RCP 8.5 all the vineyards were classified as Region V. The increase in temperature had an effect on MCC: Farm BA shifted to HI+2 (warm) in both RCPs, while Farm BAT and Farm TA shifted to CI-2 (warm nights).

The increase in temperature became more evident for the period 2061-2090, with notable differences between RCP 4.5 and RCP 8.5, since the expected effect of the countermeasures relative to RCP 4.5 became effective. In Farm BAT and Farm TA, Tmax and Tmin tended to increase to above 21 and 13 °C respectively in RCP 4.5 (average temperatures over 17 °C), and to above 22 °C and 14 °C in RCP 8.5 (average temperatures over 18 °C). Meanwhile, a smaller increase in temperature was observed for Farm BA, helped by the mitigation effect of its higher elevation compared to the other two vineyards; in RCP 4.5, it maintained an annual average temperature of 15.6 °C, which is in line with the actual regional values, while in the worst case of RCP 8.5, a temperature of 17.3 °C was reached. A mitigating impact of RCP 4.5 on WI values was observed, allowing all three vineyards to remain classified as Region V, while in RCP 8.5, Farm BAT and Farm TA exceeded the threshold of 2700 for Region V. MCC in both RCP 4.5 and RCP 8.5 shifted Farm BA to CI-2 (warm nights); this is the same class as the other two vineyards, for which no classification change occurred, excepted in terms of HI, which shifted to HI+3 (very warm).

Table 6 shows linear equation regressions (R^2 > 0.97) between HI or WI and JD for all the scenarios and time series for all three vineyards. Based on these equations, once HI or WI were equal to 2200, a box-plot of the JD ± SE needed to reach the presumed harvest date for the Italia variety was calculated (Figure 5). An early presumed maturation was found for all the vineyards, gradually becoming more intense over the years according to the different scenarios. In the historic scenario, 273 JD were necessary to reach 2200 HI and thus the presumed maturity in Farm BA, which corresponded to 30 September; this is in line with the actual period of maturation for Italia cv., a late table grape that is usually harvested in the third week of September or, at the latest, the first week of October.

© 2021 International Viticulture and Enology Society - IVES

TABLE 6. Comparison of Heliothermal Index (HI), Winkler Index (WI), Night cold index (CI) and Dryness index (DI), Geoviticulture Multicriteria Climatic Classification System (MCC) classes and acronyms, between Historic and Future Scenarios (RCP 4.5 and 8.5) in three table-grape farms located in a typical Apulian territory for table grape production. Linear regression equations of HI e WI with Julian Days (JD) and relative R2 for each Time Window and scenario are also reported.

time window	1976–2005	2021–2050		2061–2090	
Scenario	historic	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
			Farm BAT area		
WI	2261.6	2460.1	2523.2	2638.2	2846.3
WI/JD linear regression	y = 0.0838x + 110.43	y = 0.0768x + 110.11	y = 0.0759x + 108.4	y = 0.072x + 108.67	y = 0.0676x + 106.99
WI/JD R^2	R^2 = 0.9772	R^2 = 0.9771	R^2 = 0.9805	R^2 = 0.9792	R^2 = 0.9829
HI	2463.5	2647.9	2701.9	2802.3	3006.8
HI/JD linear regression	y = 0.069x + 107.42	y = 0.0642x + 107.33	y = 0.0636x + 105.8	y = 0.0608x + 106.29	y = 0.057x + 105.31
HI/JD R^2	R^2 = 0.9768	R^2 = 0.9771	R^2 = 0.9803	R^2 = 0.9794	R^2 = 0.9818
CI (°C)	17.5	18.8	19.1	19.4	20.6
DI (mm)	15	-3	-7	-1	-17
MCC acronims	HI+2	HI+2	HI+2	HI+2	HI+3
	CI-1	CI-2	CI-2	CI-2	CI-2
	DI+1	DI+1	DI+1	DI+1	DI+1
MCC classes	Warm	Warm	Warm	Warm	Very warm
	Temperate nights	Warm nights	Warm nights	Warm nights	Warm nights
	Moderately dry	Moderately dry	Moderately dry	Moderately dry	Moderately dry

(Table 6 continues on next page).

(Table 6 continued from previous page).

			Farm BA area		
WI	2003.2	2205.9	2269.4	2380.0	2603.8
WI/JD linear regression	y = 0.0927x + 113.35	y = 0.084x + 112.8	y = 0.0829x + 110.89	y = 0.0784x + 110.99	y = 0.0728x + 109.02
WI/JD R^2	R^2 = 0.9708	R^2 = 0.971	R^2 = 0.9753	R^2 = 0.9741	R^2 = 0.9788
HI	2256.6	2444.2	2496.8	2599.2	2814.6
HI/JD linear regression	y = 0.0743x + 109.75	y = 0.0687x + 109.54	y = 0.068x + 107.88	y = 0.0648x + 108.29	y = 0.0603x + 107.03
HI/JD R^2	R^2 = 0.9709	R^2 = 0.9713	R^2 = 0.9753	R^2 = 0.9744	R^2 = 0.9779
CI (°C)	16.3	17.5	17.8	18.1	19.3
DI (mm)	11	-8	-1	1	-20
MCC acronims	HI+1	HI+2	HI+2	HI+2	HI+2
	CI-1	CI-1	CI-1	CI-2	CI-2
	DI+1	DI+1	DI+1	DI+1	DI+1
MCC classes	Temperate warm	Warm	Warm	Warm	Warm
	Temperate nights	Temperate nights	Temperate nights	Warm nights	Warm nights
	Moderately dry	Moderately dry	Moderately dry	Moderately dry	Moderately dry
			Farm TA area		
WI	2247.0	2460.2	2509.0	2638.7	2849.0
WI/JD linear regression	y = 0.0834x + 111.87	y = 0.076x + 111.65	y = 0.0755x + 110.07	y = 0.0713x + 109.95	y = 0.0669x + 108.34
WI/JD R^2	R^2 = 0.9739	R^2 = 0.9736	R^2 = 0.9771	R^2 = 0.9763	R^2 = 0.9802
HI	2516.2	2714.3	2751.7	2876.7	3083.0
HI/JD linear regression	y = 0.0669x + 108.98	y = 0.062x + 109	y = 0.0617x + 107.62	y = 0.0588x + 107.74	y = 0.0552x + 106.82
HI/JD R^2	R^2 = 0.9727	R^2 = 0.9725	R^2 = 0.9758	R^2 = 0.9755	R^2 = 0.9779
CI (°C)	17.1	18.3	18.6	19.0	20.3
DI (mm)	-43	-63	-64	-54	-68
	HI+2	HI+2	HI+2	HI+2	HI+3
MCC acronims	CI-1	CI-2	CI-2	CI-2	CI-2
	DI+1	DI+1	DI+1	DI+1	DI+1
	Warm	Warm	Warm	Warm	Very warm
MCC classes	Temperate nights	Warm nights	Warm nights	Warm nights	Warm nights
	Moderately dry	Moderately dry	Moderately dry	Moderately dry	Moderately dry

© 2021 International Viticulture and Enology Society - IVES

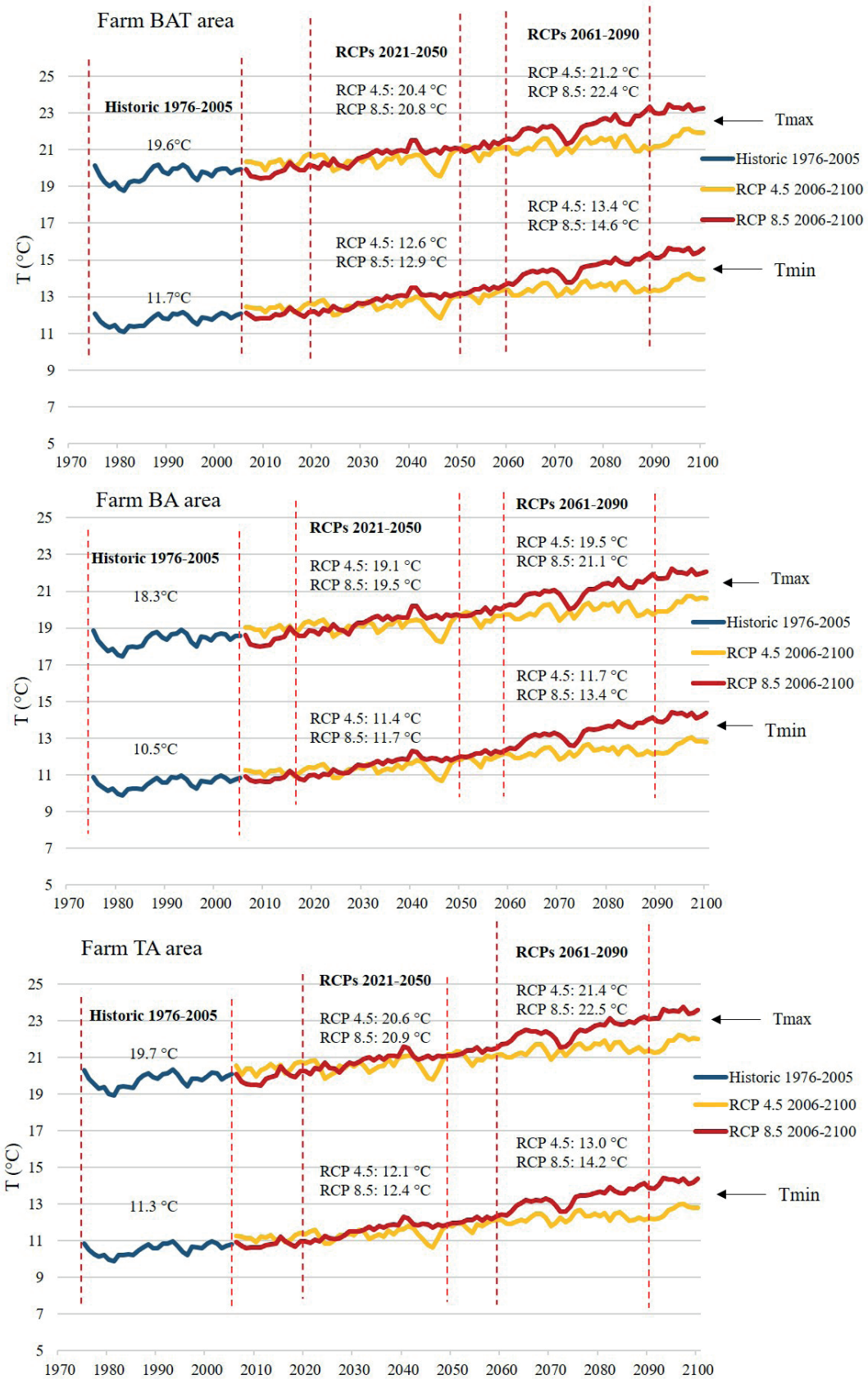


FIGURE 4. Trends of Tmax and Tmin from 1960 to 2100 in three representative table-grape farms located in a typical Apulian territory for table grape production under Historic and Representative Concentration Pathways – RCP: 4.5 and 8.5.

 © 2021 International Viticulture and Enology Society - IVES

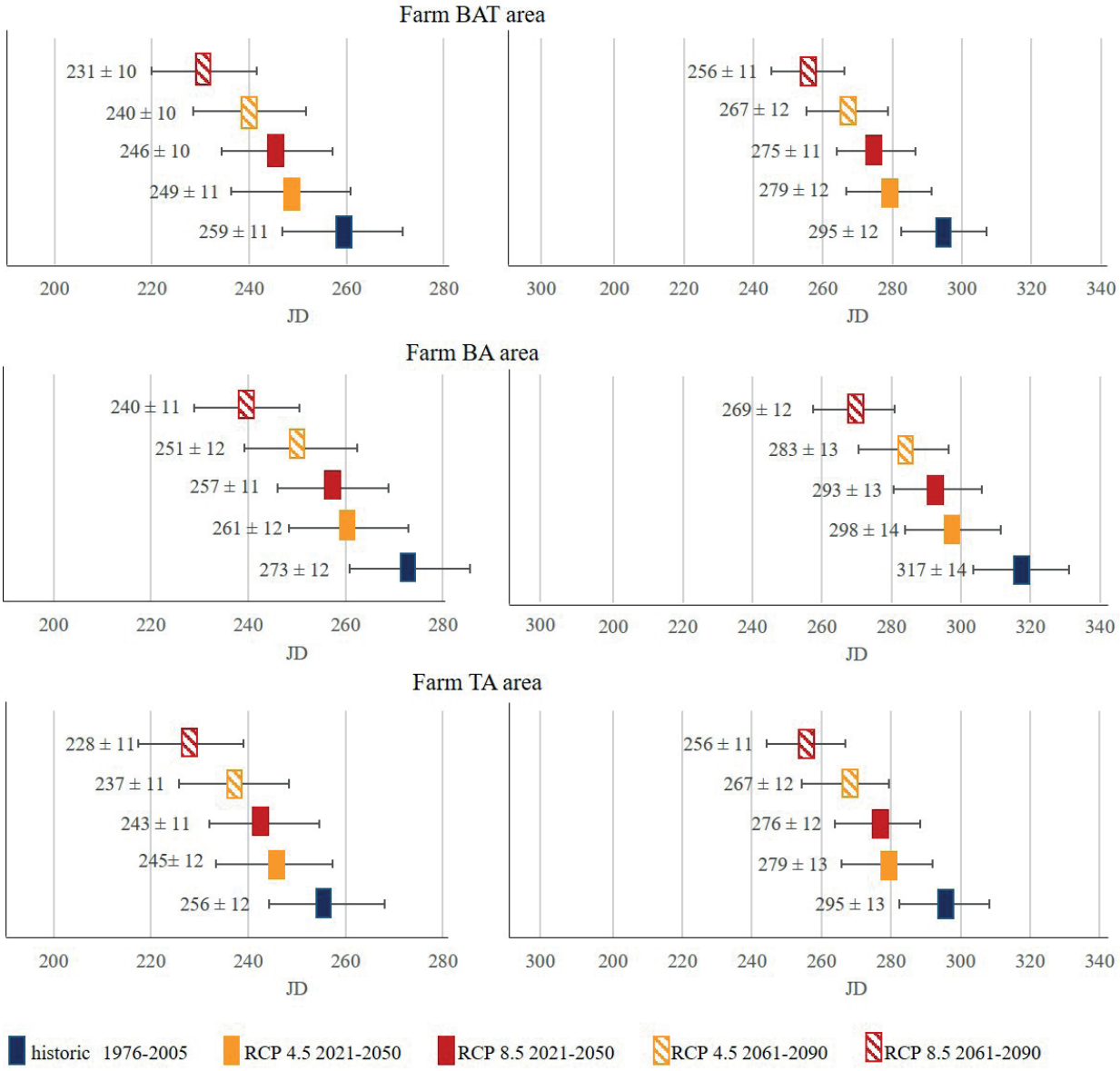


FIGURE 5. Box-plot of Julian Days (JD) ± SE needed to reach 2200 Heliothermal Index (HI - Left) and > 2200 Winkler Index (WI - Right). in three representative table-grape farms located in a typical Apulian territory for table grape production under different Scenarios: Historic and Representative Concentration Pathways – RCP 4.5 and 8.5. 2200 HI or WI were set as referred to Italia cv. (late or very late ripening cultivar). JD ± SE are calculated on the base of linear regression equations with HI or WI.

Instead, Farm TA and BAT, being located in warmer Apulian areas and at lower elevations, needed 256 and 259 JD respectively for maturation, corresponding to 13 and 16 September, two weeks earlier than Farm BA. Similarly, Farm BA achieved 2200 WI in 317 JD (13 November), which is later than expected, while 295 JD (22 October) were needed by the other two vineyards.

A shift to earlier presumed maturity was evident in the 2021–2050 period for all three vineyards in terms of HI, ranging from 10 JD for Farm BAT and 11 JD for Farm TA to 12 JD for Farm BA in RCP 4.5, with differences when compared to RCP 8.5 of 2 to 4 days. WI values showed the same trends as HI, with maturity being 20 JD, 24 JD and 19 JD earlier in RCP 4.5 for Farms BAT, BA and TA respectively, with differences when compared to RCP 8.5 of 3-5 days. As previously stated, differences between RCP 4.5 and 8.5 were found to be more substantial in the following TW, 2061-2090. According to HI, by comparing the historic scenario with RCP 4.5 and RCP 8.5, both Farm BAT and Farm TA showed an early presumed maturation of 19 JD and 28 JD respectively.

© 2021 International Viticulture and Enology Society - IVES

Farm BA was calculated to be even earlier, with a 22 and 33 JD difference when the historic scenario was compared to RCP 4.5 and 8.5 respectively.

A shift to 2200 WI was likewise reached in 2061–2090, with values ranging from 28 JD in Farms BAT and TA to 34 JD in RCP 4.5. Large differences were found in the historic scenario compared to RCP 8.5, with presumed maturity occurring 39 JD early in Farm BAT and TA, and, even more remarkably, 48 JD early in Farm BA.

However, the box-plot in Figure 5 shows that overall, when HI ± SE was calculated from the linear regressions, the ranges of historic and RCPs relating to the time window period 2021–2050 and RPC 4.5 of the 2061–2090 substantially overlap. On the other hand, a lower JD value was evident in RCP 8.5 in the period 2061–2090, in which the temporal range of the estimated JD value ± SE did not overlap with the previous scenarios, suggesting a real worsening of climate conditions which will affect grape phenology in the future. The box-plot relative to the WI values is in some ways even more emblematic in 2061–2090 for both RCP 8.5 and RCP 4.5, indicating that the countermeasures envisaged by RCP 4.5 may not even be sufficient to reduce the effects of climate change on the phenology of grapevine now and in the coming decades.

DISCUSSION

The present research aimed to characterise the changes to climate over the last decades in the Apulia region by means of bioclimatic indices spatialisation. The comparison of two thirty-year historic series allowed us to understand how climate changed in Apulia between 1961 and 2020 and to predict what will happen in the future from the recorded temperatures, which mainly result in a shift to earlier phenological events in grapevine (Koufos *et al.,* 2013).

Our results are consistent with Cotecchia (2014), who reported an average annual temperature in Apulia of 15–16 °C and higher average values in the Ionian-Salento area and Tavoliere, where rainfall values are usually recorded as being lower than the 600 mm/year regional average. In this regard, we found the same zones to accumulate the highest values of HI and WI in both TW_1 (1961–1990) and TW_2 (1991–2020). These results are in line with Santos *et al.* (2012), who analysed macroclimate and viticultural zoning in Europe in the period 1950−2009 - which overlaps both our TWs - and found significant positive trends in WI and HI, particularly for southern Europe. On the other hand, the areas with the lowest HI values were those located along the entire Murgian arch; this plateau crosses Apulia from north to south up to the hinterland of the provinces of Taranto and Brindisi, with altitudes often exceeding 300 m. a.s.l., and therefore poorly suitable in the past for the production of table grapes.

When comparing HI and WI, clear differences were found between the two bioclimatic indices in terms of the JD needed to reach the optimum of 2200. In particular, more JD were needed to reach at least 2200 WI than to reach 2200 HI, which is in line with Navrátilová *et al.* (2021), but with more fluctuations. These differences are mainly related to the periods that the formulas were based on: HI was based on the period of 1st April to 30th September, while WI was based on the period 1st April to 31th October, with the period of calculation ending after harvest. In addition, other differences can be explained by the fact that WI considers the vine to stop its development below 10 °C, while the base temperature threshold for accumulation is likely cultivar specific and is possibly as low as 5 °C (García de Cortázar-Atauri *et al.,* 2009). Furthermore, HI takes into account the average of maximum and the mean daily temperatures, and also introduces a coefficient K which takes into account the latitude and, therefore, the different durations of daylight (Piña-Rey *et al.,* 2020).

Overall, the generalised increase in average temperatures throughout the study area calls into question the maintenance of the elevation limit of 330 m a.s.l. for table grape production in Apulia. The concept of vineyard relocation, in fact, is now widely under discussion (Santos *et al.,* 2020), which focuses mainly on heat and drought escape by combining two different but complementary strategies: the exploitation of wider latitudinal bands not restricted to conventional 30 to 50 degrees latitudes in both hemispheres (Karvonen, 2014), and a shift to cooler sites characterised by higher elevations and lower solar radiation (Fraga *et al.,* 2017). It is known, in fact, that the required temperature for vines during the growing season is between 12–13 °C and 22–24 °C; Apulian temperatures normally fall within this range during the growing season (April-October), and occasionally late frost occurs. High temperatures and heatwaves, however, can increase the average seasonal temperatures to above 22–24 °C; this can induce heat stress on vine, particularly in dry climates (Schultz and Jones, 2010),

and can often result in earlier phenological stages, thereby affecting fruit metabolism and in turn grape yield and quality (Venios *et al.,* 2020).

The prediction of JD needed to reach optimum HI and WI, which was based on linear regression equations, yielded results of a systematic earlier shifting of grapevine phenology. The requirement of 2200 HI or WI corresponds to the Italia variety (chosen as an example of table grape cultivar grown in the Apulia region) reaching presumed maturity; in the present study it was obtained 9 to 28 days earlier in TW_2 respect to TW_1, depending on the bioclimatic index and the elevation of the site. Our results confirmed those stated by other authors (Jones, 2007; Alikadic *et al.,* 2019), who reported values of presumed maturity to be 6 to 25 days early for different grapevine varieties in Europe, with an average of 3 to 6 days response per 1 °C of warming during the last 30–50 years.

However, it is important to note that the most common vine training system for table grape, especially in Apulia, is the overhead *tendone* trellis (Puglia type). *Tendone* involves the distribution of the canopy on a continuous horizontal plane approximately 2 m above ground level. The canopy is supported by a trellis system and a grid of steel wires, on which shoots are trained to create an upper layer of leaves that overlaps and shadows the underside productive band of bunches (Pascuzzi, 2013).

In addition to this, table grape vineyards are normally coverd with plastic sheets, in order to protect grapes and to allow a harvest delay. Depending on the technical properties of the material from which it is made, the covering modifies the microclimate under the tendone by lowering solar radiation and air temperature, increasing RH with effects on vine water status, and preserving TSS concentration and TSS/TA ratio, polyphenol, flavonoids and volatile compounds, such as linalool, typical of 'Italia' muscat aroma (de Palma *et al.,* 2019). Moreover, late table grape cultivars like Italia are normally covered late (at veraison) with plastic sheets to protect the clusters from rain and hailstorm, thus delaying harvest by 30 to 90 days.

That said, it is well-known that the technological maturity of table grapes tends to diverge and, like Greek producers (Koufos *et al.,* 2020), Apulian growers do not regularly record observations of phenological phases and harvest dates, except for a few varieties and only sporadically. Therefore, as it was difficult to find vineyards in the region with recorded data, in the present study three vineyards representative of the production of table grapes in Apulia were identified in order to perform future projections for climate change. As expected, RCP 4.5 and RCP 8.5 did not show any large differences until around 2040. In the long term (i.e., from 2061 onwards), the effects of the countermeasures foreseen by the RCP scenario 4.5 became effective in containing the growing trend of both Tmin and Tmax. This is in line with Lionello *et al.* (2014), who reported an acceleration in temperature increase and a decrease in precipitation in Apulia in the second half of the century. In the latter case, a huge decrease in DI would be expected in our future scenario, since it is based on rainfall. In any case, rainfall amount was not predicted to change much, with just a few millimetres difference from one scenario to another.

Indeed, a weakness of DI is the use of total monthly rainfall in the formula and the fact that it does not take into account the occurrence of extreme events; these may lead to abnormal daily precipitation rates that contribute to the monthly total, but is in fact water which is not available for vineyards.

In terms of Tmin, while all the vineyards were projected to become CI-2 (Warm nights) in 2061–2090, the effect of elevation in preventing a Tmax increase was evident in Farm BA (262 m a.s.l.), which had a milder RCP 8.5 future scenario than Farm BAT and Farm TA, which are located at sea level, or, in any case below 100 m a.s.l. (Figure 1) and showed an HI of > 3000 and a WI of > 2700. In contrast, neither the historic nor future scenario showed differences in terms of DI for any of the three vineyards; they even produced negative values which increased from one thirty-year series to the next.

CONCLUSIONS

This study focused on the spatialisation and variation over time of bioclimatic indices as an indicator of past and future climate change in a typical Apulian region for table grape production. In this region, temperatures have risen in the last sixty years and will continue to do so in the future at a different intensity according to the scenarios. An increase in heat accumulation will have the obvious consequence of earlier harvest dates, which in turn will impact both the production and management aspects of the vineyard. Targeted strategies in viticulture should thus be developed - and in some cases this has already started -

© 2021 International Viticulture and Enology Society - IVES

to contain or overcome heat stress in the future by i) the adoption of technical expedients like vineyard sheet-covering to mitigate the microclimate in the vineyard, ii) the use of cultivars whose grapes can reach the optimal technological parameters, even when the duration of the phenological phases is shortened, and iii) vineyard relocation to elevations or latitudes unexplored until today.

REFERENCES

Alikadic, A., Pertot, I., Eccel, E., Dolci, C., Zarbo, C., Caffarra, A., De Filippi, R., & Furlanello, C. (2019). The impact of climate change on grapevine phenology and the influence of altitude: A regional study. *Agricultural and Forest Meteorology*, 271, 73-82. https://doi.org/10.1016/j.agrformet.2019.02.030.

Amerine, M.A., & Winkler, A.J. (1944). Composition and quality of musts and wines of California grapes. *Hilgard*, 15 (6), 493–673. https://doi.org/10.3733/hilg.v15n06p493.

Attorre, F., Alfò, M., De Sanctis, M., Francesconi, F., & Bruno, F. (2007). Comparison of interpolation methods for mapping climatic and bioclimatic variables at regional scale *International Journal of Climatology*, 27 (13), 1825-1843. https://doi.org/10.1002/joc.1495

Blasi, C., Chirici, G., Corona, P., Marchetti, M., Maselli, F., & Puletti, N. (2007). Spazializzazione di dati climatici a livello nazionale tramite modelli regressive localizzati. *Forest@* 4 (2), 213-219.

C3S Climate Bulletin (2021). Copernicus Climate Change System. Changing the reference period from 1981-2020 to 1991-2020 for the C3S Climate Bulletin. Pp. 51. https://climate.copernicus.eu/sites/default/files/2021-02/C3S_Climate_Bulletin_change_from_1981-2010_to_1991-2020_reference_period_v08-Feb-20_all.pdf

Cotecchia, V. (2014). Le acque sotterranee e l'intrusione marina in Puglia: dalla ricerca all'emergenza nella salvaguardia della risorsa. In: *Memorie descrittive della carta geologica d'Italia*. Vol. 92: pp. 31-510. Ed. ISPRA Servizio Geologico d'Italia ISBN-13: 9788893110037. https://www.isprambiente.gov.it/files2017/pubblicazioni/periodici-tecnici/memorie-descrittive-della-carta-geologica-ditalia/volume-92?b_start:int=0

FAO (1992). CROPWAT 8.0 Software. Food and Agriculture Organization. FAO Irrigation and Drainage Paper 46. Rome, Italy. Available at http://www.fao.org/land-water/databases-and-software/cropwat/en/ Accessed on December 04th 2020.

de Palma, L., Limosani, P., Marasovic, I., Pati, S., Vox, G., Scettini, E., & Novello, V. (2019). Vineyard protection with rain-shelter: relationships between radiometric properties of plastic covers and table grape quality. *CO.NA.VI. 2018 - 7° Convegno Nazionale di Viticoltura*. BIO Web of Conferences 13, 04007. https://doi.org/10.1051/bioconf/20191304007

EMBRAPA UVA E VINHO (2007). Sistema CCM Geovitícola: Sistema de Classificação Climática Multicritérios Geovitícola. Bento Gonçalves. http://www.cnpuv.embrapa.br/ccm.

Fraga, H., Atauri, I.G.D., Malheiro, A.C., Moutinho-Pereira, J., & Santos, J.A. (2017). Viticulture in Portugal: a review of recent trends and climate change projections. *Oeno One*, 51, 61-69. https://doi.org/10.20870/oeno-one.2017.51.2.1621

Fregoni, M. (2005). Viticoltura di qualità. Ed. Phytoline, Affi (Vr). ISBN: 88-8957-200-0

García de Cortázar-Atauri, I., Brisson, N., & Gaudillere, J.P. (2009). Performance of several models for predicting budburst date of grapevine (*Vitis vinifera* L.). *International Journal of Biometeorology*, 53, 317–326. https://doi.org/10.1007/s00484-009-0217-4

Gladstones, J. (1992). Viticulture and environment. Winetitles, Adelaide, Australia ISBN: 1875130128

Hengl, T., Heuvelink, G.B.M., & Stein, A. (2003). Comparison of kriging with external drift and regression-kriging. *Technical note, International Institute for Geo-Information Science and Earth Observation*. http://www.itc.nl/library/Papers_2003/misca/hengl_comparison.pdf.

Hengl, T. (2007). A Practical Guide to Geostatistical Mapping of Environmental Variables. EUR 22904 EN. Luxembourg (Luxembourg): Office for Official Publications of the European Communities; 2007. JRC38153 ISBN: 978-90-9024981-0.

Honorio, F., García, A., Moral, F.J., Paniagua, L.L., & Rebollo, F.J. (2018). Spanish vineyard classification according to bioclimatic indexes. *Australian Journal of Grape and Wine Research* 24, 335–344. https://doi.org/10.1111/ajgw.12342

Huglin, P. (1978). Nouveau mode d'évaluation des possibilities héliothermiques d'un milieu viticole. In: *Proceedings of the Symposium International sur l'ecologie de la Vigne*. Ministère de l'Agriculture et de l'Industrie Alimentaire, Contança, pp. 89–98.

ISPRA (2013). Linee guida per l'analisi e l'elaborazione statistica di base delle serie storiche dei dati idrogeologici. *Manuali e Linee Guida* 84/13, pp. 166. ISBN 978-88-448-0584-5. https://www.isprambiente.gov.it/files/pubblicazioni/manuali-lineeguida/MLG_84_2013.pdf.

Jones, G.V. (2006). Climate and terroir: impacts of climate variability and change on wine. In: Macqueen, R.W., Meinert, L.D. (eds) *Fine wine and terroir - the geoscience perspective*. Geological Association of Canada, St. John's, Newfoundland, pp 203–216, Geoscience Canada Reprint Series, Number 9.

Jones, G.V. (2007). Climate change: Observations, projections, and general implications for viticulture and wine production. In: *Whitman College Economics Department working paper. 1–7*. Whitman College. https://www.infowine.com/intranet/libretti/libretto4594-01-1.pdf

Jones, G.V., Duff, A, A, Hall, A., Myers, J.W. (2010). Spatial Analysis of Climate in Wine grape Growing Regions in the Western United States. *American Journal of Enology and Viticulture*. 61 (3), 313-326.

Karvonen, J.I. (2014). Northern european viticulture compared to Central European high altitude viticulture: Annual growth cycle of grapevines in the years 2012–2013. *International Journal of Wine Research*. 6, 1–7. http://dx.doi.org/10.2147/IJWR.S60208

Koufos, G., Mavromatis, T., Koundouras, S., Fyllas, N.M., & Jones, G.V. (2013). Viticulture–climate relationships in Greece: the impacts of recent climate trends on harvest date variation. *International Journal of Climatology*, 34, 1445–1459. https://doi.org/10.1002/joc.3775

Koufos, G.C., Mavromatis, T., & Koundouras, S., (2018). Response of viticulture-related climatic indices and zoning to historical and future climate conditions in Greece. *International Journal of Climatology*. 38, 2097–2111. https://doi.org/10.1002/joc.5320

Koufos, G.C., Mavromatis, T., Koundouras, S., & Jones, G.V. (2020). Adaptive capacity of winegrape varieties cultivated in Greece to climate change: current trends and future projections. *OENO One*, 4, 1201-1219, https://doi.org/10.20870/oeno-one.2020.54.4.3129

Li, Y., & Zhou, M. (2014). Trends in dryness index based on potential evapotranspiration and precipitation over 1961–2099 in Xinjiang, China. *Advances in Meteorology*. Article ID 548230, https://doi.org/10.1155/2014/548230

Lionello, P., Congedi, L., Reale, M., Scarascia, L., & Tanzarella, A. (2014). (2014). Sensitivity of typical Mediterranean crops to past and future evolution of seasonal temperature and precipitation in Apulia. *Reg Environ Change*. 14: 2025–2038. https://doi.org/10.1007/s10113-013-0482-y

McBratney, A., Odeh, I., Bishop, T., Dunbar, M., & Shatar, T. (2000). An overview of pedometric techniques for use in soil survey. *Geoderma.* 97 (3–4), 293–327. http://dx.doi.org/10.1016/S0016-7061(00)00043-4

Moral, F.J., Rebollo, F.J., Paniagua, L.L., & García, A. (2014). Climatic spatial variability in Extremadura (Spain) based on viticultural bioclimatic indices. *International journal of biometeorology*, 58 (10), 2139-2152. HTTPS://DOI.ORG/ 10.1007 / s00484-014-0814-8

Navrátilová, M., Beranová, M., Severová, L., Šrédl, K., Svoboda, R., & Abrhám, J. (2021). The impact of climate change on the sugar content of grapes and the sustainability of their production in the Czech Republic. *Sustainability*, 13, 222. https://doi.org/10.3390/su13010222

Neethling, E., Barbeau, G., Coulon-Leroy, C., & Quénol, H. (2019). Spatial complexity and temporal dynamics in viticulture: A review of climate-driven scales. *Agricultural and Forest Meteorology.* 276–277, 107618, https://doi.org/10.1016/j.agrformet.2019.107618

OIV (2019). Statistical Report on World Vitiviniculture. https://www.oiv.int/public/medias/6782/oiv-2019-statistical-report-on-world-vitiviniculture.pdf

Pascuzzi, S. (2013). The effects of the forward speed and air volume of an air-assisted sprayer on spray deposition in tendone trained vineyards. *Journal of Agricultural Engineering*. 49, 125-132. https://doi.org/10.4081/jae.2013.e18

Penman, H.L. (1948). Natural evaporation from open water, bare soil, and grass, A193, 1948, pp. 120-145, https://dx.doi.org/10.1098%2Frspa.1948.0037

Piña-Rey, A., González-Fernández, E., Fernández-González, M., Lorenzo, M.N., & Rodríguez-Rajo, F.J. (2020). Climate change impacts assessment on wine-growing bioclimatic transition areas. *Agriculture.* 10, 605. https://doi.org/10.3390/agriculture10120605

Polemio, M., & Lonigro, T. (2014). Trends in climate, short-duration rainfall, and damaging hydrogeological events (Apulia, Southern Italy). *Nat. Hazards.* 75 (1), 515-540, https://doi.org/10.1007/s11069-014-1333-y

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., & Rafaj, P. (2011). RCP 8.5 - A scenario of comparatively high greenhouse gas emissions. *Climatic Change*. 109, 33. https://doi.org/10.1007/s10584-011-0149-y

Riou, Ch., Becker, N., Sotes Ruiz, V., Gomez-Miguel, V., Carbonneau, A., Panagiotou, M., Calo, A., Costacurta, A., Castro de, R., Pinto, A., Lopes, C., Carneiro, L., Climaco, P. (1994). Le déterminisme climatique de la maturation du raisin: application au zonage de la teneur em sucre dans la communauté européenne. *Office des Publications Officielles des Communautés Européennes*, Luxembourg, 322 pp.

Santos, J.A., Malheiro, A.C., Pinto, J.G., & Jones, G.V. (2012). Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. *Climate Research*. 51, 89–103. http://dx.doi.org/10.3354/cr01056

Santos, J.A., Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Dinis, L.T., Correia, C., Moriondo, M., Leolini, L., Dibari, C., Costafreda-Aumedes, S., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., & Schultz, H.R. (2020). A review of the potential climate change impacts and adaptation options for European viticulture. *Applied Science*. 10 (9), 3092. http://dx.doi.org/10.3390/app10093092

Sardaro, R., Faccilongo, N., Contò, F., & La Sala, P. (2021). Adaption actions to cope with climate change: evidence from farmers' preferences on an agrobiodiversity conservation programme in the Mediterranean area. *Sustainability.* 13, 5977. https://doi.org/10.3390/su13115977

© 2021 International Viticulture and Enology Society - IVES

Schultz, H.R., & Jones, G.V. (2010). Climate induced historic and future changes in viticulture. *Journal of Wine Research*. 21, 137–145. https://doi.org/10.1080/09571264.2010.530098

Sgubin, G., Swingedouw, D., de Cortázar-Atauri, I.G., Ollat, N., & van Leeuwen, C. (2019). The impact of possible decadal-scale cold waves on viticulture over Europe in a context of global warming. *Agronomy*, 9 (7), 397. http://dx.doi.org/10.3390/agronomy9070397

Tarquini, S., & Nannipieri, L. (2017). Il DEM TINITALY con risoluzione 10 m come base transdisciplinare per l'analisi del territorio italiano: Tendenze attuali e nuove prospettive. *Geomorfologia*, 281, 108-115. https://doi.org/10.1016/j.geomorph.2016.12.022

Thomson, A.M., Calvin, K.V., Smith, S.J., Kyle, G.P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M.A., Clarke, L.E., & Edmonds, J.A. (2011). RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*. 109, 77 http://dx.doi.org/10.1007/s10584-011-0151-4

Tonietto, J. (1999). Les macroclimats viticoles mondiaux et l'influence du mésoclimat sur la typicité de la Syrah et du Muscat de Hambourg dans le sud de la France: méthodologie de caráctérisation. *Thèse Doctorat. Ecole Nationale Supérieure Agronomique*, Montpellier, 233 pp.

Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology*. 124, 81–97. https://doi.org/10.1016/j.agrformet.2003.06.001

UE Reg. n.680/2012 (2012). UE Reg. n.680/2012 of 24th July 2012 entering a name in the register of protected designations of origin and protected geographical indications [Uva di Puglia (I.G.P.)]. http://www.dop-igp.eu/flex/AppData/Redational/pdf/Uva%20di%20Puglia.pdf

Venios, X., Korkas, E., Nisiotou, A., & Banilas, G. (2020). Grapevine responses to heat stress and global warming. *Plants*, 9 (12), 1754. https://doi.org/10.3390/plants9121754

Wackernagel, H. (2003). Multivariate geostatistics: an introduction 103 with applications, 2nd Edition. *Springer-Verlag*, p. 381

This article is published under the **Creative Commons licence** (CC BY 4.0).
Use of all or part of the content of this article must mention the authors, the year of publication, the title, the name of the journal, the volume, the pages and the DOI in compliance with the information given above.