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ORIGINAL PAPER

Climate change trends, grape production, and potential alcohol concentration in wine from the "Romagna Sangiovese" appellation area (Italy)

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Abstract The trend of climate change and its effect on grape production and wine composition was evaluated using a real case study of seven wineries located in the "Romagna Sangiovese" appellation area (northern Italy), one of the most important wine producing region of Italy. This preliminary study focused on three key aspects: (i) Assessment of climate change trends by calculating bioclimatic indices over the last 61 years (from 1953 to 2013) in the Romagna Sangiovese area: significant increasing trends were found for the maximum, mean, and minimum daily temperatures, while a decreasing trend was found for precipitation during the growing season period (April–October). Mean growing season temperature was 18.49 °C, considered as warm days in the Romagna Sangiovese area and optimal for vegetative growth of Sangiovese, while nights during the ripening months were cold (13.66 °C). The rise of temperature shifted studied area from the temperate/warm temperate to the warm temperate-/warm grape-growing region (according to the Huglin classification). (ii) Relation between the potential alcohol content from seven wineries and the climate change from 2001 to 2012: dry spell index (DSI) and Huglin index (HI) suggested a large contribution to increasing level of potential alcohol in Sangiovese wines, whereas DSI showed higher correlation with potential alcohol respect to the HI. (iii) Relation between grape production and the climate change from 1982 to 2012: a significant increasing trend was found with little effect of the climate change trends estimated with used bioclimatic indices. Practical implication at viticultural and oenological levels is discussed.

1 Introduction

Grape production is strongly affected by climate conditions (Jackson and Lombard 1993; Schultz 2000; van Leeuwen et al. 2004; Keller 2010; Fraga et al. 2014a); therefore, climate change can modify grape and wine composition to a great extent. Vine sensitivity to weather properties (Jones et al. 2005b; Gladstones 2011; Holland and Smit 2014), narrow spatial surfaces suitable for producing high-quality grapes as wine industry raw material, and possibility of perennial plant exploitation (Battaglini et al. 2009; Lereboullet et al. 2014) are indicative of the need for a climate change assessment associated with winemaking. Despite the importance of the global climate change trend, from the vine grower/winemaker perspective, it is more essential to understand regional atmospheric conditions (Jones et al. 2005b; Orlandini et al. 2009) and local microclimatic environment as well. Generally, increasing average global temperature over the last few decades is more than evident, as is the increasing temperature trend, although is not homogenous in every vine-growing region (Pielke et al. 2002; Jones et al. 2005b; van Leeuwen et al. 2013). For example, Jones et al. (2005b) confirmed a significant growing season temperature trend for the majority of northern hemisphere wine-producing regions between 1950 and 1999, with an average increase of 1.26 °C. However, there was also an insignificant trend in the majority of southern

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hemisphere wine regions, which emphasizes the necessity to focus study on smaller study areas.

Since climate modifications are vastly complex, examinations of simple temperature and precipitation values are insufficient to explain climate change trends. Therefore, several bioclimatic indices (e.g., Huglin index (HI) (Huglin 1978), Cool night index (CI) (Tonietto 1999), Winkler (WI) or growing degree day (GDD) index (Winkler et al. 1974), number of days with maximum temperatures higher than 30 °C (ND > 30 °C) (Ramos et al. 2008), number of days with precipitations <1 mm (Dry spell index, DSI) (Moisselin and Dubuisson 2006), etc.) are commonly used in viticulture to provide a better insight into climate change trends. However, the selected bioclimatic indices were mainly based only on air temperature, as it has the strongest influence on overall growth, productivity, and berry ripening of the grapevine (Jones 2012).

Jones et al. (2010) showed that climate change is responsible for over 50 % of alcohol trends. Moderate water stress may positively affect berry sugar accumulation during grape-growing season (Coombe 1989), while increasing temperature advances phenological stages and speeds up sugar accumulation in grape berries (Duchêne and Schneider 2005; Barbeau 2007; Jones 2012; Bonnefoy et al. 2013). Both water stress and increasing temperature later lead to the production of wines with higher alcohol content and other microbiological, technological, sensorial, and financial implications (Mira de Orduña 2010). In particular, increase of grape sugar content at harvest may cause slow/stuck alcoholic fermentations during hot years (Coulter et al. 2008) as well as alter sensory features due to the ethanol's tendency to increase bitterness perception (Fischer and Noble 1994; Vidal et al. 2004; Sokolowsky and Fischer 2012), suppress the perception of sourness (Williams 1972), and reduce astringency perception (Williams 1972; Vidal et al. 2004). Excess of alcohol in wine is also not desirable due to harmful effects on the health of consumers and civil restrictions (Catarino and Mendes 2011). Moreover, in the USA, winemakers need to pay additional taxes if the wine contains more than 14.5 % *v*/*v* of alcohol, whereas in EU, the alcohol limit for table wine is 15.0 % *v*/*v*. Recently, consumers showed a preference for wines with lower alcohol content (between 9 and 13 % *v*/*v*) (Massot et al. 2008).

Italy is one of the top wine producers in the world and its export represents the main income for the entire agro-food sector. Although the importance of climate change is well recognized by scientists worldwide, there is a need to improve its awareness among private companies as well.

In this view, the present study aims to establish a relationship between grape sugar content, presented as potential alcohol content in Sangiovese wines, and climate change trends based on selected bioclimatic indices of the specific area of interest (Fig. 1). Moreover, the study evaluated the trend of grape production for the same area and its correlation with climate variables. It has to be noted that the examination of climatic trends and their influence on grape production and wine potential alcohol level in the "Romagna Sangiovese appellation area" was based on meteorological factors alone (e.g., temperature and precipitations). The effect of other possibly relevant factors, such as soil characteristic, effects of elevated atmospheric carbon dioxide concentration, influence of market decisions on alcohol level in wines, husbandry practices, etc., was not considered.

The study was done in collaboration with grape growers and local winery partners of the Caviro Coop (Faenza, RA, Italy), thus rendering the obtained results a valuable case study on the topic.

2 Materials and methods

2.1 Study region, potential alcohol concentration, and grape production data

The Emilia-Romagna (ER) is located in the north of Italy and accounts for about 55,000 ha of vineyards which represent 8.1% of the total Italian vineyard surface and is the second wine-producing region with 18 % of the total Italian wine production by volume. The ER include nine provinces, two of which are located within the "Romagna Sangiovese" appellation area, namely Ravenna and Forlì-Cesena, that account for 16,000 and 7000 ha of vineyard, respectively, thus representing 42 % of the total ER grape cultivated area for all varieties. The Sangiovese (main red grape variety cultivated in Italy) wine production, in the two provinces of Ravenna (1700 ha) and Forli-Cesena (3300 ha) represents ca. 72 % of the entire Emilia-Romagna region. The studied area covers more than 97 % of the Romagna Sangiovese appellation area which is mostly located between 100 and 300 m above sea level and covering an approximate area from 44° 00′ to 44° 50′ N latitude and from 11° 50′ to 12° 50′ E longitude (Fig. 1).

Potential alcohol content of Sangiovese wines was calculated (Eq. 1) from sugar content in grapes that were harvested from seven commercial wineries in the studied area for the period from 2001 to 2012. Grape sugar content was measured directly in the field, day before harvest, using a portable digital refractometer. This approach is commonly used in enology to estimate the "natural" alcohol content of wine without any contribution due to the enrichment practices, if any (i.e., grape sugar additions during fermentation).

Equation 1 Bx, sugar content in grapes expressed as Brix degrees.

$$\text{Potential alcohol}\left[\%v/v\right] = \text{Bx} \times 0.6$$

Similarly to the potential alcohol content, the amount of grapes produced per year, produced on consistent vineyard

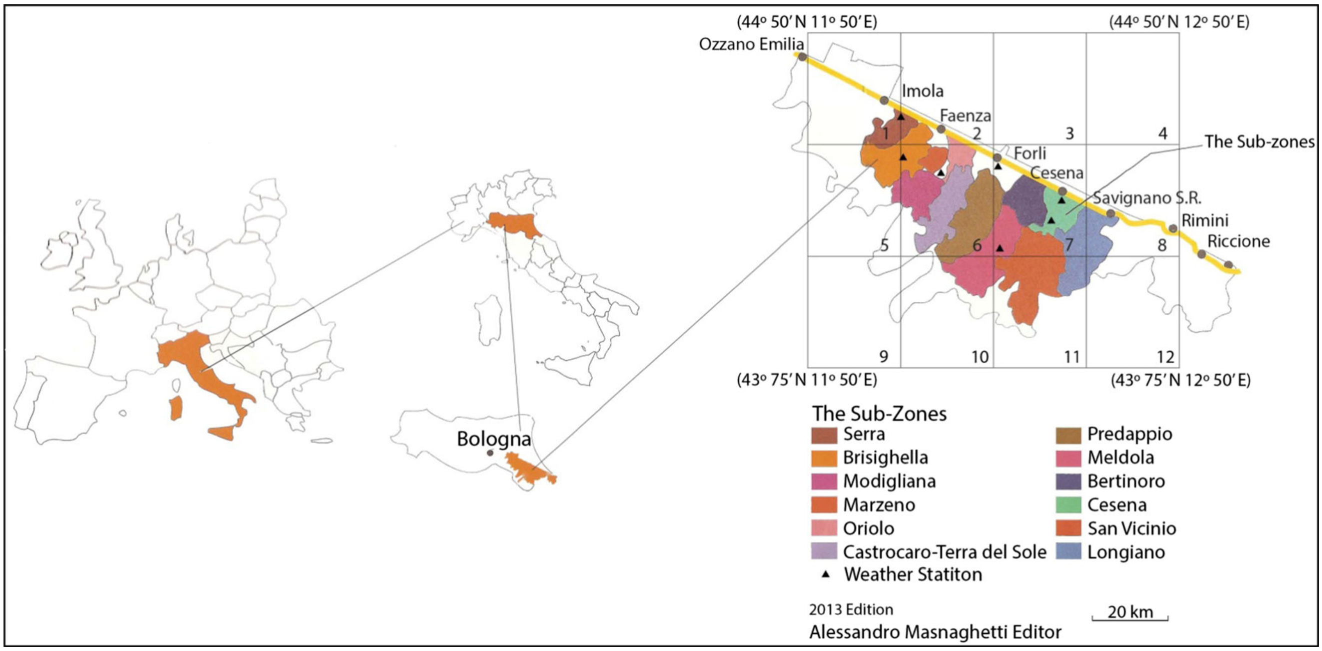

Fig. 1 Location of the Romagna Sangiovese appellation area (Italy)

surface, was obtained from the same wineries from 1982 to 2012. The dataset was averaged for every year between wineries for naturally occurring alcohol content and quantity of produced grapes.

2.2 Meteorological data and bioclimatic indices

Bioclimatic indices (BI) were computed with daily high-resolution observations of maximum, mean, and minimum temperatures and precipitation from the ENSEMBLES gridded observation dataset (E-OBS 0.25° Regular grid, version 11.0). Interpolated/gridded datasets were used for the period 1953–2013 from six grid cells which covered more than 97 % of the total vineyards in the studied area (Fig. 1; Fig. S1). Three grid cells in the bottom row (10, 11, and 12) were excluded due to the small percentage of vineyards in that area. Datasets produced by the ENSEMBLES project are used in several recent publications (Santos et al. 2012; Andrade et al. 2014; Fraga et al. 2014a, b; Männik et al. 2015; Konca-Kedzierska 2015), and further details about E-OBS dataset are described by Haylock et al. (2008).

For validation purposes, all bioclimatic indices used in the study were computed also with consistent data from seven weather stations (www.arpa.emr.it) for a short-term period (2005–2013). Locations of the weather stations are listed in Table S1.

The following bioclimatic indices were calculated (Table S2):

1. Growing season maximum ($T_{\max}$), mean (T_{mean}), and minimum temperature ($T_{\min}$) (April–October for the northern hemisphere).
2. Number of days with a maximum temperature in the range of 25–30 °C (ND 25–30 °C) over the growing season period.
3. Number of days with a maximum temperature >30 °C (ND > 30 °C) over the growing season period.
4. Winkler thermal index (WI) or Growing degree day (GDD) index was calculated during the grape-growing season by using daily minimum and maximum temperatures. Only days with a thermal base value above 10 °C were taken into account due to the minimal grapevine physiological activity threshold (Winkler et al. 1974). However, the GDD index does not take into account adjustment of increasing daylight duration with higher latitudes.
5. Heliothermal index or Huglin index (HI) is a thermal index that takes into account daily mean and maximum temperatures during the period April–September. HI gives more weights to maximum daily temperatures with respect to WI and displays improved fitting of potential sugar content of the grape; a correction factor ($k = 1.04$) was applied to the area of study to account the increasing length of the daylight towards higher latitudes (Huglin 1978; Tonietto and Carbonneau 2004).
6. Cool night index (CI) is an average value of minimum temperatures during September. CI is related to the grape's synthesis of anthocyanins (Tonietto and Carbonneau 2004), compounds responsible for the red

color of the wine that needs improvement in Sangiovese wines.

7. Diurnal temperature range (DTR) was calculated as a mean variation between daily minimum and maximum temperatures in the period from August to September (ripening months) (Ramos et al. 2008).
8. Total precipitation (T_{prec}) over the grape-growing season (April–October).
9. Dry spell index (DSI) presents the number of days with <1 mm of precipitation during the grape-growing season (Moisselin and Dubuisson 2006).
10. Selianinov index (SI) or Hydrothermal coefficient (HTC) was calculated from daily mean temperature and daily precipitation (Fregoni 2005; Selianinov 1928). Only days above 10 °C were considered. SI was used to examine hydric regimes and water supply of the vines in the studied area.

2.3 Statistical analysis

Basic descriptive statistics (i.e., mean value and standard deviation) for BI, potential alcohol level, and grape production data were calculated. Trend analysis based on the Mann-Kendal (MK) test (Mann 1945; Kendall and Stuart 1967), the most commonly used non-parametric test for detecting existing trends in meteorological, agrometeorological, and hydrological time series data (Ramos et al. 2008; Bardin-Camparotto et al. 2014), was computed with modification (Hamed and Ramachra Rao 1998) to avoid overfitting due to the auto-correlated data (Von Storch and Navarra 1995).

Relationship among BI, potential alcohol content, and grape production was examined using a multiple linear regression approach. To avoid mutual co-linearity, the number of bioclimatic indices was reduced using backward removal method until remaining indices did not satisfy criteria of tolerance value >0.2 and VIF value <4 (Neethling et al. 2012). The determination coefficient "adjusted R^2"was used as indicator of the ability of variables to explain the model (Draper and Smith 1981).

Homogeneity of data and breaking points were computed using non-parametric Pettitt test (PT) (Pettitt 1979). All statistical tests were performed at the 95 % confidence level, unless otherwise specified.

3 Results and discussions

3.1 Bioclimatic indices

BI calculated with both E-OBS and weather stations data showed a good linear correlation (>0.9); thus, the E-OBS data were suitable to use for selected area. Slightly hotter and drier conditions of BI calculated with data from weather stations can be explained by predominant locations at lower elevations of weather stations than in E-OBS, especially in grid cell 5, which is mainly mountain area (data not shown).

Growing season T_{max}, T_{mean}, and T_{min} disclosed significant trends over the selected period with increase of 0.04, 0.03 and 0.02 °C/year, respectively, with total trends estimated as 2.20, 1.65, and 1.40 °C from 1953 to 2013 (Table 1; Fig. 2a).

As the T_{mean} value suitable for production of high-quality wines ranges from 12 to 22 °C (Jones 2006), the T_{mean} value of 18.49 °C (for the period 1953–2013) found in this study showed that the studied area was characterized by warm mean growing season temperature and had optimum temperature conditions for the growth of Sangiovese (16.9–19.2 °C (Jones 2006)). The result of increasing T_{mean} is more driven by T_{max} than T_{min} and similar results are found in other grape-growing regions in Europe (Ramos et al. 2008; Neethling et al. 2012; Malheiro et al. 2013; Vršič et al. 2014). The ongoing T_{mean} increasing trend, if persistent, is commonly considered a long-term risk factor by some authors (Hannah et al. 2013). However, its effects will depend to great extent on adaptation by growers, including vineyard management and the use of grape varieties adapted to warmer conditions (van Leeuwen et al. 2013).

Breaking point of T_{mean} detected in 1989 (Fig. 2b) can be explained by abrupt anomalies starting from the beginning of the 1970s reaching maximum anomalies during the 1980s in the large-scale circulation patterns (Westerlies regimes) which characterize the North Atlantic/European sector (Werner et al. 2000; Mariani et al. 2012).

ND 25–30 °C showed a slightly significant negative trend, while ND > 30 °C had a significant positive trend (Table 1) with a total increasing trend of 32.33 days exceeding >30 °C. Critical breaking points occurred in 1984 for ND > 30 °C, whereas the ND 25–30 °C was not significant for the Pettitt test (data not shown). Days with daily maximum temperatures ranging between 25 and 30 °C are critical for plant growth due to the optimum photosynthesis processes. Although several days with maximum temperature reaching over 30 °C may be beneficial during ripening (Jones and Davis 2000), too many days with temperature >30 °C may stress the plant photosynthesis (Mullins et al. 1992), while temperature >35 °C represent upper photosynthesis limits causing total inhibition of the process (Gladstones 1992; Jackson 2008).

Similarly, the two thermal indices often used to examine the suitability of selected area for grape production, HI, and GDD, showed a significant increasing trend with 5.88 and 6.1 units per year and a total trend of 358.62 and 371.98 units during the studied period, respectively (Table 1). According to the Huglin classification, approximately in the 1980s, due to the increasing temperatures in the ER, HI trend shifted studied area from the temperate/warm temperate to the warm temperate-/warm grape-growing region (Fig. 3a). In the same period,

Table 1 Descriptive statistics, MK test, and PT applied to bioclimatic data for the period 1953-2013

Index	Mean	Std. dev.	MK *p* level	MK trend year^{-1}	MK total trend	PT *p*-level	PT breaking point
T_{max}	23.65	1.01	<0.0001	0.04	2.20	<0.0001	1984
T_{mean}	18.49	0.78	<0.0001	0.03	1.65	<0.0001	1989
T_{min}	12.09	0.69	<0.0001	0.02	1.40	<0.0001	1984
ND 25–30 °C	63.45	9.32	0.096*	−0.11	−6.71	0.266	NS
ND > 30 °C	30.57	14.69	<0.0001	0.53	32.33	<0.0001	1984
GDD	1794.89	171.97	<0.0001	6.1	371.98	<0.0001	1984
HI	2258.37	178.32	<0.0001	5.88	358.62	<0.0001	1989
CI	13.66	1.21	0.605	NS	NS	0.648	NS
DTR	11.35	0.81	0.023	0.01	0.79	0.049	1984
T_{prec}	463.88	121.39	0.043	−1.94	−118.16	0.098*	1996
DSI	161.48	8.97	0.026	0.15	9.33	0.055*	1996
SI	2.02	0.66	0.027	−0.01	−0.73	0.07*	1981

NS no significant trend

*90 % significant trend

according to the Winkler classification, GDD regression trend shifted from regions II/III to III/IV (Fig. 3b). The Pettitt test breaking points occurred in 1989 and 1984 for HI and GDD, respectively (data not shown).

The CI showed a lack of significant trend (Table 1) and lack of critical breaking point (data not shown) due to the slow increase of minimum temperatures particularly during the grape-ripening months. Mean value of CI was 13.66 °C, therefore, the Romagna Sangiovese appellation area was mostly characterized by cold nights (data not shown). Night temperatures are correlated with secondary metabolites (e.g., anthocyanins) of red grape varieties, whereat higher night

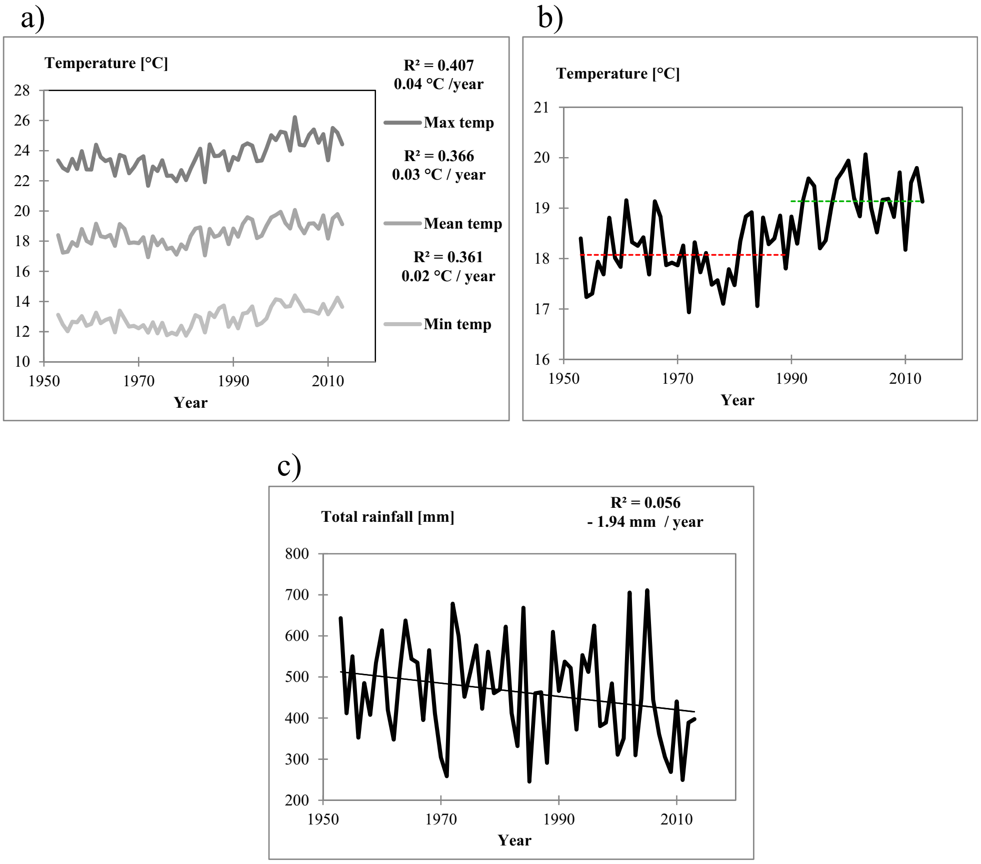

Fig. 2 **a** Linear trends of T_{max}, T_{mean}, T_{min}; **b** Pettitt homogeneity test: T_{mean}; **c** linear trend of T_{prec}; in the Romagna Sangiovese appellation area during the growing period from 1953 to 2013

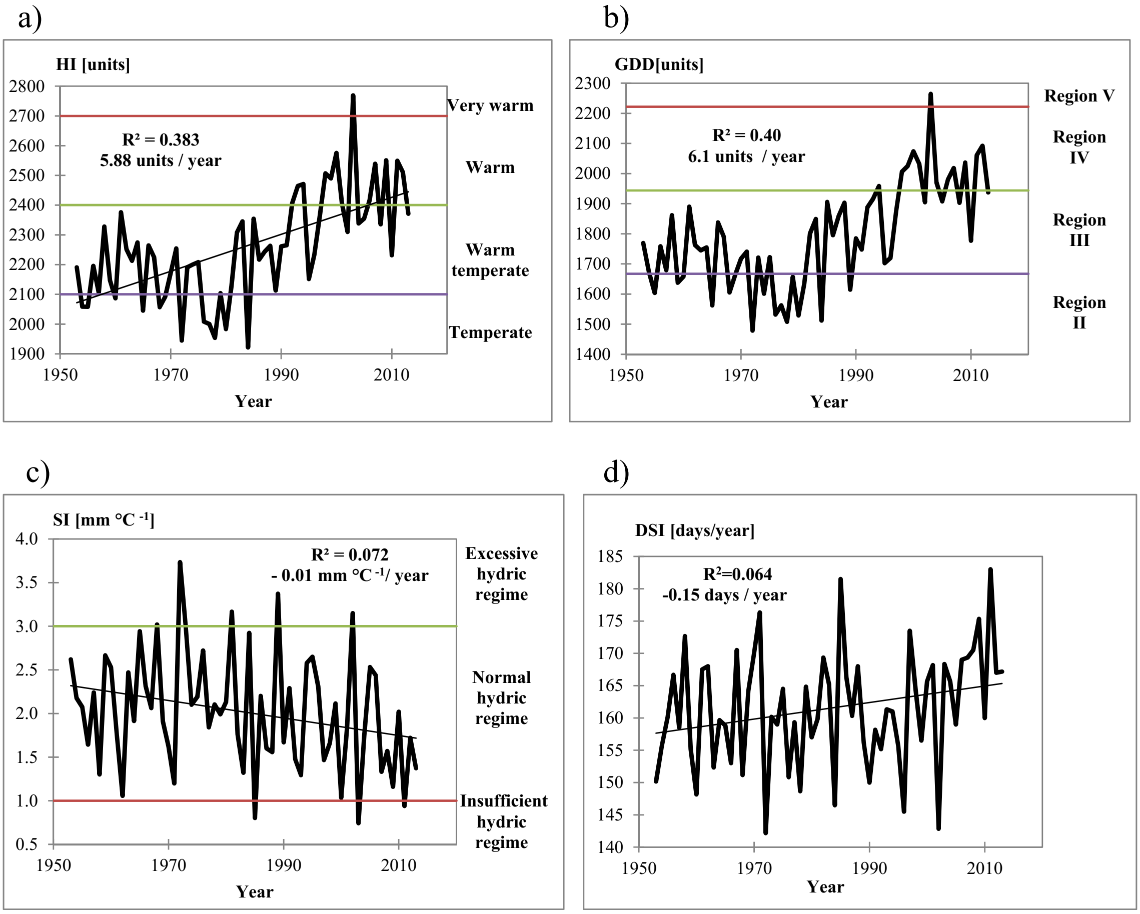

Fig. 3 Linear trends of **a** HI; **b** GDD; **c** SI; **d** DSI in the Romagna Sangiovese appellation area (Italy) during the period from 1953 to 2013

temperatures are causing higher loss of color and aroma (Jackson 2008).

DTR showed a significant positive trend with an increase of 0.01 °C/year and a total trend of 0.79 °C (Table 1) that is mostly related to the maximum temperature increase over the grape-ripening period (August–September). Although thermal amplitude between the maximum and minimum temperatures greatly affects berry composition, including its positive correlation with the synthesis of anthocyanins, an excess in diurnal temperature range negatively affects grape quality due to the plant stress with higher temperatures (Ramos et al. 2008). The Pettitt breaking point occurred in 1984 (data not shown).

Although many European vine-growing regions do not have significant precipitation trends (Ramos et al. 2008; Neethling et al. 2012) in this study, a significant negative trend was detected for precipitation, with a 1.94 mm/year and a 118.16 mm total trend decrease with high annual variations over growing season period (Table 1; Fig. 2c). These findings are consistent with other authors, focused on Italy (Brunetti et al. 2000) and on Italian region Emila-Romagna (Antolini et al. 2016). Additionally, the positive DSI trend with 0.15 days/year and 9.33 days in total revealed possible longer drought periods over the growing season in the future (Table 1; Fig. 3d). The breaking point for both total precipitation and DSI occurred in 1996 due to the mentioned abrupt anomalies in the large-scale circulation patterns (data not shown).

The SI value showed a significant negative trend with high variation before the 2000s and minor amplitude in the past 10 years (2004–2013) (Fig. 3c). The total negative trend of

Table 2 Descriptive statistics, MK test, and PT test applied to potential alcohol concentration in wine (2001–2012) and grape production (1982–2012) in the Romagna Sangiovese appellation area (Italy)

	Mean	Std. dev.	MK *p* level	MK trend year^{-1}	MK total trend	PT *p* level	PT breaking point
Potential alcohol [% *v*/*v*]	10.30	0.5	0.04	0.07	0.83	0.017	2006
Grape production [*t*]	2216.47	486.59	<0.01	33.49	1038.07	0.003	1997

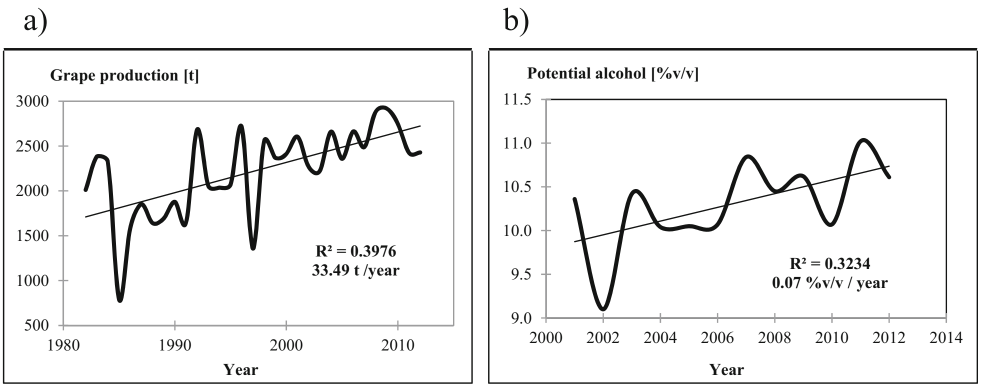

Fig. 4 Linear trends of **a** grape production (1982–2012) and **b** potential alcohol content in wines (2001–2012) in the Romagna Sangiovese appellation area (Italy)

the SI was 0.73 mm °C^{-1}, while the annual decrease was 0.01 mm °C^{-1} (Table 1). The mean value of SI during the studied period was 2.02 mm °C^{-1}, a value actually considered as a normal hydric regime. The critical point for homogeneity test occurred in 1981 (data not shown).

3.2 Grape production

Grape production showed a significant increasing trend of 33.49 tons/year and 1038.07 total tons during 31 years (1982–2012), (Table 2, Fig. 4a). Low values of adjusted R^2 obtained from multiple linear regression approach (Table 3) elucidated low impact of computed climatic variables on increasing grape production, suggesting that variables uncovered by this study, such as husbandry improvement (e.g., drainage, pesticides, canopy management, fertilizers) and soil characteristics, might have predominant influence on grape yield in the Romagna Sangiovese appellation area during last 30 years. The influence of climate change may be underestimated as the upper level of CO_2 in the atmosphere increases crop load (Bindi et al. 1996; Schultz 2000; Moutinho-Pereira et al. 2009; Kizildeniz et al. 2015), whose effect may be relevant particularly after the 1970s due to the rapid increasing in the level of CO_2 (IPCC 2014). Cutting point of increasing grape production detected in 1997 and decreasing precipitation variables (T_{prec} and DSI) breaking point in 1996, implies higher yield with lower water availability which is opposite with other studies (Ramos and Martínez-Casasnovas 2010). Therefore, low influence of calculated climate variables on grape production, obtained with multiple linear regression is supported by breaking point analysis.

The negative trend of the standardized ND 25–30 °C regression coefficient, which is related to the optimum temperature range for photosynthesis process, suggested negative impact on grape production; in other words, decrease of days with optimum temperature range may negatively affect crop load due to the reason that temperature increase leads to initial plant stress (several days exceeding >30 °C) and later to the total inhibition of the photosynthetic process (>35 °C).

$T_{\max}$ standardized coefficient obtained with multiple linear modeling, suggested a positive influence on crop load in the Romagna Sangiovese appellation area during the last decades. Similar results were found in the Rias Baixas wine region, Spain, whereas higher temperatures during the budburst and veraison significantly increased crop yield (Lorenzo et al. 2012). In the Bordeaux (France), higher temperatures shortened period from plant budburst to berry maturity into length favorable for higher yield (Jones and Davis 2000). Reversely, wine production decreased during warm seasons in the Penedès wine region, Spain (Ramos et al. 2008). Results from the mentioned studies indicate that positive/negative effect of the increasing temperature on the crop yield depends also on precipitation, atmospheric CO2 level, grape variety, and other factors. Even if detected in the Romagna Sangiovese appellation area, temperature increase may positively influence crop load up to a certain point, due to the detrimental influence of heating stress on grapevine photosynthetic process.

DSI standardized coefficient suggested that increasing number of days without rain (<1 mm) and longer drought

Table 3 Standardized coefficients, standard errors, adjusted R^2, and p level of multiple linear regression modeling applied to grape production (tons) and bioclimatic indices found in the Romagna Sangiovese appellation area (Italy) from 1982 to 2012

	$T_{\max}$	DSI	ND 25–30 °C	Adjusted R^2	p level
Standardized coefficients	0.55	-0.42	-0.19	0.21	0.025
Standard error	0.21	0.17	0.21		

Table 4 Standardized coefficients, standard errors, adjusted R^2, and p level of multiple linear regression modeling applied to naturally occurring alcohol content in Sangiovese red wines and bioclimatic indices in the Romagna Sangiovese appellation area (Italy) from 2001 to 2012

	HI	DSI	Adjusted R^2	p level
Standardized coefficients	0.14	0.84	0.81	0.0002
Standard error	0.15	0.15		

periods may reduce soil water availability causing drought stress to the grapevine, which negatively affects grape production (Ramos and Martínez-Casasnovas 2010).

3.3 Potential alcohol concentration

Naturally occurring alcohol content in Sangiovese red wines showed a significant increasing trend with 0.07 % (*v*/*v*)/year and 0.83 % (*v*/*v*) over a 12-year period (2001–2012) (Table 2, Fig. 4b).

In contrast to grape production, the high value of adjusted R^2 (0.81) suggests a large contribution of calculated climatic variables as a driver of increasing potential alcohol content in red wines from the Romagna Sangiovese appellation area (Table 4). The rest of the variables may be explained with consumer expectations in terms of full bodied, deeply colored, full-flavored red wines achieved with phenolic maturity, both skin and seed, which compels producers to prolong maturation of the grapes and increase the quantity of accumulated sugar in the grapes (García-Martín et al. 2010; Gil et al. 2013).

The increase of DSI coupled with decrease of SI and T_{prec} (not incorporated in the model due high co-linearity with DSI) suggested a positive impact on potential alcohol increase, possible only up to a certain limit. Moderate water stress may positively affect sugar accumulation in the berry as a result of inhibiting lateral shoot growth allowing transportation of carbohydrates to the fruit (Coombe 1989). Poni et al. (2007) conducted partial root-zone drying on potted Sangiovese grapevine, simulating dry (PRD) and wet conditions (WW), whereas at harvest, vines submitted to PRD showed higher total soluble solids respect to the vines treated with WW. Authors noted that use of potted vines approach may induce criticism due to the lack of real field conditions.

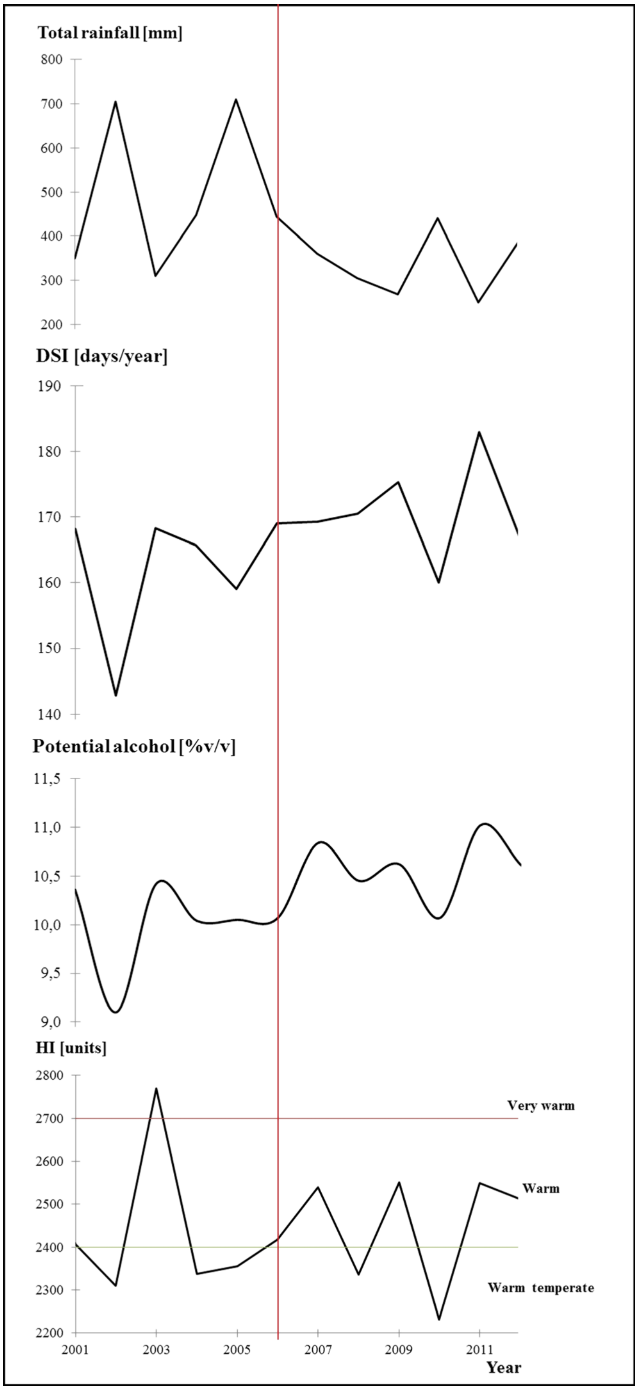

Fig. 5 Growing season trends of Huglin index (HI), potential alcohol level in Sangiovese wines (potential alcohol), dry spell index (DSI), and total precipitation (T_{prec}) in the Romagna Sangiovese appellation area (Italy) from 2001 to 2012; *red line* potential alcohol breaking point

Compared to DSI, HI regression coefficient suggested lower impact on potential alcohol in wines. Detected higher temperatures and thermal accumulation may lead to earlier occurrence phenological stages (i.e., bud-breaking, flowering, veraison, full maturity/harvest) (Webb et al. 2007) and shorter time between two phenological phases (Jones et al. 2005a). Additionally, the combination of reduced precipitation with warming may provoke even faster passage through phenological stages of the vine (Webb et al. 2012). This accelerated pace of phenological events causes faster sugar accumulation and causing grapes to arrive earlier at technological maturity (optimum quantity of sugar content and acidity), while flavor compounds remain undeveloped. On the other hand, if vine growers wait for flavor compounds to develop, acidity values may reach a below optimum level due to the respiration, while sugar content reaches a higher than optimum level (Jones

2012). Therefore, producing wines with fully developed flavor and is often coupled with a high concentration of alcohol. However, positive relation is possible up to the certain point due to photosynthesic process limitations.

Breaking point of naturally occurring alcohol level in wines occurred in 2006 (Fig. 5). Hypothesis of reduced precipitation regime (DSI, T_{prec}) coupled with increased temperature accumulation (HI) in the period after breaking point (2007–2012), comparing to the period before breaking point (2001–2006, with an exception of hot and dry 2003), may serve as an explanation. These preliminary results require further and continuous monitoring to evaluate long-term effects of climate change on grape and wine parameters.

4 Conclusions

Overall, the Romagna Sangiovese appellation area has been affected with weather anomalies in large-scale circulation patterns during the 1980s (Westerlies regimes). During the period from 1953 to 2013, the mean growing season temperature was 18.49 °C, with night temperatures during the ripening months of 13.66 °C. The increasing T_{mean} trend was rather due to a rise in maximum daily temperatures than augmentation of minimum temperatures. The precipitation and SI had a negative trend over the growing season with high annual variations. Multiple linear analysis coupled with breaking point test, displayed low impact of calculated bioclimatic indices on increase of grape production in the Romagna Sangiovese appellation area, also indicated that variables uncovered by this study, such as husbandry practices and soil characteristics, might have a significant role in grape yield determination. Using the same approach, the increase of potential alcohol level in wines during 2002–2012, was largely explained (81 %) by conducted climatic variables, whereas precipitation decrease showed higher correlation with increasing potential alcohol content in wines respect to the rising temperatures. These preliminary results require further and continuous monitoring and to evaluate long-term effects of climate change on grape and wine parameters in the Romagna Sangiovese appellation area.

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References

Andrade C, Fraga H, Santos JA (2014) Climate change multi-model projections for temperature extremes in Portugal. Atmos Sci Lett 15:1–8. doi:10.1002/asl2.485

Antolini G, Auteri L, Pavan V, Tomei F, Tomozeiu R, Marletto V (2016) A daily high-resolution gridded climatic data set for Emilia-Romagna, Italy, during 1961–2010. Int J Climatol 36:1970–1986. doi:10.1002/joc.4473

Barbeau G (2007) Climat et vigne en moyenne vallée de la Loire, France. Congress on climate viticulture, 10–14 April, Zaragosa, Spain, p. 96–101

Bardin-Camparotto L, Blain GC, Júnior MJP, Hernandes JL, Cia P (2014) Climate trends in a non-traditional high quality wine producing region. Bragantia 73:327–334. doi:10.1590/1678-4499.0127

Battaglini A, Barbeau G, Bindi M, Badeck FW (2009) European winegrowers perceptions of climate ‘change impact and options for adaptation. Reg Environ Chang 9:61–73. doi:10.1007/s10113-008-0053-9

Bindi M, Fibbi L, Gozzini B, Orlandini S, Seghi L (1996) The effect of elevated CO_2 concentration on grapevine growth under field conditions. ISHS Acta Horticulturae 427:325–330. doi:10.17660/ActaHortic.1996.427.38

Bonnefoy C, Quenol H, Bonnardot V, Barbeau G, Madelin M, Planchon O, Neethling E (2013) Temporal spatial analyses of temperature in a French wine-producing area: the Loire valley. Int J Climatol 33: 1849–1862. doi:10.1002/joc.3552

Brunetti M, Maugeri M, Nanni T (2000) Variations of temperature and precipitation in Italy from 1866 to 1995. Theor Appl Climatol 65: 165–174. doi:10.1007/s007040070041

Catarino M, Mendes A (2011) Dealcoholizing wine by membrane separation processes. Innovative Food Science and Emerging Technologies 12:330–337. doi:10.1016/j.ifset.2011.03.006

Coombe BG (1989) The grape berry as a sink. Acta Hortic 239:149–158. doi:10.17660/ActaHortic.1989.239.20

Coulter AD, Henschke PA, Simos CA, Pretorius IS (2008) When the heat is on, yeast fermentation managing director, runs out of puff. Australian New Zeal Wine Industry Journal 23:26–30

Draper N, Smith H (1981) Applied regression analysis, 2nd edn. Wiley, New York

Duchêne E, Schneider C (2005) Grapevine climatic changes: a glance at the situation in Alsace. Agronomie 25:93–99. doi:10.1051/agro:2004057

Fischer U, Noble AC (1994) The effect of ethanol, catechin concentration, and pH on sourness bitterness of wine. Am J Enol Vitic 45:6–10

Fraga H, Malheiro AC, Moutinho-Pereira J, Jones GV, Alves F, Pinto JG, Santos JA (2014a) Very high resolution bioclimatic zoning of portuguese wine regions: present future scenarios. Reg Environ Chang 14:295–306. doi:10.1007/s10113-013-0490-y

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2014b) Climate factors driving wine production in the portuguese Minho region. Agric For Meteorol 185:26–36. doi:10.1016/j.agrformet.2013.11.003

Fregoni M (2005) Viticoltura di Qualità. Techiche Nuove, Milan

García-Martín N, Perez-Magariño S, Ortega-Heras M, González-Huerta C et al (2010) Sugar reduction in musts with nanofiltration membranes to obtain low alcohol-content wines. Separation Purification Technology 76:158–170. doi:10.1016/j.seppur.2010.10.002

Gil M, Estévez S, Kontoudakis N, Fort F, Canals JM, Zamora F (2013) Influence of partial dealcoholization by reverse osmosis on red wine composition sensory characteristics. European Food Research Technology 237:481–488. doi:10.1007/s00217-013-2018-6

Gladstones J (1992) Viticulture and environment. Winetitles, Adelaide

Gladstones J (2011) Wine terroir and climate change. Wakefield Press, Kent Town

Hall A, Jones GV (2010) Spatial analysis of climate in winegrape-growing regions in Australia. Australian Journal of Grape Wine Research 16:389–404. doi:10.1111/j.1755-0238.2010.00100.x

Hamed KH, Ramachra Rao A (1998) A modified mann-kendall trend test for autocorrelated data. J Hydrol 204:182–196. doi:10.1016/S0022-1694(97)00125-X

Hannah L, Roehrdanz PR, Ikegami M, Shepard AV, Shaw MR, Tabor G, Zhi L, Marquet PA, Hijmans RJ (2013) Climate change, wine, and conservation. Proc Natl Acad Sci U S A 110:6907–6912. doi:10.1073/pnas.1210127110

Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded data set of surface temperature precipitation for 1950-2006. Journal of Geophysical Research: Atmospheres 113:1–12. doi:10.1029/2008JD010201

Holland T, Smit B (2014) Recent climate change in the Prince Edward County winegrowing region, Ontario, Canada: implications for adaptation in a fledgling wine industry. Reg Environ Chang 14:1109–1121. doi:10.1007/s10113-013-0555-y

Huglin P (1978) Nouveau mode d'évaluation des possibilités héliothermiques d'un milieu viticole. In: Symposium International sur l'écologie de la vigne. 1. Ministère de l'Agriculture et de l'Industrie Alimentaire, Constança, p 89–98

IPCC (2014) Climate change 2014: synthesis report. In: Core Writing Team, Pachauri RK, Meyer LA (eds) Contribution of working groups I, II, III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, p 151

Jackson RS (2008) Wine science: principles and applications. Elsevier, New York

Jackson DI, Lombard PB (1993) Environmental management practices affecting grape composition wine quality—a review. Am J Enol Vitic 44:409–430

Jones GV (2006) Climate and terroir: impacts of climate variability and change on wine. In: Macqueen RW, Meinert LD (eds) Fine wine and terroir–the geoscience perspective. Geological Association of Canada, Newfoundland

Jones GV (2012) Climate, grapes, wine: structure and suitability in a changing climate. Acta Hortic 931:19–28. doi:10.17660/ActaHortic.2012.931.1

Jones GV, Davis RE (2000) Climate influences on grapevine phenology, grape composition, wine production quality for Bordeaux, France. American Journal of Enology Viticulture 51:249–261

Jones GV, Duchêne E, Tomasi D, Yuste J et al. (2005a) Changes in European wine grape phenology relationships with climate. In: Proceedings of the Groupe d'Etude des Systèmes de Conduite de la vigne (GESCO 2005). Gesellschaft zur Förderung der Forschungsanstalt, Geisenheim, p 23–27

Jones GV, White MA, Cooper OR, Storchmann K (2005b) Climate change and global wine quality. Clim Chang 73:319–343. doi:10.1007/s10584-005-4704-2

Jones GV, Ried R, Vilks A (2010) A climate for wine. In: Dougherty P (ed) The geography of wine. Springer Press, Berlin, pp 109–133

Keller M (2010) Managing grapevines to optimise fruit development in a challenging environment: a climate change primer for viticulturists. Aust J Grape Wine Res 16:56–69. doi:10.1111/j.1755-0238.2009.00077.x

Kendall MG, Stuart A (1967) The advanced theory of statistics. Charles Griffin and Company, London

Kizildeniz T, Mekni I, Santesteban H, Pascual I, Morales F, Irigoyen JJ (2015) Effects of climate change including elevated CO_2 concentration, temperature water deficit on growth, water status, yield quality of grapevine (*Vitis vinifera* L.) cultivars. Agric Water Manag 159: 155–164. doi:10.1016/j.agwat.2015.06.015

Konca-Kedzierska K (2015) Comparison of selected methods of analysis for reconstructed fields of precipitation in climate scenarios over Poland. Theor Appl Climatol. doi:10.1007/s00704-015-1617-5

Lereboullet AL, Beltrando G, Bardsley DK, Rouvellac E (2014) The viticultural system and climate change: coping with long-term trends in temperature and rainfall in Roussillon, France. Reg Environ Chang 14:1951–1966. doi:10.1007/s10113-013-0446-2

Lorenzo MN, Taboada JJ, Lorenzo JF, Ramos AM (2012) Influence of climate on grape production and wine quality in the Rías Baixas, North-Western Spain. Reg Environ Chang 13:887–896. doi:10.1007/s10113-012-0387-1

Malheiro AC, Campos R, Fraga H, Eiras-Dias J, Silvestre J, Santos JA (2013) Winegrape phenology temperature relationships in the Lisbon wine region, Portugal. Journal International des Sciences de la Vigne et du Vin 47:287–299

Mann HB (1945) Non-parametric tests against trend. Econometrica 13: 245–259

Männik A, Zirk M, Rõõm R, Luhamaa A (2015) Climate paremeters of Estonia and the Baltic Sea region derived from the high-resolution reanalysis database BaltAn65+. Theor Appl Climatol 122:19–34. doi:10.1007/s00704-014-1271-3

Mariani L, Parisi SG, Cola G, Failla O (2012) Climate change in Europe and effects on thermal resources for crops. Int J Biometeorol 56: 1123–1134. doi:10.1007/s00484-012-0528-8

Massot A, Mietton-Peuchot M, Peuchot C, Milisic V (2008) Nanofiltration and reverse osmosis in winemaking. Desalination 231:283–289. doi:10.1016/j.desal.2007.10.032

Mira de Orduña R (2010) Climate change associated effects on grape wine quality production. Food Res Int 43:1844–1185. doi:10.1016/j.foodres.2010.05.001

Moisselin JM, Dubuisson B (2006) Évolution des valeurs extrêmes de température et de précipitations au cours du XXe siècle en France. Meteorologie 54:33–44. doi:10.4267/2042/20099

Moutinho-Pereira J, Goncalves B, Bacelar E, Cunha JB, Coutinho J, Correia CM (2009) Effects of elevated CO_2 on grapevine (*Vitis vinifera* L.): physiological yield attributes. Vitis-Journal of Grapevine Research 48:159–165

Mullins MG, Bouquet A, Williams LE (1992) Biology of horticultural crops: biology of the grapevine. Cambridge University Press, Cambridge

Neethling E, Barbeau G, Bonnefoy C, Quénol H (2012) Change in climate berry composition for grapevine varieties cultivated in the Loire valley. Clim Res 53:89–101. doi:10.3354/cr01094

Orlandini S, Di Stefano V, Lucchesini P, Puglisi A, Bartolini G (2009) Current trends of agroclimatic indices applied to grapevine in Tuscany (Central Italy). Idojaras 113:69–78

Pettitt AN (1979) A non-parametric approach to the change point problem. Appl Stat 28:126–135

Pielke RA, Stohlgren T, Schell L, Parton W et al (2002) Problems in evaluating regional local trends in temperature: an example from eastern Colorado, USA. Int J Climatol 22:421–434. doi:10.1002/joc.706

Poni S, Bernizzoni F, Civardi S (2007) Response of "Sangiovese" grapevines to partial root-zone drying: gas-exchange, growth and grape composition. Sci Hortic 114:96–103. doi:10.1016/j.scienta.2007.06.003

Ramos MC, Martínez-Casasnovas JA (2010) Soil water balance in rainfed vineyards of the Penedès region (northeastern Spain) affected by rainfall characteristics and land levelling: influence on grape yield. Plant Soil 333:375–389. doi:10.1007/s11104-010-0353-y

Ramos MC, Jones GV, Martínez-Casasnovas JA (2008) Structure trends in climate parameters affecting winegrape production in Northeast Spain. Clim Res 38:1–15. doi:10.3354/crPAGE00759

Santos JA, Malheiro AC, Pinto JG, Jones GV (2012) Macroclimate viticultural zoning in Europe: observed trends atmospheric forcing.

Clim Res 51:89–103. doi:10.3354/cr01056 doi:10.1007/s00484-010-0318-0

Schultz HR (2000) Climate change and viticulture: a European perspective on climatology, carbon dioxide and UV-b effects. Aust J Grape Wine Res 6:2–12. doi:10.1111/j.1755-0238.2000.tb00156.x

Selianinov GT (1928) On agricultural climate valuation. Procedding of Agricultural Meteorology 20:165–177

Sokolowsky M, Fischer U (2012) Evaluation of bitterness in white wine applying descriptive analysis, time-intensity analysis, and temporal dominance of sensations analysis. Anal Chim Acta 732:46–52. doi:10.1016/j.aca.2011.12.024

Tonietto J (1999) Les microclimats viticoles mondiaux et l'influence du mesoclimat sur la typicité de la Syrah et du Muscat de Hambourg dans le sud de la France. Disertation, l'Institut National Recherche Agronomique

Tonietto J, Carbonneau A (2004) A multicriteria climatic classification system for grape-growing regions worldwide. Agric For Meteorol 124:81–97. doi:10.1016/j.agrformet.2003.06.001

van Leeuwen C, Friant P, Choné X, Tregoat O, Koundouras S, Dubourdieu D (2004) Influence of climate, soil, cultivar on terroir. American Journal of Enology Viticulture 55:207–217

van Leeuwen C, Schultz HR, De Cortazar-Atauri IG, Duchêne E et al (2013) Why climate change will not dramatically decrease viticultural suitability in main wine-producing areas by 2050. Proc Natl Acad Sci U S A 110:3051–3052. doi:10.1073/pnas.1307927110

Vidal S, Courcoux P, Francis L, Kwiatkowski M, Gawel R, Williams P et al (2004) Use of an experimental design approach for evaluation of key wine components on mouth-feel perception. Food Qual Prefer 15:209–217. doi:10.1016/S0950-3293(03)00059-4

Von Storch H, Navarra A (1995) Analysis of climate variability: applications of statistical techniques. Springer Press, Berlin

Vršič S, Šuštar V, Pulko B, Šumenjak TK (2014) Trends in climate parameters affecting wine grape ripening in northeastern Slovenia. Clim Res 58:257–266. doi:10.3354/cr01197

Webb LB, Whetton PH, Barlow EWR (2007) Modelled impact of future climate change on the phenology of wine grapes in Australia. Aust J Grape Wine Res 13:165–175. doi:10.1111/j.1755-0238.2007.tb00247.x

Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR (2012) Earlier wine-grape ripening driven by climatic warming drying management practices. Nat Clim Chang 2:259–264. doi:10.1038/nclimate1417

Werner PC, Gerstengarbe FW, Fraedrich K, Oesterle H (2000) Recent climate change in the North Atlantic/European sector. Int J Climatol 20:463–471. doi:10.1002/(SICI)1097-0088(200004)20:5<463::AID-JOC483>3.0.CO;2-T

Williams AA (1972) Flavour effects of ethanol in alcoholic beverages. The Flavour Industry 3:604–607

Winkler AJ, Cook JA, Kliewer WM, Lider LA (1974) General viticulture. University of California Press, Berkley