Original papers

Simulations of quantitative shift in bio-climatic indices in the viticultural areas of Trentino (Italian Alps) by an open source R package

Emanuele Eccel[a, *]

emanuele.eccel@fmach.it

Alessandra Lucia Zollo[b, c]

Paola Mercogliano[b, c]

Roberto Zorer[d]

[a]Department of Sustainable Agro-ecosystems and Bioresources, Research and Innovation Centre, Fondazione Edmund Mach (FEM), Via E. Mach 1, 38010 San Michele all’Adige, Italy

[b]Meteorology Laboratory, Centro Italiano Ricerche Aerospaziali (CIRA), Via Maiorise s.n.c., 81043 Capua, Italy

[c]Regional Models and Geo-Hydrogeological Impacts Division, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Via Maiorise s.n.c., 81043 Capua, Italy

[d]Department of Biodiversity and Molecular Ecology, Research and Innovation Centre, Fondazione Edmund Mach, Via E. Mach 1, 38010 San Michele all’Adige, Italy

*Corresponding author.

Abstract

In consideration of the steady entanglements of viticulture with the environmental features – including climate – it is of concern to project which climatic conditions an area is expected to face in a changing climate scenario. A quantitative approach helps in assessing class shift in climate classification; both “generic” climatic and bioclimatic indices were considered in this study, namely: Köppen – Geiger types and subtypes, aridity (6 indices), and “International vine and wine organization” (OIV) classification (10 indices). All indices were easily calculated by an open source R library (ClimClass), which also includes tools for base pre-processing of weather series. Future climate scenarios for this study were obtained using the Regional Climate Model (RCM) COSMO-CLM, employing two IPCC’s greenhouse gas concentrations (RCP 4.5 and RCP 8.5), statistically downscaled to 39 weather stations in Trentino, a region in the Italian Alps. The simulations envisage the new climatic profile of the area, with a shift towards warmer and somewhat drier conditions. While no limitation to wine growing is expected in the lower altitude areas, new climatic suitability is projected for mountain areas, presently devoted to other soil uses. The latter analysis was the result of a calibration of a thermal requirement index to the present soil use condition in the region.

Keywords: Grapevine; Climate change; Models; Indices; OIV; Italy

1 Introduction

Among all crops, grapevine is one of those which inspired the highest number of bioclimatic analysis related to climate change (Hall and Jones, 2009; Anderson et al., 2012; Molitor et al., 2014; Koufos et al., 2014; Dunn et al., 2015). The term “*terroir*” itself stems from the idea that wine production is steadily entangled with the environmental features – including climate – which characterize origin and growing of a variety. Climate change obviously poses urgent questions about the future of premium wine production in many wine-growing regions. More than for most crops, the maintenance of the link of many wines with their typical production areas is an added value which impacts on the cultural and – ultimately – market value of the products. Hence, it is of concern for wine growers – as well as for all the wine production spin-offs – to know which climatic conditions an area is going to face in a changing climate scenario.

Generally speaking, warmer and drier conditions have mostly contributed to an increase of wine quality in many regions of the world (Jones et al., 2005; Dalu et al., 2013). If the latter authors highlighted above all the improvements of wine quality in the last 50 years, attributing an important role to warmer climate conditions, on the other hand, the same authors claimed that a further increase could take the bioclimatic physical driver beyond the optimum, leading to a worsening of ratings. For warm vine-growing regions, a temperature increase would probably bring with itself the undesired effect of a dramatic restriction of the suitable viticultural areas (White et al., 2006; Hall and Jones, 2009). Moriondo et al. (2011) suggested possible negative effects of temperature increase on wine quality in the Mediterranean area (particularly Italy). The recorded advance in phenological timing (Caffarra and Eccel, 2011; Tomasi et al., 2011; Fraga et al., 2015) is a clear warning against a change in the match between a variety and its long-lived growing context, questioning the subsistence of the balance between the ripening process and the meteorological conditions occurring in the relevant period (Mullins et al., 1992). The action of meteorological drivers on physiological development may also affect yield (Bindi et al., 1996; Duchêne and Schneider, 2005; Webb et al., 2008), due to an expected higher, unsatisfied water demand in summer, and to a shorter ripening period.

Spreading viticultural areas northward entails the shortcoming of a shift of production areas to regions which may be new to either specific varieties or even to vine growing (Fraga et al., 2016; Jones, 2006). Moriondo et al. (2011) suggested possible negative effects of temperature increase on wine quality in the Mediterranean area, highlighting that spreading the cultivation areas to higher altitudes within the same geographic context offers the chance to meet better conditions than the ones expected in the traditional production areas at lower elevations, according to the climatic scenarios. Trentino, a temperate wine-producing area in the Italian Alps, can benefit of the altitudinal range of mountain regions to face a progressive warming of climatic conditions.

This work aims at providing an in-depth analysis of the projected change in the quantitative bioclimatic indices that have been developed to assess the landscape suitability for viticulture. The model chain for this analysis was built by applying a code which calculates climate indices to the output of climate simulations.

2 Materials and methods

2.1 Geographical, climatological and viticultural features

Trentino is a 6212 km^2 region in the central-eastern Italian Alps (Fig. 1). Altitude ranges between 70 m a.s.l. (lower Sarca Valley) to 3769 m (Cevedale peak). Trentino climate is mostly oceanic, with some areas showing features of transition to a more continental-alpine climate, cooler and often drier, more typical of the inner mountain valleys. Precipitation is mostly distributed over two maxima, in the autumn (main) and in the spring (secondary).

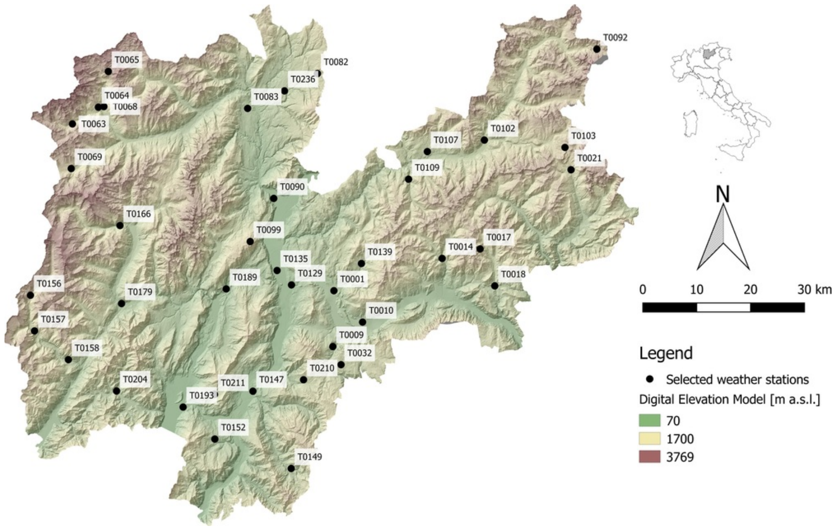

Fig. 1 Map of the 39 selected weather stations (PAT MeteoTrentino).

The current viticultural areas in Trentino consist of about 10,000 ha, distributed from 70 to 850 m a.s.l. The list of the cultivated grapevines (*Vitis vinifera* ssp. *vinifera*) includes both red and white varieties, mainly from France (white: Pinot gris, Chardonnay, Sauvignon; rosé: Gewürztraminer; red: Pinot noir, Merlot, Cabernet Sauvignon) in addition to some local cultivars (white: Nosiola; rosé: Schiava gentile; red: Teroldego, Marzemino, Lagrein) and the Swiss Müller Thurgau, which is successfully cultivated up to the highest elevations.

The most updated land use map (August 2003), including viticulture, has been drawn and it is provided by the urban planning service of the Autonomous Province of Trento. The map is available as Esri shapefile at the Trentino OPENdata website (http://dati.trentino.it/) under Creative Commons Zero – CC0 v1.0 Universal terms of use.

2.2 Observational dataset

39 daily meteorological series of precipitation and temperature were made available from Meteotrentino, the meteorological service of the Autonomous Province of Trento (Fig. 1). The series covered all the altitudinal range of the region, from the 90 m a.s.l. of Torbole, in the proximity of Lake Garda, to 2600 m a.s.l. of Careser dam, an artificial reservoir in the heart of central Alps. These series are the same (Please delete "are the same")were chosen according to their length and quality to bias-correct and downscale the model output in Orientgate project (http://www.orientgateproject.org/) – see further.

2.3 Climate simulations

Climate data for this study were obtained using the Regional Climate Model (RCM) COSMO-CLM (Rockel et al., 2008), the climate version of the operational non-hydrostatic mesoscale weather forecast model COSMO-LM developed by the German Weather Service (DWD) and optimized at CMCC, REMHI division. The main features of the model and of its setup are reported in Bucchignani et al. (2015) and are briefly recalled in Table 1. Simulations were performed over Italy, employing a spatial resolution of 0.0715° (about 8 km). Initial and boundary conditions were provided by global model CMCC-CM (Scoccimarro et al., 2011), whose atmospheric component (ECHAM5) has a horizontal resolution of about 85 km. The time period considered was 1976–2070; specifically, the CMIP5 historical experiment (based on historical greenhouse gas concentrations) was used for the period 1976–2005, while, for the period 2006–2070, two different simulations were performed, employing the IPCC RCP 4.5 and RCP 8.5 greenhouse gas (GHG) concentrations. RCP 4.5 scenario is characterized by a stabilization in GHG emissions after year ~ 2070, while RCP 8.5 by a rapidly increasing GHG concentration. Numerical simulations were performed employing 512 cores on a cluster of 30 IBM P575 nodes, installed at CMCC with an aggregate peak power of 18 TFlops. The elapsed time required to simulate one climatological year was about 20 h.

Table 1 Main features of COSMO-CLM simulation setup.

COSMO-CLM model version	4.8_clm13
INT2LM model version	1.10_clm2
Horizontal discretization	Second-order difference technique
Horizontal resolution	0.0715°
Computational mesh	224 × 230 grid points
Time step	40 s
Time integration scheme	Third-order Runge–Kutta
Convection scheme	Tiedtke
Number of vertical levels	40
Number of soil levels	7
Soil model	TERRA_ML
Frequency update boundary conditions	6 h

The simulations have been deeply analysed in Bucchignani et al. (2015) and – in terms of extreme events – in Zollo et al. (2015a), showing a general good agreement with observed data. Furthermore, as explained in Bucchignani et al. (2015), the results of these simulations are consistent, in terms of both mean bias and projections, with those obtained from the EURO-CORDEX ensemble data (Giorgi et al., 2009), which represent the 'state-of-the-art' of regional climate simulations over Europe at 0.11° of horizontal resolution. Although RCMs are powerful tools for describing small scale climate conditions, their direct use in impact studies is still challenging since they are commonly biased. In order to provide corrected climate scenarios, simulated data were bias-corrected considering a statistical downscaling approach based on quantile mapping (Zollo et al., 2015b). Specifically, simulated data were downscaled at station level using data from the available meteorological stations described in Section 2.2.

2.4 Climatic and bioclimatic indices

All indices were calculated by the R package ClimClass 2.0.1 (Eccel et al., 2015), freely available at R Cran repository (https://cran.r-project.org/). The package makes use of monthly or daily series, according to the class of indices to be calculated: monthly for Köppen – Geiger climate classification, for aridity indices, and for Riou's drought index (one of the OIV indices), daily for all bioclimatic indices except Riou's. The codes can carry out gap filling operations, if required, for the instrumental series. Mean daily and monthly temperatures were calculated as averages between corresponding minima and maxima, available either as records or climate projections, accordingly.

2.4.1 Climate classification

(i) Köppen – Geiger climate types and sub-types. The classical climate classification follows the description given in Trewartha and Lyle (1980). There are five main climate types (A ~~to~~ –please replace F with EF), and more sub-types, according to the general precipitation regime and to its distribution along the year.

(ii) Aridity indices. Five annual indices are calculated: Ia – De Martonne, Im – Thornthwaite, Q – Emberger, R – Lang, Io – Rivas-Martinez and Rivas-Sáenz (details in Appendix 1 – Supplementary Material, and in ClimClass user manual).

2.4.2 Bioclimatic indices for viticulture

OIV (2012) selected and suggested a list of 10 indices useful for assessing the climatic classification of wine-growing regions. In the present work, we used a reduced list of the proposed indices (description in Appendix 1) grouped by physiological meaning. Growing Season average Temperature (GST), Winkler Index (WI), or Growing Degree Days (GDD), Biologically Effective Degree Days (BEDD), Huglin heliothermic Index (HI) are indicators of the heat requirements, necessary for a proper vine development and grape ripening. These four indices were tested against the actual grapevine presence in the area, to assess a rough viticultural area according to the future, expected conditions, as simulated by the climatic model. For the assessment of exposure of grapevine to biotic and abiotic adversities we considered the minimum temperature during rest period (Tn_rest), minimum temperature during vegetative period (Tn_veg), and maximum temperature during vegetative period (Tx_veg).

Tonietto and Carbonneau (2004) proposed to classify world viticultural areas according to three bioclimatic indices, among those listed above: Huglin's heliothermic Index (HI), Cool night Index (CI), and Riou's Drought Index (DI). All these indices (see Appendix 1, Supplementary material) were calculated to assess climate-driven changes.

2.5 Assessment of changes in the viticultural area

The potential enlargement of the viticultural areas, with respect to climate change scenarios and geo-morphological features, has been assessed using open source GIS software (QGIS Geographic Information System ver. 2.8.2, QGIS Development Team), a high resolution digital elevation model (10 m), and finally a landuse map, both provided by the "P.A.T. Sistema Informativo Ambiente e Territorio" service of the Province of Trento.

3 Results

3.1 Simulated climate changes in Trentino

The bias-corrected and downscaled climate data described in Section 2.3 were analysed in terms of climate change signal over Trentino, considering the anomaly between the mean climatology in the reference past period and in two different future periods: 2021–2050 and 2041–2070.

As concerns precipitation, the projected climate change signal indicates a general decrease of total rainfall and number of rainy days; in contrast, an increase of mean precipitation amount on wet days and precipitation maximum is projected. Furthermore, an increase in the number of consecutive dry days and a decrease in the number of consecutive wet days is expected. In general, comparison of results obtained with scenarios RCP 4.5 and RCP 8.5 indicates that the sign of the climate change signal generally remains the same for both scenarios, but the intensity of the signal is greater for RCP 8.5.

For temperature, the climate change signal indicates a significant increase. Specifically, this increase is higher for the more distant future period (2041–2070), is more accentuated for scenario RCP 8.5, and affects both minimum and maximum temperature. In line with this increase in temperature, the numbers of frost and ice days (days with Tmin < 0 °C and Tmax < 0 °C, respectively) show a decrease and the number of summer days (days with Tmax > 25 °C) an increase. For the vegetative season (April to October), the mean of the expected increase on all stations is 1.4–1.5 °C for the time window 2021–2050, while for 2041–2070 the extent of the increase and the range of values are much higher: 2.5 ~~to~~ –3.0 °C.

3.2 Simulated changes in climate classification of viticultural areas

In general, the areas which are – or would eventually become – suitable for vine growing in Trentino, can be ascribed to one climate type according to Köppen – Geiger (Trewartha and Lyle, 1980): "C" (mild temperate, rainy) – Table 2. The sub-type is always "f", which denotes absence of a true dry season. The further sub-type of Cf can be "a", "b", or "c" according to summer temperature, "hot", "cool", or "cool and short", respectively; the shift from one sub-type to the other occurs within a transition range between about 250 and 500 m a.s.l. The other stations in Trentino belong to "microthermal" climate belt D, with one alpine station in the "polar" type ET (tundra-like climate). In the first future time window (2021–2050) a trend is evident to the increase of stations of subtype “a”, further increasing in the second time step (2041–2070).

Table 2 Köppen – Geiger climate classification for all stations according to several time windows and scenarios. Table cells contain the number of stations in each class.

Period & RCP scenario	′76–′05	′21–′50		′41–′70	
		4.5	8.5	4.5	8.5
Cfa	6	11	11	15	17
Cfb	24	21	21	19	20
Cfc	1	0	3	1	0
Dfb	1	0	1	3	1
Dfc	6	6	2	1	1
ET	1	1	1	0	0

The analysis of aridity classes is more complex, involving a number of different indices (Table 3). As a general rule, as expected, the climate change leads to a shift of a number of sites towards drier classes, from the generally humid or very humid categories to generally sub-humid classes, with even some cases of dry classes in the farthest time window, mostly limited to scenario RCP 8.5.

Table 3 Aridity indices classification for all stations according to several time windows and scenarios. Table cells contain the number of stations in each class. See ClimClass manual for index formulations and classification tables.

Period & RCP scenario	′76–′05	′21–′50		′41–′70		Period RCP scenario	′76–′05	′21–′50		′41–′70	
		4.5	8.5	4.5	8.5			4.5	8.5	4.5	8.5
Ia						Io					
Dry	0	0	0	0	0	Ultrahyperarid	0	0	0	0	0
Semidry	0	0	0	0	0	Hyperarid	0	0	0	0	0
Mediterranean	0	0	0	0	0	Arid	0	0	0	0	0
Semihumid	0	0	0	0	0	Semiarid	0	0	0	0	0
Humid	0	0	0	0	2	Dry	0	0	0	0	0
Very humid.a	18	21	18	22	24	Subhumid	6	12	11	14	16
Very humid.b	21	18	21	17	13	Humid	25	21	20	22	22
						Hyperhumid	8	6	8	3	1
Q						Ultrahyperhumid	0	0	0	0	0
Desert	0	0	0	0	0						
Arid	0	0	0	0	0	Im					
Semiarid	0	0	0	0	0	Arid (E)	0	0	0	0	0
Subhumid	3	9	1	9	9	Semiarid (D)	0	0	0	0	0
Humid	36	30	38	30	30	Dry sub-humid (C1)	0	1	0	1	2

						Moist sub-hum. (C2)	2	11	2	8	12
R						Humid (B1)	11	4	11	8	4
Steppe	1	0	0	0	0	Humid (B2)	4	3	4	2	7
Semiarid	0	0	0	0	5	Humid (B3)	1	7	1	8	4
Temper, warm	11	16	15	19	20	Humid (B4)	8	4	8	3	3
Temper. humid	15	13	14	12	7	Perhumid (A)	13	9	13	9	7
Humid	12	10	10	8	7						

More in detail, Thornthwaite moisture index (Im), which offers a higher degree of detail, shows a general shift towards less humid classes, so that in the farthest time window the most populated class would be “moist sub-humid”, instead of “humid – B1”, most frequent in the present time; one or two stations reach the “dry sub humid” class. Rivas-Martinez and Rivas-Sáenz’s ombrothermic index attains the same qualitative result, almost equally sharing the majority of present vine-growing area between the humid and sub-humid types.

In scenario ′41–′70, RCP 8.5, the number of sub-humid stations is increased by a factor of 2.7, with respect to the initial conditions; the “hyperhumid” class is reduced to just one site, whereas at the beginning the stations in this class were six.

The simulations of Emberger’s Q factor also lead to a shift from the humid to the sub-humid type (in the nearest time window only for RCP 4.5 scenario – a more homogeneous signal is detectable for the second time window). Lang’s pluviometric factor R showed negligible changes until ′41–′70 RCP 8.5 scenario; in this case, five sites would fall into a “semiarid” type. An interesting feature is that simulations for Q and Im indices, in the 2021–2050 RCP 8.5 case, yield either no significant changes or even a strengthening of humid types. Finally, De Martonne index (Ia) shows minor changes in the simulations, mainly as changes within the two subclasses of “very humid” type.

Aridity indices showed a generally good collinearity, in some cases with the exception of the lower values (drier sites) and elevations. In order to create an index that summons up all classifications, irrespective of the unit of each index, ranks have been calculated for each station and index, and the median of ranks has been taken as a synthesis index. A very strong ($p < 0.001$) negative correlation of aridity with elevation can be inferred (Fig. 2), yielding the expected result of less humid classes at the lowest elevation sites.

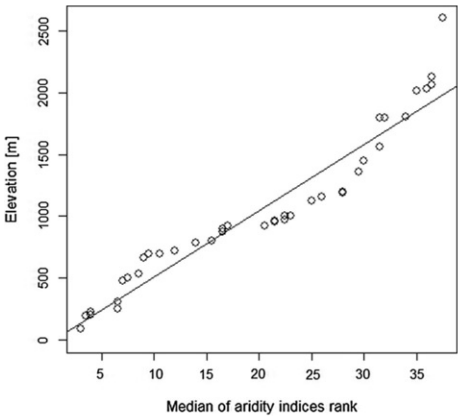

Fig. 2 Aridity (median of ranks of six indices) vs. elevation for stations in viticultural areas for period 1976–2005. Lower values reflect higher aridity.

3.3 Simulated changes in viticultural indices

The most common viticultural bioclimatic indices were considered – see Appendix 1, Supplementary material, for definitions – seven by OIV (2012) (BEDD, GST, WI, HI, Tn_rest, Tn_veg, and Tx_veg), and three suggested by Tonietto and Carbonneau (2004). Results are summarized in Table 4.

Table 4 Classification according to OIV bioclimatic indices for all stations according to several time windows and scenarios. Table cells contain the number of stations in each class. See Appendix 1, Supplementary material, for index formulations.

Period & RCP scenario	′76–′05	′21–′50		′41–′70		Period RCP scenario	′76–′05	′21–′50		′41–′70	
		4.5	8.5	4.5	8.5			4.5	8.5	4.5	8.5
Tm_veg						WI					
Too cool <13 °C	18	11	11	9	8	Too cool <850	19	10	10	9	8
Cool 13–15 °C	10	11	11	6	3	Region Ia 850–1111	8	9	9	2	2
Intermediate 15–17 °C	6	6	6	12	12	Region Ib 1111–1389	4	8	8	11	9
Warm 17–19 °C	5	8	7	5	8	Region II 1389–1667	5	4	4	5	8
Hot 19–21 °C	0	3	4	7	5	Region III 1667–1944	3	4	4	4	3
Very hot 21–24 °C	0	0	0	0	3	Region IV 1944–2222	0	4	4	5	4
Too hot >24 °C	0	0	0	0	0	Region V 2222–2700	0	0	0	3	5
						Too hot >2700	0	0	0	0	0
HI											
Too cool <1200	13	9	9	8	8	BEDD					
Very cool 1200–1500	11	4	4	2	1	<1000	27	19	19	11	11
Cool 1500–1800	4	11	11	9	4	1000–1200	4	8	8	12	11
Temperate 1800–2100	5	4	4	8	11	1200–1400	6	5	5	6	6
Warm temper 2100–2400	6	5	5	3	4	1400–1600	2	7	7	8	8
Warm 2400–2700	0	6	6	6	5	1600–1800	0	0	0	2	3
Very warm 2700–3000	0	0	0	3	5	1800–2000	0	0	0	0	0
Too hot >3000	0	0	0	0	1	>2000	0	0	0	0	0

According to Gladstones’ biological effective degree days index (BEDD), a large part of land in Trentino does not meet the minimum thermal requirement for wine growing (less than 1000 BEDD). However, roughly half of weather stations which are presently in viticultural areas fall in the 1200–1400 BEDD class; a few sites fall in a warmer class, while others fit in the colder classes. The simulated progressive warming reduces the number of the selected sites, currently unsuitable for viticultural use because too cool, to less than half of the initial extent in the ′41–′70 time window (Fig. 3).

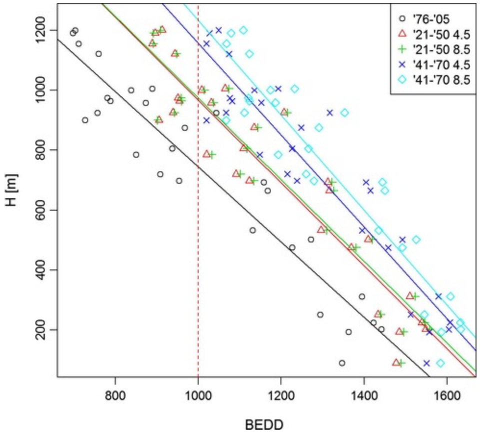

Fig. 3 Correlations between Biologically Effective Degree Days and elevation, according to current and future climatic conditions, based on climate change scenarios. Too cool areas (less than 1000 BEDD) are not considered suitable for viticulture.

The correlation between BEDD and elevation can be considered linear below 1800 m a.s.l. and therefore for each scenario the upper limit for viticulture was assessed using the linear regression’s coefficients (Table 5) and a threshold value of 1000 Biologically Effective Degree Days, which is considered sufficient to fulfil the thermal requirements, needed to complete both the vegetative and reproductive cycle of grapevine.

Table 5 Linear regressions between BEDD and elevation for current and future conditions, based on climate change scenarios. The upper limits for viticulture have been calculated using the regression coefficients (slope and intercept) of each scenario and the lowest value of BEDD (1000). Pearson coefficients and the number of weather stations (nr. of sites) falling into the suitable area are also reported.

Ref. period	1976–2005	2021–2050		2041–2070	
Scenario	Current	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Slope	−0.64	−0.64	−0.65	−0.63	−0.61
Intercept	1478	1640	1654	1736	1760
Pearson	−0.98	−0.98	−0.98	−0.98	−0.98
Upper limit (m a.s.l.)	750	992	1000	1161	1243
Nr. of sites	13	22	22	26	28

Huglin’s index (HI) assesses the main class shifts from “temperate” or “cool” classes to the warmer ones in the farthest period, thanks to the increased suitable area, but with a growing number of cases in the warmer classes and one site even in the “too warm” class.

As far as vegetative season index (GST) is concerned, the “intermediate” class (15–17 °C) remains for all scenarios the most populated in the present viticultural area, but with a trend of a progressive depopulation of the colder classes, and the consequent increase of members in the warmer ones, with a few sites reaching the class “very hot”; the area which is too cool for grapevine undergoes a reduction of the same magnitude as that predicted by BEDD.

Similar results are obtained from the analysis of Winkler’s index (WI), which is highly correlated to GST, being both measures of mean thermal conditions during growing season (see formulation in Appendix 1, Supplementary material). Classes of “Region Ia” are strongly reduced in the ′41–′70 RCP 8.5 scenario. “Region IV”, today not represented in the potentially viticultural areas of the region, begins to be populated by some sites in the ′21–′50 time window, and even the thermal higher class of “Region V”, the last before the class defined as “too hot”, has some sites fitting in.

The analysis of indices of extreme temperature (Table 6) has entailed fixing thresholds to assess the recurrence of undesirable or dangerous events; indeed, no standards were proposed for such indices. The values have been chosen also taking into account their modelled occurrence in the present conditions, and considering their ability in tracking changes in the different time windows and scenarios, as follows.

Table 6 Classification according to OIV bioclimatic indices for extreme temperatures for all stations according to several time windows and scenarios. Table cells contain the number of stations in each class. See Appendix 1, Supplementary material, for index formulations.

Period & RCP scenario	′76–′05	′21–′50		′41–′70	
		4.5	8.5	4.5	8.5
Tn_rest					
Below −15 °C	30	30	16	18	10
Above −15 °C	9	9	23	21	29
Tn_veg					
Below −2 °C	39	37	36	36	36
Above −2 °C	0	2	3	3	3
Tx_veg					
Below 35 °C	34	26	26	21	15
Above 35 °C	5	13	13	18	24

Tn_rest. Grapevine during dormancy can tolerate temperatures as low as −15 °C to −25 °C, according to sources (Düring, 1997; Lisek, 2009). In the viticultural areas of Trentino, the latter temperature was never attained, while some damages could already occur at minimum air temperature of about −15 °C (Zulini et al., 2010). This was the threshold chosen for Tn_rest, calculated as the minimum reached in each 30-year period. The analysis of simulations starts with a large majority of stations where extremely low temperatures occur at least once in 30 years, and the same condition is maintained for ′21–′50 RCP 4.5. The following scenarios show a progressive decrease of the number of stations where extremely low temperatures are attained, and in ′41–′70 RCP 8.5 the ratio of the areas below and above the threshold is almost reversed.

Tn_veg. Given that the “vegetation period” according to the index is set to start from April, a rather early period for sprouting, a temperature of −2 °C, generally accepted as a damage threshold for reproductive buds, was set as a discriminating value for frost episodes during the sensitive period, calculated as the minimum reached in each 30-year period. The trend for this index shows only minor changes along the timeline and the severity of scenarios, with a modest decrease in the number of stations where frost during the vegetative period is still simulated to occur.

Tx_veg. A reasonable threshold for physiological impairment in grapevine is 35 °C (Hunter and Bonnardot, 2011); owing to a frequent attainment of this threshold in full summer, the median of each 30 year maximum values was considered a better indicator for the occurrence of hot summer conditions. As reference temperatures progressively grow as long as scenarios become more severe, the percentage of series where the 35 °C threshold is trespassed rises progressively, becoming the majority in ′41–′70 RCP 8.5, when the viticultural area is mostly expected to fall in this class.

In general, all the selected indices show a strong dependence with elevation, which is maintained in future scenarios with similar features for “mean temperature” indices (BEDD, GST, HI, WI). This relationship is represented in Fig. 3 for BEDD, the index chosen to assess the areal extension.

Tonietto – Carbonneau’s synthetic classification makes use of three indices, as explained in Section 2 (Table 7). One is a slight simplification of Huglin’s index (HI) classification, whose results have already been discussed; according to this classification, in ′41–′70 RCP 8.5 the full range of HI classes are present in Trentino. The second is the “Cool night index”; most of the series still belong to the coolest class, but as the reference scenario gets warmer, an increasing number of sites are expected to fall into a “negative” coolness class (CI −1), highlighting the shift to the macro-category of “warm” viticultural climates for those sites, where night temperature in the proximity of harvest are generally higher than desirable. The Riou’s drought index (DI) shows a progressive appearance of sites where, on average, moderately dry conditions take place in the last month of ripening (September), whereas, at present, moist conditions prevail for all sites.

Table 7 Classification according to Tonietto and Carbonneau's bioclimatic indices for all stations according to several time windows and scenarios. Table cells contain the number of stations in each class. See text for explanations on indices.

Period & RCP scenario	′76–′05	′21–′50		′41–′70		Period & RCP scenario	′76–′05	′21–′50		′41–′70	
		4.5	8.5	4.5	8.5			4.5	8.5	4.5	8.5
CI −2	0	0	0	0	0	HI −3	24	13	13	10	9
CI −1	1	1	3	4	6	HI −2	4	11	11	9	4
CI +1	4	5	4	5	8	HI −1	5	4	4	8	11
CI +2	34	33	32	30	25	HI +1	6	5	5	3	4
						HI +2	0	6	6	9	10
DI −2	24	10	19	14	9	HI +3	0	0	0	0	1
DI −1	15	19	19	20	15						
DI +1	0	10	1	5	15						
DI +2	0	0	0	0	0						

3.4 Simulated changes in the viticultural area

According to the climate change scenarios, the current viticultural area will present higher thermal availability leading to early phenological events (Jones and Davis, 2000), an improvement of grape quality for late-ripening varieties, and early harvest, particularly for sparkling wine production. Moreover, a potential extension of the suitable area for viticulture to higher regions is expected, although the real growth potential should comply with other important constraints (Table 8), such as gentle slope, favourable orientation, large availability of potential daily mean sun-hours (AvgSunHursVeg) and cumulated global solar radiation (CumGloRadVeg) during the vegetative period. Finally, new potential areas should be large and contiguous enough to justify and sustain the costs for vineyard establishment. A minimum surface of 1 ha was set.

Table 8 Criteria applied to spatial queries, to assess the landscape suitability for viticulture, based on current climatic conditions, climate change scenarios (RCP 4.5 and 8.5), and favourable topographic conditions for the establishment of vineyards. AvgSunHursVeg: potential daily mean sun-hours. CumGloRadVeg: cumulated global solar radiation.

Ref. period	Scenario	Elevation (m a.s.l.)	Slope (%)	Aspect (DEG from North = 0 CW)	AvgSunHoursVeg (h)	CumGloRadVeg (kW h m^{-2})
1976–2005	Current	<= 750	<= 15	>= 67.5 AND <= 292.5	>= 10	>= 850
2021–2050	RCP 4.5	>750 AND <= 992				
	RCP 8.5	>992 AND <= 1000				
2041–2070	RCP 4.5	>1000 AND <= 1161				
	RCP 8.5	>1161 AND <= 1243				

According to the current climatic conditions and future climate change scenarios, the suitable areas for viticulture, as a result of the spatial queries (Table 8, Fig. 4), present to date three main land uses: annual and perennial crops (mainly grapevine, apple, berries, horticulture), pastures and meadows, and urban or commercial areas. The percentages of new available soil for each scenario, from the current climatic conditions to the warmest climate change scenario (′41–′70 RCP 8.5) are summarized in Fig. 5.

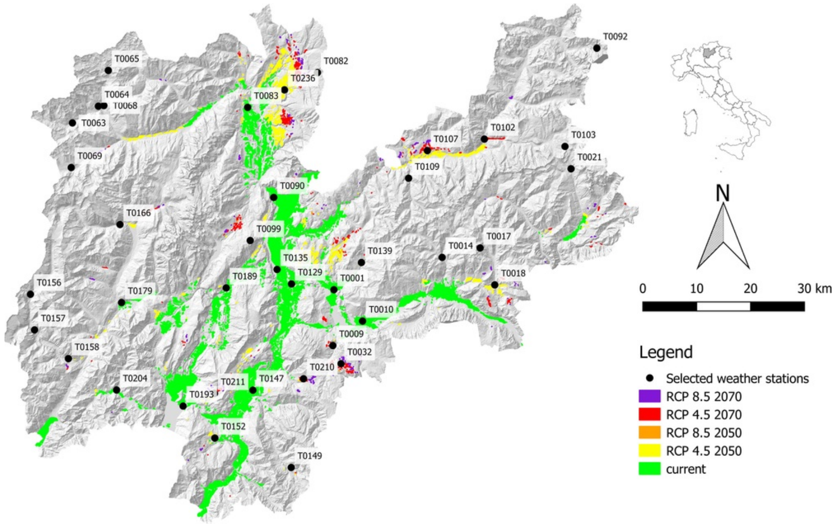

Fig. 4 Results of GIS spatial queries, used to assess the landscape suitability for viticulture in Trentino, according to current climatic conditions and future scenarios.

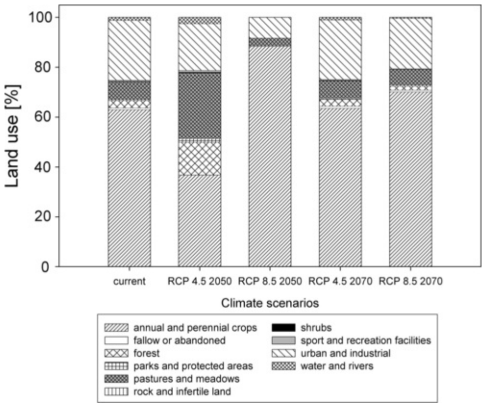

Fig. 5 Classification (%) of new, incremental available soil (with respect to the previous scenario/time), according to the different climatic scenarios and reference periods.

4 Discussion

The climate simulations performed according to RCP 4.5 and RCP 8.5 greenhouse gas concentrations depict a future climate scenario characterized by higher temperature, especially if the RCP 8.5 is considered, and a general reduction of precipitation and increase in the number (Please insert "of")consecutive dry days. Future climate scenarios considered in this study were obtained by a single Regional Climate Model (COSMO-CLM). In order to assess uncertainty, as suggested by IPCC, the reliability of projections might be improved by multi-model ensembles, weighting single elements with model skill measures. However, the huge computational costs required to perform high-resolution simulations with model ensembles represent a limit, leaving this solution to future works. Indeed, COSMO-CLM results have been proved to be consistent with the 'state-of-the-art' of regional climate simulations (Bucchignani et al., 2015; Zollo et al., 2015a).

The wide variety of climates considered in this study, from the 90 m lower valley bottom to high-mountain sites, covers the full range of present and future possible viticultural areas.

In general, the expected effects of warmer and drier conditions would lead to better ripening and sanitary status of the grapes of red varieties, increasing their quality rating (Grifoni et al., 2006), and to earlier harvest of white varieties, particularly for sparkling wine production, and a possible enlargement of the viticulture area to higher elevation. Only a few white grapevine varieties grown in the region, such as Müller

Thurgau, are particularly affected by warm conditions and new planting are recommended right now in the cooler areas (above 450 m a.s.l.), to fulfil optimal ripening; such varieties are less resilient and are going to face some limitations in the lower areas, where temperature is expected to attain too high values.

Beside a probable general improvement of the growing conditions for grapevine, as a whole, the typical thermal regimes of the areas which are presently occupied by vineyards are expected to shift towards different bioclimatic classifications, but only partially is this feature going to affect the choice of the grapevine varieties, thanks to their general resilience to warmer conditions.

Extreme warm and dry conditions are likely to occur more often in the future, leading to a higher number of undesirable events; however, in Trentino most vineyards are nowadays equipped with irrigation plants, important to confront the occurrence of drought events. The expected higher frequency of dry condition(conditions), however, should be taken into account if the results of this study are extended to similar areas, lacking such facilities, or where irrigation is not envisaged in the production protocol.

An assessment of the expected, plausible expansion of viticultural areas should also consider the current land use and exclude unsuitable soil (i.e. urban and industrial areas, parks and protected areas, touristic places) from calculation. Pastures and meadows represent the most affordable areas for an enlargement of viticulture in a warmer climatic scenario. In fact, it is unlikely that perennial crops (i.e. in the apple producing area of Non Valley) and high quality productions (horticulture, berries) will be replaced due to climate change, if not driven by a decrease of production and quality; in such conditions, changes in profit due to the market rules could indeed become the drivers of possible changes in both grape variety and crop.

No restriction of viticultural areas is predicted to take place at the lower valley bottom, even if the change is likely to suggest – at least in the strongest hypothesis of thermal increase – to consider the convenience of a varietal change.

5 Conclusions

In this study a high-resolution modelling chain was applied to an Alpine area to assess the change in climatic and bioclimatic indices, with particular reference to the viticultural area. The results come from the application of functions from an open-source R library (ClimClass) to the output of a Regional Climate Model (COSMO-CLM). While some changes are already observable (Eccel et al., 2015), the shift expected for the future can be quantitatively assessed by the use of climatic classifications and indices, specifically created for viticultural purposes. The implementation of these indices in an open-source library may enhance their use as “standards”; moreover, the R library ClimClass supplies useful tools for pre-processing climatic series, facilitating their preparation and analysis in view of the assessment of climatic and bio-climatic indices.

A general increase in the occurrence of warmer and – with a lesser extent – drier seasons is predicted for every time window (2021–2050 and 2041–2070) and reference scenario (RCP 4.5 and RCP 8.5); of course, the change is more pronounced in the farthest period and for the scenario envisaging a continuous increase in GHG emission (RCP 8.5).

Indices reflect the effect of this driver: viticulture could benefit from the expected effects of climate change, which include higher air temperature and drier conditions, with better ripening and sanitary status of the grapes, and spreading to new suitable areas, but at the expense of annual and perennial crops or meadows and pastures, which are part of the rural mountain landscape. All these important degrees of freedom in the vocational choice of agricultural areas, together with others arising either from agricultural policy or from the economical aspects of wine market and farm management, will probably play the major role in the determination of the real wine-growing areas. Nevertheless, for the first time after the end of the “Little Ice Age” period, at about the half of 19th century, there are now some premises for witnessing a return of climate as a co-driver in the choice of crops.

6 Uncited reference

Michalet (1991).

Acknowledgments

Work co-funded by Climate Change Funds of Provincia Autonoma di Trento, 2013, project IndiClima, and by SEE Transnational Cooperation Programme of EU, 2012, project OrientGate. Thanks to Meteotrentino and the CTT-SIG unit of Fond. Mach for data supply.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compag.2016.05.019.

References

Anderson J.D., Jones G.V., Tait A., Hall A. and Trought M.C.T., Analysis of viticulture region climate structure and suitability in New Zealand, *J. Int. Des Sci. De La Vigne Et Du Vin* **46** (3), 2012, 149–165.

Bindi M., Fibbi L., Gozzini B., Orlandini S. and Miglietta F., Modeling the impact of future climate scenarios on yield and yield variability of grapevine, *Clim. Res.* **7**, 1996, 213–224.

Bucchignani E., Montesarchio M., Zollo A.L. and Mercogliano P., High resolution climate simulations with COSMO-CLM over Italy: performance evaluation and climate projections for the 21st century, *Int. J. Climatol.* 2015, http://dx.doi.org/10.1002/joc.4379.

Caffarra A. and Eccel E., Projecting the impacts of climate change on the phenology of grapevine in a mountain area, *Aust. J. Grape Wine Res.* **17** (1), 2011, 52–61.

Dalu J.D., Baldi M., Dalla Marta A., Orlandini S., Maracchi G., Dalu G., Grifoni D. and Mancini M., Mediterranean climate patterns and wine quality in North and Central Italy, *Int. J. Biometeorol.* **57**, 2013, 729–742, http://dx.doi.org/10.1007/s00484-012-0600-4.

Dunn M.R., Lindesay J.A. and Howden M., Spatial and temporal scales of future climate information for climate change adaptation in viticulture: a case study of User needs in the Australian winegrape sector, *Aust. J. Grape Wine Res.* **21**, 2015, 226–239.

Eccel, E., Cordano, E., Zottele, F., Toller, G.B., 2015. ClimClass and ClimClassMap: two R-packages for climatic and agro-bioclimatic indices. An application to Trentino. XVIII Convegno Nazionale di Agrometeorologia, 9–11 giugno 2015, San Michele all'Adige (TN), Book of Extended Abstract.

Fraga H., Santos J.A., Moutinho-Pereira J., Carlos C., Silvestre J., Eiras-Dias J., Mota T. and Maleiro A.C., Statistical modelling of grapevine phenology in Portuguese wine regions: observed trends and climate change projections, *J. Agric. Sci.* **1-17**, 2015, http://dx.doi.org/10.1017/S0021859615000933.

Fraga H., Santos J.A., Malheiro A.C., Oliveira A.A., Moutinho-Pereira J. and Jones G.V., Climatic suitability of Portuguese grapevine varieties and climate change adaptation, *Int. J. Climatol.* **36**, 2016, 1–12, http://dx.doi.org/10.1002/joc.4325.

Giorgi F., Jones C. and Asrar G.R., Addressing climate information needs at the regional level: the CORDEX framework, *WMO Bull.* **58** (3), 2009, 175–183.

Grifoni D., Mancini M., Maracchi G., Orlandini S. and Zipoli G., Analysis of Italian wine quality using freely available meteorological information, *Am. J. Enol. Viticult.* **57**, 2006, 339–346.

Hall A. and Jones G.V., Effect of potential atmospheric warming on temperature based indices describing Australian winegrape growing conditions, *Aust. J. Grape Wine Res.* **15** (2), 2009, 97–119.

Hunter J.J. and Bonnardot V., Suitability of some climatic parameters for grapevine cultivation in South Africa, with focus on key physiological processes, *S. Afr. J. Enol. Viticult.* **32** (1), 2011, 137–154.

Jones G.V., Climate and terroir: impacts of climate variability and change on wine, In: Macqueen R.W. and Meinert L.D., (Eds.), *Fine Wine and Terroir – The Geoscience Perspective. Geoscience Canada,* 2006, Geological Association of Canada; Newfoundland, Canada.

Jones G.V. and Davis R.E., Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France, *Am. J. Viticult. Enol.* **51** (3), 2000, 249–261.

Jones G.V., White M.A., Cooper O.R. and Storchmann K., Climate change and global wine quality, *Clim. Change* **73** (3), 2005, 319–343.

Koufos G., Mavromatis T., Koundouras S., Fyllas N.M. and Jones G., Viticulture–climate relationships in Greece: the impacts of recent climate trends on harvest date variation, *Int. J. Climatol.* **34**, 2014, 1445–1459.

Michalet R., 1991 Une approche synthétique biopédoclimatique des montagnes méditerranéennes: exemple du Maroc septentrional, 1991, Doctorat université Joseph Fourier; Grenoble I, 273.

Molitor D., Caffarra A., Sinigoj P., Pertot I., Hoffmann L. and Junk J., Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region, *Aust. J. Grape Wine Res.* **20** (1), 2014, 160–168.

Moriondo M., Bindi M., Fagarazzi C., Ferrise R. and Trombi G., Framework for high-resolution climate change impact assessment on grapevines at a regional scale, *Reg. Environ. Change* **11** (3), 2011, 553–567.

Mullins M.G., Bouquet A. and Williams L.E., Biology of the Grapevine, 1992, Cambridge University Press; Great Britain, 239.

OIV, 2012. OIV Guidelines for Vitiviniculture Zoning Methodologies on a Soil and Climate Level. Resolution OIV-VITI 423-2012 REV1. Adopted by the 10th General Assembly of the OIV. June 2012, Izmir, Turkey. Available at: <http://www.oiv.int/oiv/info/enresolution2012?lang=en>.

Rockel B., Will A. and Hense A., The regional climate model COSMO-CLM (CCLM), *Meteorol. Z.* **17**, 2008, 347–348, http://dx.doi.org/10.1127/0941-2948/2008/0309.

Scoccimarro E., Gualdi S., Bellucci A., Sanna A., Fogli P.G., Manzini E., Vichi M., Oddo P. and Navarra A., Effects of tropical cyclones on ocean heat transport in a high resolution coupled general circulation model, *J. Clim.* **24**, 2011, 4368–4384, http://dx.doi.org/10.1175/2011JCLI4104.1.

Tomasi D., Jones G.V., Giust M., Lovat L. and Gaiotti F., Grapevine phenology and climate change: relationships and trends in the Veneto region of Italy for 1964–2009, *Am. J. Enol. Viticult.* **62** (3), 2011, 329–339.

Tonietto J. and Carbonneau A., A multicriteria climatic classification system for grape-growing regions worldwide, *Agric. For. Meteorol.* **124** (1–2), 2004, 81–97.

Trewartha G.T. and Lyle H.H., An Introduction to Climate, sixth ed., 1980, MacGraw-Hill, (Appendix: Koeppen’s Classification of Climates).

Webb L.B., Whetton P.H. and Barlow E.W.R., Modelled impact of future climate change on the phenology of wine grapes in Australia, *Aust. J. Grape Wine Res.* **13**, 2008, 165–175, http://dx.doi.org/10.3354/ cr00739.

White M.A., Diffenbaugh N.S., Jones G.V., Pal J.S. and Giorgi F., Extreme heat reduces and shifts United States premium wine production in the 21st century, *Proc. Natl. Acad. Sci. USA* **103** (30), 2006, 11217–11222.

Zollo A.L., Rillo V., Bucchignani E., Montesarchio M. and Mercogliano P., Temperature and precipitation extreme events over Italy: assessment of high resolution simulations with COSMO-CLM and future scenarios, *Int. J. Climatol.* 2015a, http://dx.doi.org/10.1002/joc.4401.

Zollo A.L., Turco M. and Mercogliano P., Assessment of hybrid downscaling techniques for precipitation over the Po river basin, *Eng. Geol. Soc. Territory* **1**, 2015b, 193–197.

Zulini L., Fischer C. and Bertamini M., Chlorophyll fluorescence as a tool for evaluation of viability in freeze-stressed grapevine buds, *Photosynthetica* **48** (2), 2010, 317–319.

Appendix A. Supplementary material

Multimedia Component 1

Supplementary data 1

Highlights

- A warming climate can lead to new climatic conditions in viticultural areas.
- The change can be assessed by applying bioclimatic indices to climate model output.
- Climate indices were calculated by a dedicated open-source R library.
- A spread of wine-growing areas to the mountain can be quantified.
- Higher temperature generally increases opportunities in cool viticulture climates.

Queries and Answers

Query: Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact s.sekar@elsevier.com immediately prior to returning your corrections.
Answer: OK

Query: The author names have been tagged as given names and surnames (surnames are highlighted in teal color). Please confirm if they have been identified correctly.

Answer: Yes.

Query: Please check the edits made in the affiliations, and correct if necessary.
Answer: Yes

Query: The country name has been inserted for the affiliations ‘b’ and ‘c’. Please check, and correct if necessary.
Answer: Yes

Query: The citation ‘Hall and Jones (2008)’ has been changed to match the year in the reference list. Please check, and correct if necessary.
Answer: Yes

Query: References ‘Duchêne and Schneider (2005)’, ‘Düring (1997), and Lisek (2009)’ are cited in the text but not provided in the reference list. Please provide them in the reference list or delete these citations from the text.
Answer: Duchêne E., Schneider, C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. Agron Sustain Dev 25, 93-99. doi:10.1051/agro:2004057

Düring, H., 1997. Potential frost resistance of grape: Kinetics of temperature-induced hardening of Riesling and Silvaner buds. Vitis. 36(4), 213-214

Lisek, J., 2009. Frost damage of buds on one-year-old shoots of wine and table grapevine cultivars in Central Poland following the winter of 2008/2009. Journal of Fruit and Ornamental Plant Research. 17(2), 149-161.

Query: This section comprises references that occur in the reference list but not in the body of the text. Please position each reference in the text or, alternatively, delete it. Any reference not dealt with will be retained in this section.
Answer: Please delete.