

Temperature trends in the Campania Region (Southern Italy) deduced from some bioclimatic indices

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Abstract: The Campania Region (Italy) is world-renowned for its artistic, monumental and historical beauty and possesses no less than six famous UNESCO Sites. But this Region, the most populated in Southern Italy, is also known for its inestimable environmental, geological and agricultural heritage. In its innermost, landlocked part, placed on the Apennine Chain, the most prized and award-winning vine plant varieties are cultivated. This preliminary research focuses its interest on the most intensive vine-growing areas and sets out to analyse the trend of variation in air temperatures through the use of some significant bioclimatic indices such as Cool Night Index and Huglin Index, as well as the variation in mean annual temperatures. The results, based on temperature data collected by measurement agencies in the Campania Region and referring to the period 2001-2024, seem to indicate an upward trend in all index values, which is well known in the Mediterranean area. This has to be seen in relation to the climate changes that are also occurring in small and medium-sized regions and that lead to the changes in vegetation and water availability that we have witnessed in recent decades, with obvious implications for land management.

Key words: Campania region, Southern Italy, Huglin index, cool night index, annual mean temperature, viticulture, climate change.

Temperaturni trendi v regiji Campania (južna Italija), izpeljani iz nekaterih bioklimatskih indeksov

Izvleček: Regija Campania (Italija) je svetovno znana po svoji umetniški, monumentalni in zgodovinski lepoti, ima pa tudi kar šest znanih Unescovih območij. Toda ta regija, najbolj naseljena v južni Italiji, je znana tudi po svoji neprecenljivi okoljski, geološki in kmetijski dediščini. V njenem skrajnem, neobalnem delu, ki leži na Apeninski verigi, gojijo najbolj cenjene in nagrajene sorte vinske trte. Ta preliminarne raziskave se osredotoča na najbolj intenzivna vinogradniška območja in si prizadeva analizirati trend nihanja temperatur zraka z uporabo nekaterih pomembnih bioklimatskih indeksov, kot sta Cool Night Index in Huglinov indeks, ter variacije srednjih letnih temperatur. Rezultati, ki temeljijo na temperaturnih podatkih, ki so jih zbrale merilne agencije v regiji Campania in se nanašajo na obdobje 2001–2024, kažejo trend naraščanja vseh vrednosti indeksa, kar je dobro znano na območju Sredozemlja. To je treba obravnavati v povezavi s podnebnimi spremembami, ki se pojavljajo tudi v majhnih in srednje velikih regijah in vodijo do sprememb v vegetaciji in razpoložljivosti vode, ki smo jim priča v zadnjih desetletjih, z očitnimi posledicami za upravljanje zemljišč.

Ključne besede: regija Campania, južna Italija, Huglinov indeks, indeks hladnih noči, povprečna letna temperatura, vinogradništvo, podnebne spremembe.

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1 INTRODUCTION

Campania is a region located in the south of the Italian peninsula, facing the Tyrrhenian Sea and inland comprising a large part of the southern Apennine chain (Fig. 1). Although modest in size (13.671 km²), it has a high population density (409 inhabitants km⁻² as of 2023), most of which is concentrated in the coastal areas, while in the inland areas - the subject of this research - the same demographic indicator is decidedly lower (based on ISTAT data from 2023, the province of Benevento: 124 inhabitants km⁻² and that of Avellino: 140 inhabitants km⁻²). It is precisely the latter two provinces, landlocked, located entirely along the axis of the Apennine chain and home to almost all the measuring stations used in this study, that possess the highest percentage of UAA (Utilized Agricultural Area) in the Region and the largest areas under vines in hectares (Tab. 1):

Throughout the world, Campania is known not only for its countless historical and artistic assets but also for its unparalleled natural landscapes and its rich and varied agro-alimentary heritage that includes numerous universally recognised excellences. The latter includes dozens of PDO (Protected designation of origin), PGI (Protected geographical indication), and TSG (traditional speciality guaranteed). World-recognised excellence are also its wines, since ancient times (Buono & Vallariello, 2002).

Agricultural practices are widespread throughout the region, which is divided into mountainous areas for 34.6 %, extensive hilly areas for 50.8 %, and extensive floodplains, coastal or intermountainous areas for 14.7 % (ISTAT, 2014).

It does not seem superfluous to emphasise that: 1) hilly areas and, to a lesser extent, lowland areas are intensively exploited for agricultural use with valuable crops;

2) the orographic context also determines temperature variations closely correlated to crop production. A correlation, has already been noted by Castellari *et al.* (2014), who highlighted that climate change, and therefore also temperature changes, in the Mediterranean area and in Italy can also have negative impacts on crops with important socio-economic consequences. In particular, viticulture, which is widely practised in the Campania region and in Italy in general, seems to be particularly sensitive to variations in climatic trends with direct effects on grape yield, composition and quality of wines (van Leeuwen *et al.*, 2024). Temperature and other climate parameters variability with effects on viticulture have been documented in various parts of the world (Jones & Davis, 2000; Duchêne & Schneider, 2005; Jones *et al.*, 2005), highlighting their direct impact on the lengthening of the vine's growing season or on the tendency to shift phenological events such as budding and flowering in time. It is, therefore, a phenomenon of climate resilience (Acevedo *et al.*, 2020; Tscholl *et al.*, 2024) that in Italy still needs to be investigated locally, especially in the light of the scientific evidence of Spano *et al.* (2020) and the IPCC (Intergovernmental Panel on Climate Change, 2022) on the risks for agricultural practices induced by the current climate change. For these purposes, Italy, and in particular the territory of Campania that is the subject of this study, due to its orographic-altimetric layout, its exposure to western currents and the high number of thermo-pluviometric stations, lends itself particularly well to a detailed investigation that with this study will be conducted on the thermic trends characteristic of the 2001-2024 period and their possible impacts on agricultural and territorial planning (Giuliani & Antenucci, 2017; IPCC, 2022) in a predictable scenario of environ-

Tab. 1: Some indicators on agricultural crops in Campania and its five provinces.

Indicators	Campania	Napoli	Avellino	Benevento	Caserta	Salerno	Average for Provinces	SD for Provinces
Extension (ha)	1367095	117113	279164	208000	265100	495400	272955	124970
UAA (%) ¹	36.8	25.0	42.9	49.0	33.4	33.1	36.68	8.37
Vineyard surface (ha) ²	25601	2013	6200	10550	2548	4290	5120	3085
Vineyard surface (%) ²	1.87	1.72	2.22	5.07	0.96	0.87	2.17	1.53
Hectolitres of wine produced ²	1475869	165551	193720	804000	82898	229700	295173	258977
		11.2%	13.1%	54.5%	5.6%	15.6%		

Sources: 1. (AGREGCAM, 2022)

2. (AGREGCAM, 2023)



Fig. 1: Location of the study area.

mental transformations (F. Bencardino & Cresta, 2004; M. Bencardino et al., 2007).

2 MATERIALS AND METHODS

Figure 1 shows the territory of the Campania Region among those directly bordering it, subdivided into five altimetric bands with respect to sea level (0-200 m, 201-400 m, 401-600 m, 601-800 m, and more than 800 m) that will help to understand the orographic variations of the temperature trends analysed below. The latter were obtained from measurements taken at 52 meteorological stations (Fig. 2), one of which (Bella) falls within the territory of the neighbouring Basilicata Region, distributed at altitudes between 52 and 865 m above sea level.

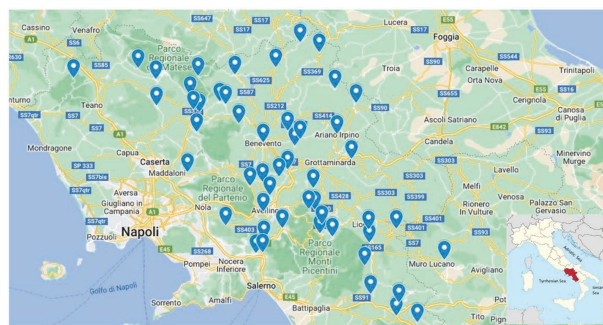


Fig. 2: The study area, the Campania region, with the location (drop symbols) of the weather stations.

Tab. 2: Distribution of weather stations by altitude zones.

Elevation ranges	
(m asl)	Number of stations
0-200	13
201-400	12
401-600	12
601-800	13
> 800	2

Tab. 2 shows the number of weather stations in each altitude band. Weather stations belong to two separate measurement networks:

1) 13 stations, activated since 2001, are monitored by the network of the Agrometeorological Service of the Campania Region (AGM, 2025);

2) 39 stations, with longer continuous time series, are monitored by the network of the Civil Protection Multihazard Centre of the Campania Region (CMR, 2025).

Table 3 shows the complete list of weather stations, their geographical location and the measurement network to which they belong.

Comparison of figures 1 and 2 clearly shows that the area covered by the weather stations largely occupies the inland sector of Campania, near the orographic watershed, oriented NW-SE, between the Tyrrhenian Sea, to the West, and the Adriatic Sea, to the East. Using the available rainfall data and a generally well-distributed air temperature record based on altitude, it was possible to classify the climate of the study area as humid warm temperate (Cf) with a very hot (Cfa) to hot (Cfb) summer. This classification was achieved using the method by W. Köppen (Di Lisio et al., 2009), with characteristics very similar to those already identified in the neighbouring Molise region (Aucelli et al., 2007).

For the analysis of the temperature data of the period 2001-2024, the following three thermal indicators were used, referring to the time (monthly, half-yearly and yearly) and to the altimetric belts in which the weather stations fall:

- monthly index: the Cool Night Index (CI) (Tonietto, 1999) was used, which in the agronomic field is an important bioclimatic index that takes into account the minimum temperatures during the vine ripening period (September) and is also one of the strictly thermal indices (Tonietto & Carbonneau, 2004).

- half-year index: the Huglin Index (HI) (Huglin, 1978) was used, which is considered one of the most reliable, particularly for its useful indications for viticulture.

- the average annual temperatures (AMT) referring

Tab. 3: List of pluvio-thermometric stations from which the analysed data were obtained.

Stations	Altitude (m asl)	Latitude	Longitude	Measurement Network
Sorgenti di Grassano	52	41.222	14.501	CMR
San Lorenzo Maggiore	72	41.218	14.635	AGM
Santa Maria a Vico	98	41.027	14.485	CMR
Alife	117	41.339	14.333	CMR
Benevento 1	119	41.142	14.762	CMR
Paduli	130	41.148	14.834	CMR
Mercato San Severino	141	40.778	14.752	CMR
Contursi Terme	149	40.676	15.252	CMR
San Salvatore Telesino	167	41.247	14.472	CMR
Torrecuso	172	41.197	14.705	AGM
Guardia Sanframondi	173	41.238	14.597	AGM
Melizzano	190	41.167	14.505	CMR
Auletta	194	40.552	15.428	CMR
Montoro (San Pietro)	209	40.818	14.787	CMR
Conca della Campania	233	41.367	14.008	AGM
Alvignano	235	41.218	14.394	CMR
Benevento 2	236	41.115	14.825	CMR
Fisciano	244	40.785	14.786	CMR
Faicchio	304	41.284	14.475	AGM
Serino	327	40.891	14.844	CMR
Pietraderusi	341	41.055	14.880	AGM
Altavilla Irpina	352	41.006	14.783	CMR
Santa Paolina	355	41.251	14.653	AGM
Avellino (Genio Civile)	360	40.912	14.783	CMR
Cusano Mutri	364	41.327	14.520	CMR
Caposele	428	40.816	15.221	CMR
Sicignano degli Alburni	448	40.582	15.337	CMR
Luogosano	450	40.984	15.003	CMR
Cassano Irpino	460	40.880	15.029	CMR
Montella	489	40.848	15.050	CMR
Montefredane	490	41.254	14.507	AGM
Pietrastornina	495	40.992	14.734	CMR
Montemarano 1	527	40.933	15.025	AGM
Flumeri	538	41.082	15.171	AGM
Buccino	560	40.608	15.390	CMR
Senerchia	578	40.738	15.205	CMR
Apice	597	41.127	14.971	AGM
Morcone	630	41.335	14.666	CMR
Greci	641	41.234	15.138	AGM
Postiglione	660	40.562	15.237	CMR
Apice (Rocchetta)	670	41.124	14.970	CMR

Ariano Irpino	678	41.148	15.085	CMR
Bagnoli Irpino	729	40.827	15.074	CMR
Bella (Basilicata)	744	40.733	15.593	CMR
San Bartolomeo in Galdo	750	41.422	15.040	CMR
Castelfranco in Miscano	751	41.299	15.088	CMR
Castelvetere in Val Fortore	768	41.424	14.915	AGM
Conza della Campania	770	40.862	15.282	CMR
Colle Sannita	776	41.369	14.839	CMR
Caposele (Boiara)	780	40.841	15.242	CMR
Quindici (Toriello)	840	40.847	14.625	CMR
Montemarano 2	865	40.914	15.003	CMR
Average	431.65	41.033	14.874	--
Standard deviation	241.59	0.243	0.321	

to the entire meteorological year for each location were used.

The three indicators, obtained by means of algorithms applied to the temperature data provided by AGM and CMR, were calculated in Excel and the results, shown below, are illustrated in graphic form.

2.1 STATISTICAL METHODOLOGIES

The Mann-Kendall test was used for the analysis of time series trends. This is a non-parametric statistical tool that is useful for detecting the presence of monotonic (increasing or decreasing) trends and that does not require any assumptions about the distribution of the data; it is a test that is particularly suitable for the analysis of climate data that, as in our case, have non-normal distributions and outliers. The test assesses the statistical significance, also in terms of time, of the observed trend.

To estimate the intensity of the trend identified by the Mann-Kendall test, the Theil-Sen slope was used: a non-parametric technique that provides an excellent estimate of the angular coefficient of a trend line. This method calculates the median of the slopes of all possible pairs of values in the time series, being particularly resistant to the presence of outliers and suitable for non-normally distributed data.

However, the presence of serial autocorrelation, which is frequent in climate series, can alter the statistical significance of trend tests (Mann, 1945). In this case, to correct for this effect, pre-whitening techniques were applied to remove the autocorrelation while keeping the trend information intact. In particular, the Trend-Free Pre-whitening technique (Yue & Pilon, 2004), which

separates the trend component from the autocorrelation component, and the iterative approach (Zhang et al., 2000) maximum, minimum and mean temperatures along with diurnal temperature range (DTR, which acts cyclically to isolate and neutralise the serial dependency.

In the present work, the first of these techniques was implemented using the zyp package (Bronaugh et al., 2023) from R (R core team, 2021).

2.2 THE COOL NIGHT INDEX (CI)

The cool night index (CI) is calculated using the series of minimum temperatures (Tmin) in September: an indicator of night temperature conditions during grape ripening (Tonietto, 1999; Tonietto & Carbonneau, 2004). Like the others, this indicator is also representative of the variability of the grape climate with regard to varietal requirements, vintage quality (sugar content, colour, aroma) and wine typicality, which is why it is also used in the Multi-Criteria Climate Classification (MCC) (Tonietto & Carbonneau, 2004). The index is composed of 4 classes each corresponding to a certain range of minimum night temperatures in September (Tab. 4).

Tab. 4: CI values and Tmin ranges.

CI Values	Tmin Intervals
Very cool nights	< 12 °C
Cool nights	12 °C–13.9 °C
Temperate nights	14 °C–18 °C
Warm nights	> 18 °C

2.3 THE HUGLIN INDEX (HI)

The algorithm for calculating this important bioclimatic index is given by the formula:

$$HI = K \sum_{01.04}^{30.09} \frac{(T_{mean} - 10) + (T_{max} - 10)}{2}$$

where:

Tmean: mean daily temperature (°C);

Tmax: maximum daily temperature (°C);

K: multiplier coefficient depending on the length of the day. For the study area 1.02 is the commonly used value.

In the agronomic field, the HI is calculated for the vegetation period from 1 April to 30 September each year. In the scientific literature, this index is particularly suitable for characterising wine-growing areas at mid-latitudes (Malheiro *et al.*, 2010; Donnici *et al.*, 2021) and in those areas with high temperature fluctuations, such as those in the mid-hills, where average temperatures tend to prevail over high daytime temperatures for photosynthesis - in fact, HI does not take night-time temperatures into account because no photosynthesis takes place. It is also useful for highlighting the suitability and varietal suitability of grape varieties according to the earliness of grape ripening (Turri & Intrieri, 1987), as Tab. 5 shows.

2.4 ANNUAL MEAN TEMPERATURES (AMT)

In addition to the bioclimatic indicators, the values (°C) of the annual mean temperatures obtained from the recording and validation of the daily mean air temperatures for each location as a function of altitude range were calculated. The data used come from the AGM and CMR online archives.

The time series, which are sorted according to the time variable, constitute a finite part of the stochastic process adopted to understand the thermal trends of the three indicators as a function of altitude. The data obtained were finally averaged, without breakdown by altitude, and the overall trend line was derived from this.

3 RESULTS AND DISCUSSION

The application of the algorithms for the calculation of the three climate indicators provided interesting information on temperature trends in the study area. The results obtained for each indicator are presented below.

3.1 THE COOL NIGHT INDEX

In the elaborations carried out on the available time series, the CI shows a discrete annual variability with a clear upward trend (Fig. 3). The trend lines for altitude bands confirm this upward trend with differences in the minimum and maximum values ranging from approximately 1.1 °C to 1.8 °C during the period 2001-2024. In fact, the estimated slopes for all altimetric bands (Table 6) and also the overall slope are all

Tab. 5: Huglin Index classes for some typical grape varieties (Turri and Intrieri, 1987).

HI Values		Selected grape varieties
< 1500	Very cool	too cold for grape cultivation
≥ 1500 < 1600	Cool	Müller – Thurgau, Traminer
≥ 1600 < 1700		Pinot Blanc, Gamay Noir, Pinot Grigio
≥ 1700 < 1800		Riesling, Chardonnay, Sylvaner, Sauvignon Blanc, Pinot Noir
≥ 1800 < 1900	Temperate	Cabernet Franc, Lemberger, Ciliegiuolo
≥ 1900 < 2000		Cabernet-Sauvignon, Merlot, Sangiovese, Albana, Pignoletto, Trebbiano
≥ 2000 < 2100		Ugni Blanc, Primitivo, Malvasia Bianca, Inzolia, Pinot Nero
≥ 2100 < 2200	Warm temperate	Grenache, Nebbiolo,
≥ 2200 < 2300		Carignan, Palomino, Barbera, Pignoletto, Montuni
≥ 2300 < 2400		Aramon, Refosco, Lambrusco, Sangiovese, Trebbiano Romagnolo
≥ 2400 < 3000	Warm	Very alcoholic or dessert wines

HI values above 3000 (“very hot”) indicate situations of vegetative stress resulting in poor production (Tonietto and Carbonneau, 2004).

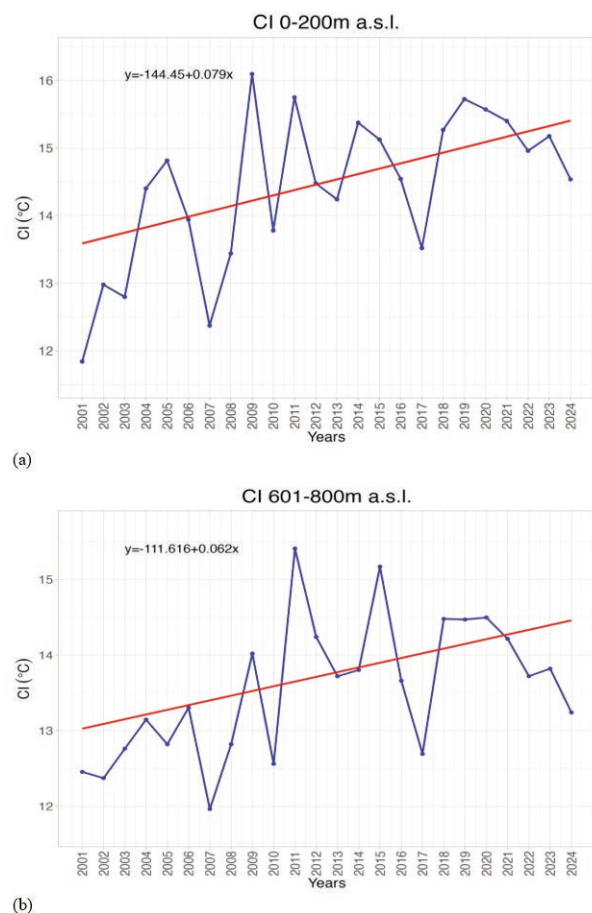


Fig. 3: CI trend lines by altitude bands: (a): 0-200 m; (b): 600-800 m.

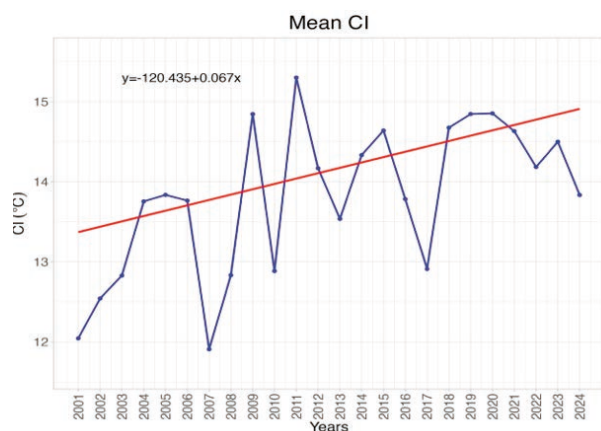


Fig. 4: Trend line of CI variation averaged over altitude ranges.

positive. Furthermore, the estimated parameters are all statistically significant because the p -value is lower than

Tab. 6: CI values by altitude classes and relative increases deduced from trend lines.

Elevation zones (m asl)	Increase in CI	Slope of the trend line	p -value
0-200	+ 1.8 °C	0.079	0.039
201-400	+ 1.5 °C	0.078	0.008
401-600	+ 1.1 °C	0.046	0.008
601-800	+ 1.5 °C	0.062	0.030

the generally accepted threshold of 0.05 (in many cases it is close to zero).

In Figure 4, the annual fluctuations of the CI time series are analysed with respect to the trend line, calculated using the ZYP method (Yue & Pilon, 2004) on the mean values of the altitude ranges. The trend line, in red, shows a progressive increase in temperatures: from about 13.4 °C to 14.9 °C, with an overall change of 1.5 °C.

The CI values calculated for the altitude bands according to the trend lines are summarised in Table 6. In this table it can be seen that the value (1.8 °C) of CI increase in the altitude band 0-200 m a.s.l. is certainly the highest; in the following bands the minimum of 1.1 °C is recorded in the altitude band 401-600 m, followed by a new rise in the CI value in the last band (601-800 m).

With reference to the classification of the CI shown in Table 4, the averages of this indicator for the period 2001-2024 show a shift in all altitude bands from “cold nights” to “temperate nights”. Finally, in the same time interval examined, 2001-2024, the positive CI anomalies show a clear increase starting from the year 2011 (except for 2013, 2016, 2017, 2022 and 2024). The years 2009 and 2011 have the highest CI values in the considered period (Fig. 4).

3.2 THE HUGLIN INDEX

The Huglin Index also shows positive trend lines with altitude, although with a steeper slope in the 0-200 elevation band (Fig. 5). The increase in the index value is over 380, while it varies between 220 and 320 in the other ranges (Tab. 7). The same table shows the estimated values of the slope, all positive and statistically significant, and the p -values.

The annual changes in HI for each altitude classes are summarised in Fig. 6 with the trend line (in red) averaged across the elevation bands.

The HI increments for altitude classes are as follows (Tab. 7):

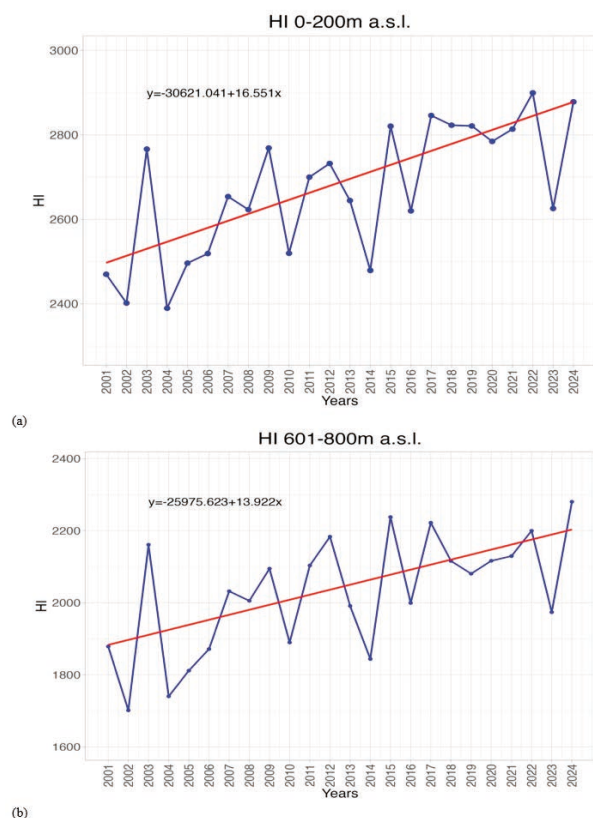


Fig. 5: HI trend lines in the different altitude ranges: (a) 0-200 m; (b) 600-800 m.

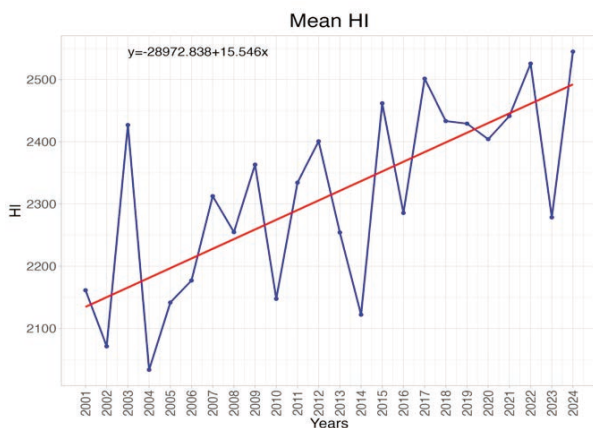


Fig. 6: Trend line relating to average HI.

In the first decade of the time interval analysed (2001- 2024), HI values were almost always below the general average for all altitude classes (with the exception of the years 2003, 2007 and 2009). The average HI values are above 2400 in the years 2003, 2015, 2017, 2022 and

Tab. 7: HI values for altitude classes and relative increases deduced from trend lines.

Elevation zones (m slm)	Increase of HI	Slope of the trend line	<i>p</i> -value
0-200	+381	16.551	0.000
201-400	+227	9.883	0.024
401-600	+259	11.251	0.024
601-800	+320	13.922	0.000

in the very hot 2024; minima below 2200 are recorded in the years 2002, 2004, 2005, 2006, 2010 and 2014.

3.3 MEAN ANNUAL TEMPERATURES

Results for this indicator (AMT) are of considerable interest. Before 2014, fluctuations were more pro-

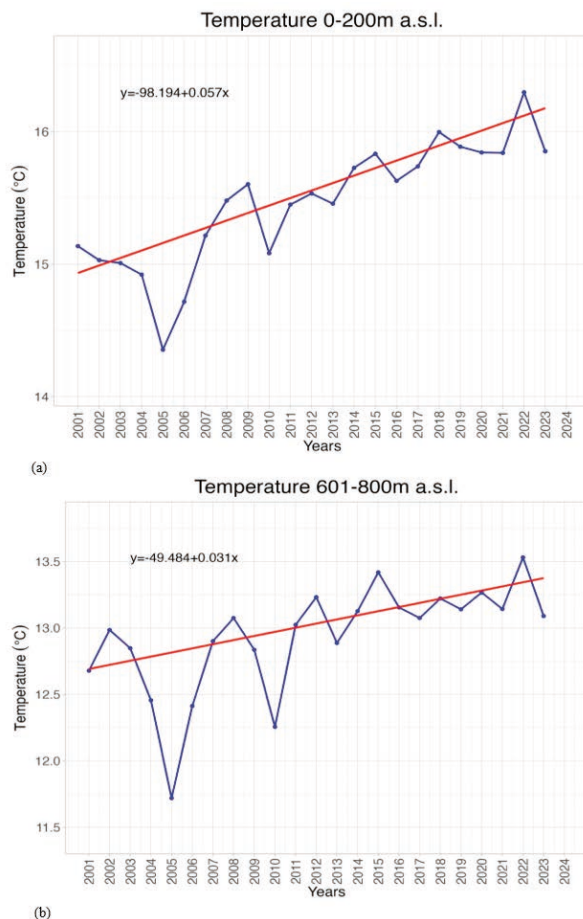


Fig. 7: Trend lines and AMT values for each altitude band: (a) 0-200 m; (b) 600-800 m.

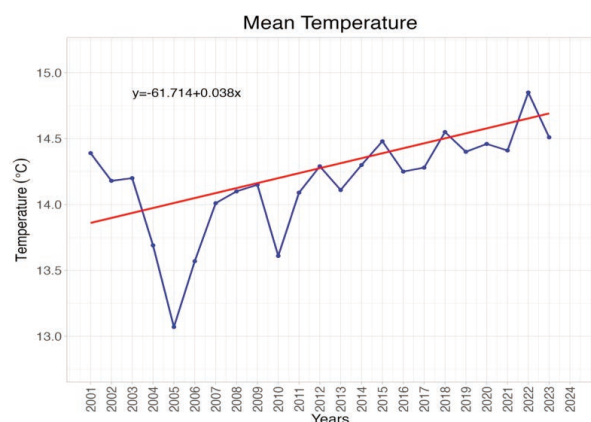


Fig. 8: Average trend line relative to the average AMT of the various elevation zones.

Tab. 8: AMT values referring to altitude classes and increases in °C over the period 2001-2024 derived from trend lines.

Elevation zones (m asl)	AMT increase	Slope of the trend line	<i>p</i> -value
0–200	+ 1.3 °C	0.057	0.000
201–400	+ 1.2 °C	0.054	0.000
401–600	+ 0.6 °C	0.028	0.004
601–800	+ 0.7 °C	0.031	0.021

nounced; from that year onwards, AMT values have been closer to the general trend line.

The numerical values of the AMT by altitude classes shown in Fig. 7 show consistently ascending trend lines, albeit with different slopes that decrease with increasing altitude.

The estimated slope for the trend line using the ZYP method is 0.056; therefore, the average temperature is expected to increase by 0.056 °C per year (i.e. 0.56 °C per decade). Similarly, for the other altitude bands, it can be said that there is a positive trend with slightly smaller slopes. In particular, for the 200–400 m band, the expected average increase per decade is 0.54 °C, while for the other two bands (400–600 m and 600–800 m) the increase per decade is 0.28 °C and 0.31 °C respectively.

Tab. 9: Positive and negative anomalies in the last decade of the absolute values of the three indicators calculated compared to the average of the reference period 2001-2024 (in grey the years with concordant rising indices).

Indicators	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Average	Sd
CI	+0.830	-0.027	-0.899	+0.865	+1.035	+1.043	+0.822	+0.374	+0.690	+0.024	+0.476	0.586
HI	+149.05	-27.15	+188.65	+120.45	+116.35	+91.35	+128.45	+212.85	-34.35	+232.35	+117.80	85.519
AMT	+0.308	+0.078	+0.108	+0.378	+0.228	+0.288	+0.238	+0.678	+0.338	-	+0.294	0.165

The general trend is summarised in Figure 8.

Tab. 8 summarises the results obtained for the AMTs. It also shows the estimated slopes and the *p*-values.

Finally, Table 9 summarises the percentage changes that emerge as positive and negative anomalies from the calculation of the three indicators (CI, HI, AMT) compared to the average of the time interval analysed (2001-2024). As can be seen, in the last decade 2015-2024 all calculated indicators showed positive anomalies in regards with the average of the 2001-2024 period for 7 years.

The data obtained from the thermometric series for inland Campania for the period 2001-2024 allow us to deduce important considerations regarding the trends in the New Millennium of the three climate bio-indicators (CI, HI and AMT) analysed and their impact on viticulture.

A comparison of the graphs of the AMT and CI trends (Fig. 9) reveals a substantial non-concordance of the trends, which would demonstrate that the seasonal variations of the two thermal parameters do not follow a linear path.

The disaggregated data by altitude zones of the three indicators analysed (Tab. 10) also lead to a similar conclusion in the time interval 2001-2024. In fact, these clearly show the existence of seasonal thermal variations with altitude, according to positive increases albeit of different magnitudes.

Furthermore, all indicators show marked increases in each altitude class, but with similar trends overall. In particular, in the first altitude zone (0-200 m) the most pronounced increases are recorded, among which the HI (+381) stands out: it seems that the September nights somehow continue the hot Mediterranean summer rather than heralding the approach of the warm autumn. In the second altitude zone (201-400 m) the increases persist and are comparable with those in the previous altitude band.

The exception is HI, whose increase (+ 227) appears to be the least pronounced of the others. In the third altitude band (401-600 m), smaller increases in CI and AMT are found, but the increase in HI is more pronounced (+ 259). The values in this band therefore represent those

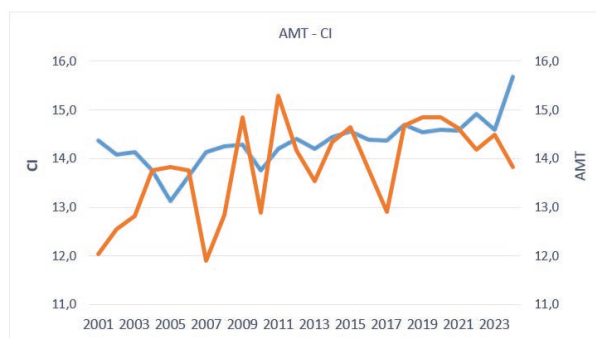


Fig. 9: Comparison of CI (orange line) and AMT value (blue line) over the period 2001-2024.

typical of the Campania wine-growing context, since it is precisely in this band that the largest extension of land - hilly but with a cool, sunny climate - in which wine-growing is practised falls. Lastly, in the fourth altitude band (601-800 m), there is a considerable increase in all indices, albeit lower than the values reached in the first two altitude zones.

The temperature data analysed clearly show changes since 2014 (Table 9) of all three calculated bioclimatic indicators, denoting an increase in the six-monthly temperatures on which the HI index is based for defining the warmest climatic period (April-September) in the Mediterranean area. Indeed, it is observed that after 2013 the average values of the HI index exceed the threshold of 2400 at all altitudes below 400 m a.s.l.; this implies a shift from 'warm temperate' to 'warm' in the climatic classification according to HI (Tab. 5), exactly as found in other contexts in southern Italy where the planting of late-ripening vines instead of early ripening vines has been suggested (Alba *et al.* 2021). At altitudes above 400 m, the HI index consistently exceeds the value of 2200, and above 600 m it is almost always greater than 2100.

The average increases in AMT (+ 0.95 °C) found in this study (Tab. 10) are in agreement with those recorded in other areas of southern Italy (SPNA, 2024). The average values of the IC (+ 1.55 °C) indicate a conspicuous

increase in night-time minima, presumably similar to that of other warm months in the Mediterranean area: in the Calabria region, increases in autumn minima of around + 0.5 °C were found (Pellicone *et al.* 2019). The same rate of increase in Tmin was recorded in the Basilicata Region (southern Italy) in the period 1981-2022 (Cirigliano *et al.* 2024). For southern Italy, an upward trend in average T of $+ 0.36 \pm 0.04$ °C is estimated (SNPA, 2024), while in Tuscany, similar studies have reported an increase in maximum temperature (+ 0.44 °C per decade) and minimum temperature (+ 0.38 °C per decade) in the period 1955–2004 (Bartolini *et al.*, 2008) many studies showed a significant worldwide warming, and consequently, changes in frequency and persistence of extreme high-temperature events were observed. In order to analyse summer Tuscany (Italy).

For the Italian peninsula as a whole, the rate of increase in maximum temperature ($+ 0.42 \pm 0.05$ °C per decade) is higher than that of minimum temperature ($+ 0.38 \pm 0.04$ °C per decade) in the four decades from 1981 to 2019. On a seasonal scale, the most pronounced warming trends are observed in summer and spring, with average temperature increases of $+ 0.60 \pm 0.09$ °C per decade and $+ 0.34 \pm 0.09$ °C per decade, respectively (SNPA, 2024). Therefore, the results of this study, which indicate an increase of about 1 °C in 24 years, are in line with the general trend; the study also highlights the particularly significant increase in summer temperatures.

In addition, the increases in the HI values found in this study are also comparable with those recorded in central Italy (Zacconi, 2020), in other areas of southern Italy (Gentile *et al.*, 2023) and in various parts of the world (Mariani *et al.*, 2018) seen as the preferential pathway for the Holocene spread of grapevine and many other crops in Eurasia. Spectral analysis was considered as the criterion of investigation and the Holocene cycles were analyzed considering different geochemical and biological proxies, of which seven are directly referred to vine. In this context the relation of the abovementioned proxies with spectral peaks of possible causal factors like Solar activity (SA. Increases in various continents since

Tab. 10: Increase in the values of the three analysed indices disaggregated by altitudinal classes.

Altitudinal classes (m asl)	CI		HI		AMT	
	Increase	Slope	Increase	Slope	Increase	Slope
0-200	+ 1.8	0.079	+ 381	16.551	+ 1.3	0.057
201-400	+ 1.5	0.078	+ 227	9.883	+ 1.2	0.054
401-600	+ 1.1	0.046	+ 259	11.251	+ 0.6	0.028
601-800	+ 1.5	0.062	+ 320	13.922	+ 0.7	0.031
Mean value	+ 1.55	0.067	+ 296.8	15.542	+ 0.95	0.038

the 1980s continue without any apparent reversal of the trend (Toreti and Desiato, 2008; Toreti et al., 2010), have been closely related to ongoing climate change (Alba et al., 2021; Alba et al. 2024) fearing adverse consequences, both in the agronomic and social fields (Nanni et al., 2009; Castellari & et al., 2014; IPCC, 2022).

The temperature data reported and analysed in this study ultimately all appear to be in line with the scientific literature in the field of viticulture: this agricultural practice develops in areas where the average annual temperature is between 10 °C and 20 °C (Mosedale et al., 2016; Schultz & Jones, 2010) and central-southern Italy with Campania Region, in the centre of the Mediterranean, can be perfectly recognised in these thermal indicators. Thus, temperature is a determining factor in the development of the vine, but warming trends, which can also be predicted on a global scale at the beginning of this millennium, as the results of this study also show, affect, and anticipate, the flowering, ripening and harvesting of grapes (Mavromatis et al., 2020; van Leeuwen & Destrac-Irvine, 2017; Wang et al., 2020)2017; Wang et al., 2020. Furthermore, Kizildeniz et al. (2018) showed that the increase in temperature reduces the quality of the grapes, producing an increase in sugars and a decrease in acidity (Leolini et al., 2019), negatively influencing metabolites (Teslić et al., 2017; Biasi et al., 2019) and accelerate or inhibit developmental stages (Cuccia et al., 2014; Molitor & Junk, 2019)GFV. The rise in temperature also impacts viticulture with significant environmental effects such as the prolongation of drought periods - these lead to high concentrations of salts in the soils and the massive use of irrigation - leading to high water and energy consumption (Kizildeniz et al., 2018; Funes & et al., 2020)agricultural production is being affected by a sharp increase in atmospheric CO₂ concentration. Due to the greenhouse effect gases, crops are impacted by enhanced temperatures and concomitantly by increased scarce water availability. All arid and semiarid areas, including Mediterranean viticulture, must face these three climate change-related factors: atmospheric CO₂ concentration and temperature increases, and scarce water for irrigation. Scarce water is a problem even in irrigated viticulture, as irrigation is becoming more and more restricted. Within this context, the aim of this work was to investigate grapevine (*Vitis vinifera* L. cv. red and white Tempranillo. Drought stress also reduces shoot growth and berry size, increasing the content of tannins, anthocyanins and phenolic compounds in the skin (van Leeuwen & Darriet, 2016; van Leeuwen & Destrac-Irvine, 2017)2017. These considerations, now widely confirmed, lead one to reflect on the fact that even in the Campania Region, as emerges from this study, the increase in HI, especially in the hilly area (401-600 m), where most

of the land devoted to viticulture is concentrated, raises serious concerns about the need for altitudinal (but also latitudinal) shifts in cultivated land in order to preserve the production and quality of wine products. A prospect already limited in some Mediterranean and foreign areas (Kryza et al., 2015; Irimia et al., 2018) and which is probably not without future risks (agricultural abandonment, anthropic overexploitation of ever smaller and less serviced portions of land, land consumption, etc.). In fact, in terms of spatial expansion or displacement, the regional response of viticulture to the established warming trend (IPCC, 2022), as also shown in this study, seems to follow two directions with opposing effects:

1) in regions with a cold temperate climate, global warming will enable winegrowers to cultivate a wider range of varieties and obtain better quality wines (Mosedale et al., 2016; Meier et al., 2018; Jobin-Poirier et al., 2019; Maciejczak & Mikiciuk, 2019)2019;

2) in warm temperate regions, such as the Mediterranean, the global warming trend could lead to a significant drop in fruit quality for high quality wines (Resco et al., 2015; Teslić et al., 2017; Lazoglou et al., 2018; Fraga et al., 2019; Cardell et al., 2019).

On the whole, the impact on crops (Yuan et al., 2024) and in particular on viticulture produced by the warming trend, demonstrated in this study for the territory of inland Campania, could, in the future, oblige “insiders” to redesign the geographical distribution of wine-growing areas and this would not exclude the possibility of negative socio-economic repercussions also in the wine tourism perspective (Magliulo et al., 2020), as already demonstrated in other parts of Italy (Nunes & Loureiro, 2016)an important tourist region in Italy and renowned for its enchanting countryside. Thus, vinery landscape and high-quality wine production have been included as explanatory variables in our model for tourism flows. This model has been estimated for both international and domestic markets for the whole region of Tuscany. Estimation results confirm that land areas devoted to the production of these superb Tuscan wines, in the particular case of Siena including the Brunello di Montalcino, play an important role in explaining international tourism flows. In this context, we estimate climate-change-induced impacts on vinery landscape and quality wines in the tourism sector. These are estimated to cause a loss in the tourism revenues of nearly 15 and 20 million Euros a year, respectively, for 2020 and 2050, for the Tuscany region. Such losses are quite significant, and reiterate the urgency to identify and implement adequate policy options so as to moderate such land use changes, and respective negative welfare impacts. For this reason, there is an urgent need to become aware of the current phenomenon and its consequences (Neethling et al., 2019; de Rességuier et

al., 2020) where climate is a key environmental component of plant suitability and productivity. From field to farm level, climate also plays a prominent role in ongoing practices, shaping winegrowers' decision making and adaptive management. With a changing climate, the wine sector faces many environmental and socio-economic challenges, to which winegrowers are required to adapt. Given the perennial nature of grape growing, there is a need to develop strategies that deal with both short- and long-term climate changes, while likewise accounting for contextual vulnerability. The content of this article aims to provide an overview of climate-driven scales, outlining the spatial complexity and temporal dynamics in viticulture. In addressing these aspects, this literature review offers a framework of scale and cross-scale interactions for policymakers and stakeholders to use when considering responses to attenuate climate change and to reduce its impacts on grape and wine production. The article concludes by discussing the local and context-dependent nature of viticulture in a changing global climate, by emphasizing that the question of scale is fundamental to assessing expected impacts, understanding uncertainty and framing sustainable policies and responses over space and in time. Climate is a major factor of the physical environment influencing terroir expression in viticulture. Thermal conditions strongly impact vine development and grape composition. Spatializing this parameter at local scale allows for more refined vineyard management. In this study, temperature variability was investigated over an area of 19,233 ha within the appellations of Saint-Émilion, Pomerol and their satellites (Bordeaux, France and to think about new adaptation strategies.

4 CONCLUSIONS

This study analysed the air temperature data for the 2001-2024 time interval, confirming a trend of air warming already noted at the end of the last century and which continues today. The data concern the internal regional territory of Campania Region and are in line with those of other regions of peninsular Italy and, in general, of the Mediterranean area. In particular, the data, which concern homogeneous series of air temperature values measured at 52 meteorological stations well distributed spatially over the territory of the innermost Campania and monitored on the network by the Campania Region's weather agencies, were analysed using well-known statistical methodologies, focusing on certain thermal indices (CI, HI, AMT) identified as bioclimatic indicators for their effectiveness in terms of impact on agricultural production in general and on viticulture in particular, recognising that the latter is particularly vulnerable to

climate change. The warming trend identified on a regional scale with this study allows useful comparisons with what has been estimated and recognised in similar sector studies and clearly shows that it manifests itself through annual peaks that appear more pronounced in the summer months. From the analysis of the series examined, it emerges that the first 12 years of the period considered already show anomalies with respect to the normal characteristics of the Mediterranean climate in the study area. These anomalies are accentuated from 2014 and for each of the three bioclimatic indices analysed. In the year 2024, moreover, average values of HI and T mean are recorded that have never been reached before in the New Millennium. In addition, the 401-600 m altitude band, with the most significant increases in temperature, is a critical zone in that it is, at least for our study area, the one in which viticulture is most widespread, raising fears of negative repercussions on grape cultivation and the quality of wine products. A situation that suggests possible future expansions towards higher altitudes of this agricultural production with unforeseeable socio-economic scenarios given the limited extension and elevation of the Campania orographic relief and its particular geomorphological structure. Finally, the data confirm the warming trend, if possible even more pronounced over the time period examined, for all areas below the 400 m elevation, where the vast majority of the study area falls. This evidence, which has also been found in similar climate studies, seems to affect the southern regions of Europe and the Mediterranean coastal areas the most, suggesting worrying future scenarios. This is especially true with regard to possible prolonged periods of drought with consequent effects in terms of desertification. In conclusion, the research has highlighted and confirmed the climate warming trend for the Campania Region also for this first two decades of the 21st century and the possible negative consequences for the practice of viticulture, which is important for the region's agricultural economy, with cascading effects on ecosystem services that require important risk mitigation interventions. It is therefore necessary to proceed in the wake of the National Strategy for Adaptation to Climate Change (SNAC, 2013) for the implementation of sectoral action plans.

Statements & Declarations

Founding

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Competing Interests

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Michele Sisto, Antonio Lucadamo and Filippo Russo. The first draft of the manuscript was written by Michele Sisto and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated during and/or analysed during the current study are available in the <https://agricoltura.regione.campania.it/meteo/agrometeo.html> and <https://centrofunzionale.regione.campania.it> repository.

5 REFERENCES

- Acevedo, M., Pixley, K., Zinyengere, N., Meng, S., Tufan, H., Cichy, K., Bizikova, L., Isaacs, K., Ghezzi-Kopel, K., & Porciello, J. (2020). A scoping review of adoption of climate-resilient crops by small-scale producers in low-and middle-income countries. *Nature plants*, 6(10), 1231–1241.
- AGM. (2025). *Archivio storico dei dati agrometeorologici*. <https://agricoltura.regione.campania.it/meteo/agrometeo.htm>
- AGREGCAM. (2022). *Statistica agraria*. https://agricoltura.regione.campania.it/statistica/statistica_VII_censimento.html
- AGREGCAM. (2023). *Statistiche colture agrarie*. <https://agricoltura.regione.campania.it/statistica/vite.html>
- Alba, V., GentileSCO, G., & Tarricone, L. (2021). Climate change in a typical Apulian region for table grape production: Spatialisation of bioclimatic indices, classification and Future Scenarios. *Oeno One*, 55(3), 317–336.
- Aucelli, P. P. C., Izzo, M., Mazzarella, A., & Roskopf, C. M. (2007). The Climatic Classification Of The Molise Region. *Bollettino Della Società Geografica Italiana*, 907–930. <https://www.bsgi.it/index.php/bsgi/article/view/7162>
- Bartolini, G., Morabito, M., Crisci, A., Grifoni, D., Torrigiani, T., Petralli, M., Maracchi, G., & Orlandini, S. (2008). Recent trends in Tuscany (Italy) summer temperature and indices of extremes. *International Journal of Climatology*, 28(13), 1751–1760. <https://doi.org/10.1002/joc.1673>
- Bencardino, F., & Cresta, A. (2004). Il territorio tra sviluppo rurale e turismo enogastronomico: Le potenzialità del Sannio. *Bencardino F, Marotta G, Nuovi turismi e politiche di gestione della destinazione, FrancoAngeli Editore*.
- Bencardino, M., Cresta, A., & Greco, I. (2007). La Campania nella dimensione europea: Politiche e processi territoriali. *GEOTEMA*, 94–102.
- Biasi, R., Brunori, E., Ferrara, C., & Salvati, L. (2019). *Assessing Impacts of Climate Change on Phenology and Quality Traits of Vitis vinifera L.: The Contribution of Local Knowledge*. <https://www.mdpi.com/2223-7747/8/5/121>
- Bronaugh, D., Schoeneberg, A., & Zeman, L. (2023). *zyp: Zhang + Yue-Pilon Trends Package* (Versione 0.11-1) [Software]. <https://cran.r-project.org/web/packages/zyp/index.html>
- Buono, R., & Vallariello, G. (2002). Introduzione e diffusione della vite (*Vitis vinifera* L.) in Italia. *Delpinoa*, 44, 39–51.
- Cardell, M. F., Amengual, A., & Romero, R. (2019). Future effects of climate change on the suitability of wine grape production across Europe. *Regional Environmental Change*, 19(8), 2299–2311. <https://go.gale.com/ps/i.do?p=AONE&sw=w&issn=14363798&v=2.1&it=r&id=GALE%7CA716399539&sid=googleScholar&linkaccess=abs>
- Castellari, S., & et al. (2014). *Rapporto sullo stato delle conoscenze scientifiche su impatti, vulnerabilità ed adattamento ai cambiamenti climatici in Italia*.
- Cirigliano, P., Esposito, S., Di Giuseppe, E., & Cresti, A. (2024). Mitigating effect of the sea on temperatures along Mediterranean coastal areas: The case of the vine territory of the Matera DOP in Basilicata (Italy). *Atmosphere*, 15(11), 1295.
- CMR. (2025). *Dati giornalieri*. <https://centrofunzionale.regione.campania.it/#/pages/dashboard>
- Cuccia, C., Bois, B., Richard, Y., Parker, A. K., Cortázar-Atauri, I. G. de, Leeuwen, C. van, & Castel, T. (2014). Phenological model performance to warmer conditions: Application to Pinot Noir in Burgundy. *OENO One*, 48(3), 169–178. <https://doi.org/10.20870/oeno-one.2014.48.3.1572>
- de Rességuier, L., Mary, S., Le Roux, R., Petitjean, T., Quénot, H., & van Leeuwen, C. (2020). Temperature variability at local scale in the Bordeaux area. Relations with environmental factors and impact on vine phenology. *Frontiers in Plant Science*, 11. <https://doi.org/10.3389/fpls.2020.00515>
- Di Lisio, A., Lo Curzio, S., Russo, F., & Sisto, M. (2009). Rappresentazione degli indici climatici in ambiente GIS per la caratterizzazione paesaggistica dell'Appennino Sannita (Campania). *Atti 13a Conferenza Nazionale ASITA*, 1–4.
- Donnici, S., Serandrei-Barbero, R., Gao, X., Tang, C., & Tosi, L. (2021). Utilizing benthic foraminifera to explore the environmental condition of the Laizhou Bay (Bohai Sea, China). *Marine Pollution Bulletin*, 167, 112323. <https://doi.org/10.1016/j.marpolbul.2021.112323>
- Duchêne, E., & Schneider, C. (2005). Grapevine and climatic changes: A glance at the situation in Alsace. *Agronomy for Sustainable Development*, 25(1), 93–99.
- Fraga, H., Pinto, J. G., & Santos, J. A. (2019). Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: A multi-model assessment. *Climatic Change*, 152(1), 179–193. <https://doi.org/10.1007/s10584-018-2337-5>
- Funes, I., & et al. (2020). Soil water availability as a tool for adapting viticulture to climate change. *Quaderns Agrar*, 49, 35–52.
- GentileSCO, G., Coletta, A., Tarricone, L., & Alba, V. (2023). Bioclimatic characterization relating to temperature and subsequent future scenarios of vine growing across the Apulia region in southern Italy. *Agriculture*, 13(3), 644.
- Giuliani, D., & Antenucci, F. (2017). Valori medi climatici dal 1951 al 2000 nella Regione Abruzzo. *Regione Abruzzo, Dipartimento Politiche dello Sviluppo Rurale e della pesca, Servizio Presidi Tecnici di Supporto al Settore Agricolo. DPD023, Ufficio Coordinamento servizi vivaistici e agrimeteo, Scerni (CH)*.
- Huglin, M. P. (1978). Nouveau mode d'évaluation des possibilités heliothermiques d'un milieu viticole [climatologie].

- Comptes rendus des Séances de l'Académie d'Agriculture de France*, 64.
- IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Irimia, L. M., Patriche, C. V., & Murariu, O. C. (2018). The impact of climate change on viticultural potential and wine grape varieties of a temperate wine growing region. *Applied Ecology and Environmental Research*, 16(3), 2663–2680. https://doi.org/10.15666/aeer/1603_26632680
- ISTAT. (2014). *Annuario Statistico Italiano*. Roma.
- Jobin-Poirier, E., Pickering, G., & Plummer, R. (2019). Doom, gloom, or boom?: Perceptions of climate change among Canadian winegrowers. *International Journal of Wine Research*, 11, 1–11. <https://doi.org/10.2147/IJWR.S188787>
- Jones, G. V., & Davis, R. E. (2000). Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *American Journal of Enology and Viticulture*, 51(3), 249–261.
- Jones, G. V., White, M. A., Cooper, O. R., & Storchmann, K. (2005). Climate change and global wine quality. *Climatic Change*, 73(3), 319–343.
- Kizildeniz, T., Irigoyen, J. J., Pascual, I., & Morales, F. (2018). Simulating the impact of climate change (elevated CO₂ and temperature, and water deficit) on the growth of red and white Tempranillo grapevine in three consecutive growing seasons (2013–2015). *Agricultural Water Management*, 202, 220–230. <https://doi.org/10.1016/j.agwat.2018.02.006>
- Kryza, M., Szymanowski, M., Błaś, M., Migala, K., Werner, M., & Sobik, M. (2015). Observed changes in SAT and GDD and the climatological suitability of the Poland-Germany-Czech Republic transboundary region for wine grapes cultivation. *Theoretical and Applied Climatology*, 122(1), 207–218. <https://doi.org/10.1007/s00704-014-1296-7>
- Lazoglou, G., Anagnostopoulou, C., & Koundouras, S. (2018). Climate change projections for Greek viticulture as simulated by a regional climate model. *Theoretical and Applied Climatology*, 133, 551–567. <https://doi.org/10.1007/s00704-017-2198-2>
- Leolini, L., Moriondo, M., Romboli, Y., Gardiman, M., Costafreda-Aumedes, S., Cortázar-Atauri, I. G. de, Bindi, M., Granchi, L., & Brilli, L. (2019). Modelling sugar and acid content in Sangiovese grapes under future climates: An Italian case study. *Climate Research*, 78, 211–224. <https://doi.org/10.3354/cr01571>
- Maciejczak, M., & Mikiciuk, J. (2019). Climate change impact on viticulture in Poland. *International Journal of Climate Change Strategies and Management*, 11, 254–264. <https://doi.org/10.1108/IJCCSM-02-2018-0021>
- Magliulo, P., Di Lisis, A., Sisto, M., & Valente, A. (2020). Geotouristic enhancement of high-quality wine production areas: Examples from Sannio and Irpinia landscapes (Campania Region, Southern Italy). *Geoheritage*, 12(1), 18.
- Malheiro, A. C., Santos, J. A., Fraga, H., & Pinto, J. G. (2010). Climate change scenarios applied to viticultural zoning in Europe. *Climate Research*, 43, 163–177. <https://doi.org/10.3354/cr00918>
- Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, 13(3), 245–259. <https://doi.org/10.2307/1907187>
- Mariani, L., Cola, G., Maghradze, D., Failla, O., & Zavatti, F. (2018). Influence of climate cycles on grapevine domestication and ancient migrations in Eurasia. *Science of The Total Environment*, 635, 1240–1254. <https://doi.org/10.1016/j.scitotenv.2018.04.175>
- Mavromatis, T., Koufos, G., Koundouras, S., & Jones, G. V. (2020). Adaptive capacity of winegrape varieties cultivated in Greece to climate change. *OENO One*, 54, 1201–1219. <https://doi.org/10.20870/oeno-one.2020.54.4.3129>
- Meier, M., Fuhrer, J., & Holzkämper, A. (2018). Changing risk of spring frost damage in grapevines due to climate change? A case study in the Swiss Rhone Valley. *International Journal of Biometeorology*, 62(6), 991–1002. <https://doi.org/10.1007/s00484-018-1501-y>
- Molitor, D., & Junk, J. (2019). Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the Luxembourgish grapegrowing region. *OENO One*, 53(3). <https://doi.org/10.20870/oeno-one.2019.53.3.2329>
- Mosedale, J. R., Abernethy, K. E., Smart, R. E., Wilson, R. J., & Maclean, I. M. D. (2016). Climate change impacts and adaptive strategies: Lessons from the grapevine. *Global Change Biology*, 22(11), 3814–3828. <https://doi.org/10.1111/gcb.13406>
- Nanni, T., Maugeri, M., & Brunetti, M. (2009). La variabilità e le tendenze del clima in Italia nel corso degli ultimi due secoli. In *I cambiamenti climatici in Italia: Evidenze, vulnerabilità e impatti* (pp. 11–45). Bononia university press.
- Neethling, E., Barbeau, G., Coulon-Leroy, C., & Quéno, 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>
- Nunes, P. A. L. D., & Loureiro, M. L. (2016). Economic valuation of climate-change-induced vinery landscape impacts on tourism flows in Tuscany. *Agricultural Economics*, 47(4), 365–374. <https://doi.org/10.1111/agec.12236>
- Pellicone, G., Caloiero, T., & Guagliardi, I. (2019). The de Martonne aridity index in Calabria (Southern Italy). *Journal of Maps*, 15(2), 788–796.
- R core team. (2021). *R: The R Project for Statistical Computing*. <https://www.r-project.org/>
- Resco, P., Iglesias, A., Bardaji, I., & Sotés, V. (2015). Exploring adaptation choices for grapevine regions in Spain. *Regional Environmental Change*, 16. <https://doi.org/10.1007/s10113-015-0811-4>
- Schultz, H. R., & Jones, G. V. (2010). Climate induced historic and future changes in viticulture. *Journal of Wine Research*, 21(2–3), 137–145. <https://doi.org/10.1080/09571264.2010.530098>
- SNAC. (2013). *Strategia Nazionale di Adattamento ai Cambiamenti Climatici*. MATTM. https://www.mase.gov.it/sites/default/files/archivio/allegati/clima/documento_SNAC.pdf
- SNPA. (2024). *Il clima in Italia nel 2023*. SNPA.
- SPNA. (2024). *Il clima in Italia nel 2024*.
- Teslić, N., Vujadinović, M., Ruml, M., Antolini, G., Vukovic, A., Parpinello, G. P., Ricci, A., & Versari, A. (2017). Climatic

- shifts in high quality wine production areas, Emilia Romagna, Italy, 1961-2015. *Climate Research*, 73, 195–206. <https://doi.org/10.3354/cr01468>
- Tonietto, J. (1999). *Les macroclimats viticoles mondiaux et l'influence du mesoclimat sur la typicité de la Syrah et du Muscat de Hambourg dans le sud de la France: Methodologie de caracterisation*.
- Tonietto, J., & Carbonneau, A. (2004). A multicriteria climatic classification system for grape-growing regions worldwide. *Agricultural and Forest Meteorology*, 124(1–2), 81–97.
- Toreti, A., & Desiato, F. (2008). Temperature trend over Italy from 1961 to 2004. *Theoretical and Applied Climatology*, 91, 51–58.
- Tscholl, S., Candiago, S., Marsoner, T., Fraga, H., Giupponi, C., & Egarter Vigl, L. (2024). Climate resilience of European wine regions. *Nature Communications*, 15(1), 6254.
- Turri, S., & Intrieri, C. (1987). Mappe isothermiche ed insediamenti viticoli in Emilia Romagna. *VigneVini*, 10, 37–41.
- van Leeuwen, C., & Darriet, P. (2016). The impact of climate change on viticulture and wine quality. *Journal of Wine Economics*, 11(1), 150–167. <https://doi.org/10.1017/jwe.2015.21>
- van Leeuwen, C., & Destrac-Irvine, A. (2017). *Modified grape composition under climate change conditions requires adaptations in the vineyard*. <https://oeno-one.eu/article/view/1647>
- van Leeuwen, C., Sgubin, G., Bois, B., Ollat, N., Swingedouw, D., Zito, S., & Gambetta, G. A. (2024). Climate change impacts and adaptations of wine production. *Nature Reviews Earth & Environment*, 5(4), 258–275.
- Wang, J., Zhang, X., Su, L., Li, H., Zhang, L., & Wei, J. (2020). Global warming effects on climate zones for wine grape in Ningxia region, China. *Theoretical and Applied Climatology*, 140(3), 1527–1536. <https://doi.org/10.1007/s00704-020-03170-y>
- Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., Huang, S., Chen, H., & Ao, X. (2024). Impacts of global climate change on agricultural production: A comprehensive review. *Agronomy*, 14(7), 1360.
- Yue, S., & Pilon, P. (2004). A comparison of the power of the t test, Mann-Kendall and bootstrap tests for trend detection / Une comparaison de la puissance des tests t de Student, de Mann-Kendall et du bootstrap pour la détection de tendance. *Hydrological Sciences Journal*, 49(1), 21–37. <https://doi.org/10.1623/hysj.49.1.21.53996>
- Zacconi, F. (2020). *Innovazione nel sistema di allevamento della vite come strategia di adattamento al riscaldamento globale* [Tesi Magistrale, Università Politecnica delle Marche]. <https://tesi.univpm.it/retrieve/3610d6b9-2a-8a-4388-ba90-6f52206ab3d5/Tesi.pdf>
- Zhang, X., Vincent, L. A., Hogg, W. D., & Niitsoo, A. (2000). Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean*, 38(3), 395–429. <https://doi.org/10.1080/07055900.2000.9649654>