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Global change and viticulture in the Mediterranean region: a case of study in north-eastern Spain

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Abstract

Viticulture in the Mediterranean region has been improved by agronomic methods based on ecophysiological and genetic knowledge of the species and varieties cultivated. Plant growth, yield and quality are highly dependent on climate. Grape sugar content and wine alcohol content are considered as important quality parameters. The objective of our study is to analyse the effects of the current global change on the percentage of alcohol by volume (ABV) in red wines from vineyards located in the Montsant Designation of Origin (DO) (Priorat County, north-eastern Spain). We present an annual series of percentage of ABV in red wines over the 1984-2008 period (25 years), which is one of the longest series of this viticultural variable in Spain. We do not detect any significant trend of alcohol levels in red wines from the Montsant DO along the 1984-2004 subperiod, but a sharp increase about 1% (by volume) is observed after 2004; we statistically checked that the last four years constitute an outlier period in the series. We consider climate evolution over the 1984-2004 period in the study area in order to find some relation with alcohol levels in red wines. Agronomic practices and land cover changes are also taken into account. Results show that the interannual variability of the alcohol levels in red wines are partially explained by temperature and precipitation conditions few days before the vintage. The high percentages of ABV since 2005 may be associated with new trends in viticulture techniques rather than with climate change.

Additional key words: climate change; land cover changes; Mediterranean Basin; Montsant DO; percentage of alcohol by volume; Priorat QDO; red wine; vineyards.

Introduction

Agriculture in the Mediterranean basin involves a high number of crops, the productivity of which is limited as a result of environmental conditions. Nowadays, however, improvements have been made by means of agronomic methods and systems based on the ecophysiological and genetic knowledge of the cultivated species. But despite this degree of specialisation, agriculture remains highly sensitive to climate variability, which is the main source of global yearly variability in production (Rosenzweig & Tubiello, 1997; Aggarwal, 2008).

Climate change can cause temperatures to rise at regional or global scale (IPCC, 2007; Sheffield & Wood, 2008). At the regional level, not all of the Earth's regions will be affected by the same changes in environmental conditions, and consequently, the more

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This work has 1 Supplementary Figure that does not appear in the printed article but that accompanies the paper online.

Abbreviations used: ABV (alcohol by volume); DO (Designation of Origin); INCAVI (Institut Català de la Vinya i el Vi; Catalan Institute of Vine and Wine); LCMCs (Land Cover Maps of Catalonia); OIV (International Organisation of Vine and Wine); QDO (Qualified Designation of Origin).

exposed places will be potentially more vulnerable to climate change and consequently to direct or indirect losses of agricultural productivity. The Mediterranean Basin is the only region of the Earth where most models coincide on predicting less precipitation, above all, in the warm half of the year (Christensen *et al*., 2007). In our case north-eastern (NE) Spain and by extension the Mediterranean ecosystem is characterised by a double stress, caused by winter cold and summer drought, which simultaneously promotes plant and water deficit in crops (Terradas & Savé, 1992). In summer, low soil water availability, along with high vapour pressure deficit at atmospheric level, promotes inhibitions in plant growth and various negative effects on their development (Di Castri & Mooney, 1973; Savé *et al*., 1999). Some climate models predict that the NE Spain would be affected by long-term droughts after 2060 more frequently than at present (Lopez-Bustins *et al*., 2013). It is known that a changing global climate, together with an enhanced interannual variability in the agricultural sector due to economical conditions (Reguant *et al*., 2011), will increase the difficulties and risks in the winemaking sector in Southern Europe (Fraga *et al*., 2013).

Worldwide, viticulturists have been finding that an important parameter to define optimal grape maturity is correlated with the sugar content (Winkler *et al*., 1974; Conde *et al*., 2007). Winemakers have been using the ratio between sugars and acids as an indication of degree of ripeness to determine when the grapes are ready for harvesting (González-San José *et al*., 1991; Hunter *et al*., 2004; Ribéreau-Gayon *et al*., 2006). Grape sugar level at harvest has been taken as an economic indicator for grape growers. Both the sugar levels of grapes and the alcohol levels of wines have been considered as quality parameters for many years (González-San José *et al*., 1991; Kennedy, 2002). Indeed, there is a vital need for information on the concentration and quality of the phenolic compounds of the skins and seeds of berries. Certain measurements are being considered in relation to the possibility of global warming favouring a sudden increase in these parameters and worsening wine quality (Jones, 2007; Jones & Alves, 2012). In the last two decades, winemakers have started measuring phenol concentration in order to increase their knowledge of phenolic maturity and in consequence, to harvest at the optimal stage of ripeness. Among the many factors influencing the fruit ripening process (*e.g.,* grape varieties, soil materials, agronomic practices and overall environment conditions), climate seems to be the most important with regard to grape composition and wine quality (Tonietto & Carbonneau, 2004; Ramos *et al*., 2008; Camps and Ramos, 2012). Climate change may shift the suitability of vineyards to cooler lands, *i.e.,* to higher altitudes and latitudes (Hannah *et al*., 2013) and to coastal areas (Fraga *et al*., 2014). Iglesias *et al*. (2010) studied the future production of several crops in Spain at the end of the current century and detected that grapes showed the highest variability response depending on local climate conditions.

The main objectives of the present research are (1) to construct an annual series of percentage of alcohol by volume (ABV) of wines in a Mediterranean region and (2) to study the effects of the current global change on this series. We selected a small Mediterranean wine production area, the Priorat County (NE Spain). It is located in the north-western Mediterranean basin and is potentially affected by global change (global warming and socioeconomical changes; Martín-Vide, 2009). We study the evolution of climate conditions together with changes in the alcohol levels over two decades in the study area. Furthermore, we consider land cover, different grape varieties, agronomic practices and changes in wine trends during last years in the Priorat County.

Material and methods

Site details

The study focuses on the Montsant region (41°09'N; 0°49'E), mostly located in the Priorat County, NE Spain (Fig. 1). It is a small Mediterranean region with an area of 36,171 ha. The wines produced therein have been awarded the Montsant Designation of Origin (DO), comprising 17 municipalities. The study area is made up of the valleys of the Siurana River, a downstream tributary of the Ebro River, and its tributaries, the Montsant and Cortiella creeks. It is a mountainous landscape beyond the littoral mountains and presents Mediterranean climate conditions (Terradas & Savé, 1992), characterised by hot, dry summers and cold winters. Wine has been produced in the study area since the 12th century (Iglésies, 1975). The soils composition of the study area is available from the Landscape Report of the Priorat County drawn up by several institutions of the Catalan Government in 2011. The soils comprise different

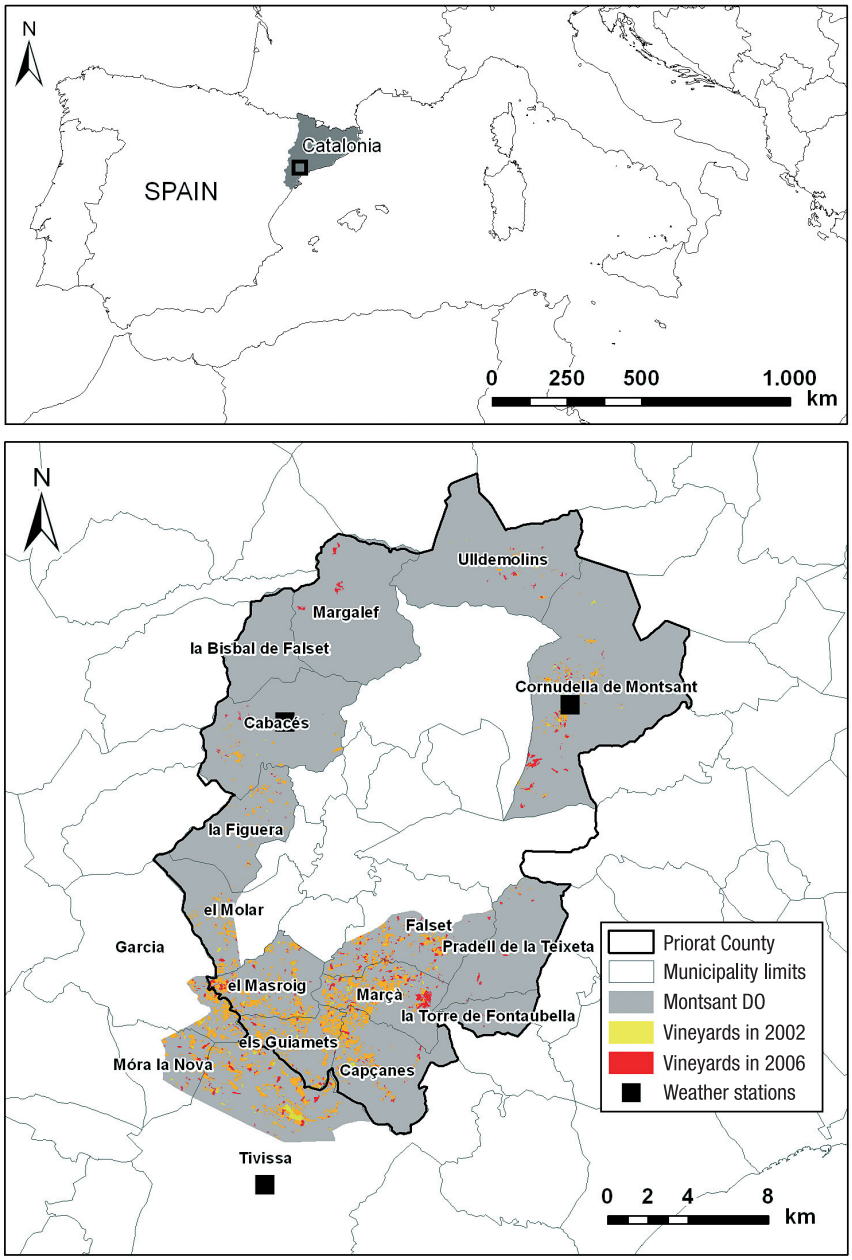

Figure 1. Location of the Priorat County (southern Catalonia), Catalonia (north-eastern Spain), the Montsant Designation of Origin (DO), the three weather stations and the 17 municipalities, totally or partially, included within the Montsant DO. Vineyard extension throughout municipalities' areas within the Montsant DO in 2002 and 2006 is shown (data provided by the Land Cover Maps of Catalonia, LCMCs). The orange polygons are the vineyards with no area changes between 2002 and 2006.

original materials: limestone, granite and shale. They give rise to a wide variety of soil types, in general shallow and dry. All soils are quite infertile and have an organic matter content of between 0.6 and 0.9% (Nadal, 1993). The autochthonous red grape varieties of the study area are Grenache, noir and peluda, and Carignan, which have been cultivated for more than 60 years (Nadal, 2002).

The Land Cover Maps of Catalonia (LCMCs) show that the area dedicated to vineyards in the Montsant DO expanded from 2002 to 2006 (Fig. 1); it greatly increased in 16% during this short period (Table 1).

Table 1. Landscape typologies in the Montsant Designation of Origin (DO) in 1993, 2002 and 2006

Landscape typologies	1993		2002		2006	
	(ha)	(%)	(ha)	(%)	(ha)	(%)
Forestlands	22,022	60.9	24,433	67.6	24,999	69.1
Crops	13,706	37.9	11,265	31.1	10,499	29.0
(Vineyards)	(no data)	(no data)	(2,138)	(5.9)	(2,489)	(6.9)
Urban lands	336	0.9	376	1.0	519	1.5
Water	107	0.3	97	0.3	154	0.4

Crops as a whole, however, noticeably declined in the Montsant DO, whereas forestland presented an important increase. Crops represented less than 30% of the Montsant DO in 2006, whereas this was almost 40% 13 years earlier. In few years, forestlands encroached on abandoned crop fields as a result of socioeconomic changes in the region. Urban land currently presents a notable increase in the study area.

Percentage of alcohol by volume series

The data on wine alcohol content was gathered from the historical archive of the Catalan Institute of Vine and Wine (INCAVI) in Reus Enological Station (Province of Tarragona, NE Spain). This public institution certifies wine qualities and has official analyses of wine samples since 1984. We obtained a data series of 25 years covering the 1984-2008 period. The analysed data of wine samples were digitalised in spring 2009 thanks to a funded and temporary campaign of research. It was a long and laborious manual labour, since we had to classify old typewritten cards according to the wine type, the DO and the date. Fortunately, the analysed data of the last years of the study period were directly extracted from a digital database of INCAVI. The percentage of ABV was the most frequent and continuous parameter in all the wine samples as it can be seen in the data analysis card [Suppl. Fig. 1 (pdf)]. Actually, alcohol levels are considered as the real measure of ethanol or ethyl content in wine. This parameter is the common basis for characterising wine in commercial transactions. The INCAVI has two methods for analysing alcohol content, near infrared spectroscopy, and more commonly, distillation (OIV, 2010). Furthermore, it was important to mind the date to assign the percentage of ABV to the right year harvest; for instance, card in Suppl. Fig. 1 (pdf) was certified on 8 January 1987 but its information belongs to the harvest of 1986. Each card indicated the origin of the wine sample in order to know its DO.

Most of the wine samples registered in the branch office of INCAVI in Reus Enological Station along the 1984-2008 period came from the Montsant DO and the Priorat Qualified Designation of Origin (QDO). The Priorat QDO is located next to the Montsant DO within the Priorat County. We digitalised a total of 2,399 wine samples, whose type, date, percentage of ABV and origin were clearly written. An amount of 1,632 samples (68.0%) were from the Montsant DO and 767 samples (32.0%) from the Priorat QDO. Samples of red wines (1,774; 74.0%) were much more abundant than those of white (516; 21.5%) and rosé (109; 4.5%) wines in both DOs. We established a threshold of 10 samples per year to guarantee an annual mean of the percentage of ABV in each wine type. White and rosé wines did not achieve this threshold in most of the years in both DOs, so these wine types were discarded from the study. Moreover, the red wines from Priorat QDO were also discarded from the study because there were less than 10 red wine samples per year along the 1984-1995 period. The red wine samples of the Montsant DO constituted the only valid series for the study with 1,313 samples (54.7% of the 2,399 original samples). Nevertheless, we detected a gap in 1998 and 1999 in the red wine samples of the Montsant DO which was filled by complementary information (59 red wine samples for 1998 and 54 samples for 1999) from a local cooperative in Capçanes (Fig. 1). This cooperative yearly collects about 1 million kg of grapes, which represents 50% approximately of the total Montsant DO. Finally, 1,426 red wine samples of the Montsant DO were considered in order to build the 1984-2008 series of percentage of ABV and to analyse their time trends by means of the Mann-Kendall non-parametric test.

Climate data series

The climatic series used correspond to the Tivissa, Cabacés and Cornudella de Montsant (here in after referred to as Cornudella) weather stations, located in the study area (Fig. 1). These series present the longest records within or close to the Priorat County. The climatic series provide precipitation, maximum temperature (Tmax) and minimum temperature (Tmin) at monthly resolution covering the 1984-2008 period, except for the Cornudella series which only cover the 1988-2007 period. According to the study data and period, these series denote a typical Mediterranean continental climate with an average precipitation of 500-550 mm, an annual mean temperature typical of a Mediterranean area (15.0°C) and an annual temperature range of a continental climate (17.5°C). These climate values reveal that this location is somehow protected from the influence of the sea.

We attempt to determine climate trends in the study area by means of the Mann-Kendall test, and the relationship between the annual percentage of ABV and the monthly and seasonally climatic series using the Pearson's correlation coefficient in order to detect those months and seasons when climate has a potential influence on red wines. Monthly and seasonally precipitation series are used in this analysis; these series are normally distributed and, therefore, suitable for calculating Pearson's correlation coefficients. Furthermore, we carry out a multiple regression with the climatic series having a largest influence on the percentage of ABV.

Agronomic data

We studied changes in vineyard extension throughout municipalities of the Montsant DO between 2002 and 2006 using the LCMCs. The 2002 and 2006 editions of the LCMCs include spatial information on vineyards which enable us to detect changes in their area and spatial distribution. It should be highlighted that the resolution of the LCMCs is high, the minimal spatial unit to be mapped is 500 m^2, and the spatial resolution of the product is 2 m.

Furthermore, we studied some agronomic variables such as varietal cultivated percentage of grapes in the Montsant DO. We obtained the original data from the Tarragona DO vine and wine registry of 1978 and 1993, because at the time the Montsant DO was included in Tarragona DO [Montsant DO Council statement was approved in 2001 (DOGC, 2001)], and the Montsant DO Council data of 2010. We assessed which varieties had been recently introduced, as these might have altered the percentage of ABV of the red wines.

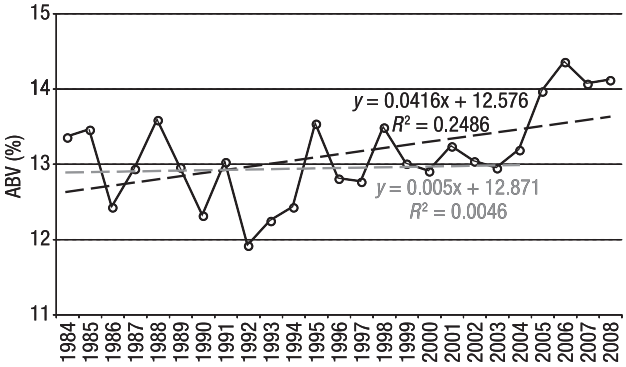

Figure 2. Evolution of the percentage of alcohol by volume (ABV) of red wines from the Montsant DO throughout the 1984-2008 study period. The least-square linear fitting is drawn as a black/grey dashed line for the 1984-2008/1984-2004 period, respectively. The equations and the R^2 values are shown.

Results

The percentage of ABV of red wines in the Montsant DO is on average 13.12% for the 1984-2008 study period. Alcohol levels show a significant increase of 0.042% $year^{-1}$ during the study period at the 95% confidence level (Fig. 2). The average alcohol levels rose from 12.60% to 13.65% along the 1984-2008 study period, 1.05% of ABV. The highest values are detected in the last four years, around 14% of ABV. Before 2005 the percentage of ABV hardly surpassed 13.5% level. These anomalous high values lead us to carry out a statistical test to the series in order to detect some anomalous subperiod in the percentage of ABV values. The Students's t-test enables us to detect a breakpoint in the time series in 2005 and we consider the 2005-2008 period as an outlier subperiod. Fig. 2 shows that there is no significant trend for the homogenous 1984-2004 period and the percentage of ABV of red wines in the Montsant DO for this period is on average 12.93%.

Climate data show that annual precipitation has no significant trend during the study period in the Montsant DO (Table 2). On the other hand, the annual Tmax sharply increases along the study period, being significant in Tivissa and Cabacés. The annual Tmin only significantly increases in Tivissa, and no significant changes are detected in Cabacés and Cornudella. The overall increase of the annual Tmax

Table 2. Time trends of annual precipitation, maximum temperature (Tmax) and minimum temperature (Tmin) in Tivissa, Cabacés and Cornudella along the 1984-2008 study period. The trends were calculated using least-square linear fitting and the significance thereof by means of the Mann-Kendall non-parametric test (** significant at the 95% confidence level)

	Tivissa	Cabacés	Cornudella
Annual precipitation (mm year^{-1})	7.2	0.3	–5.9
Annual Tmax (°C year^{-1})	0.056**	0.083**	0.059
Annual Tmin (°C year^{-1})	0.062**	0.004	0.003

and Tmin along the study period and the three series is 1.7°C and 0.6°C, respectively. The monthly and seasonally correlation analyses could reveal whether these climate trends are the cause of the current rising of the percentage of ABV in red wines in the Montsant DO.

The percentage of ABV of red wines from the Montsant DO shows a noticeable relationship with the climatic series in autumn along the homogeneous period 1984-2004, above all, a positive and significant correlation with the Tmax (Table 3). Moreover, a negative and significant correlation is obtained between the percentage of ABV and precipitation in autumn. October weather is detected to have the largest effect on alcohol levels in red wines in the Montsant DO (Table 3). Precipitation and Tmax are negatively and positively, respectively, correlated with the percentage of ABV in all three weather stations in October. We carried out a multiple regression of the percentage of ABV modelled by Tmax and precipitation in October, and calculated for this month mean series of Tmax and precipitation using Tivissa and Cabacés series, which have continuous data along the whole study period. The multiple regression was calculated for the homogeneous period 1984-2004 and explained 47.8% of the variability of the percentage of ABV (Fig. 3). There was an overall good agreement (R = 0.69) between the model and the alcohol levels for the 1984-2004 period. The model was then extrapolated to the last four years 2005-2008 and a clear disagreement between the real and modelled data was observed; the variability explained by the model falled to 31.4% (R = 0.56) when the whole study period was considered.

In 1988 and 1995 red wine samples showed a high percentage of ABV, 13.58% and 13.53%, respectively, and they were well predicted by the model. In 1988 and 1995 October months were anomalously warm (22.3°C

Table 3. Significant Pearson's correlation coefficients between the percentage of alcohol by volume (ABV) of the Montsant DO and precipitation, Tmax and Tmin of Tivissa, Cabacés and Cornudella during the 1984-2004 period for each month, season and annually

	Precipitation			Tmax			Tmin		
	Tivissa	Cabacés	Cornudella	Tivissa	Cabacés	Cornudella	Tivissa	Cabacés	Cornudella
January	...	...	...	0.46**	...	0.62**	...	...	0.56**
February	...	...	...	...	...	...	...	...	...
March	...	...	...	...	...	...	...	...	...
April	...	...	...	...	...	...	...	...	...
May	...	...	...	...	...	...	–0.46**	–0.47**	...
June	...	...	...	...	...	...	...	...	...
July	...	...	...	...	...	...	...	...	...
August	...	...	...	...	...	...	...	...	...
September	–0.43**	–0.57***	...	...	...	...	...	...	...
October	–0.51**	–0.47**	–0.49**	0.67***	0.58***	0.69***	...	...	...
November	...	...	...	...	...	...	...	...	...
December	...	...	...	...	...	...	...	...	...
Winter (DJF)	...	...	...	...	...	...	...	...	...
Spring (MAM)	...	...	...	...	...	...	...	...	...
Summer (JJA)	...	...	...	...	...	...	...	...	...
Autumn (SON)	–0.46**	–0.49**	–0.51**	0.64***	0.46**	0.64**	...	...	...
Annual	...	...	...	...	...	0.60**	...	...	...

… no significant correlation; ** significant correlation at the 95% confidence level; *** significant correlation at the 99% confidence level.

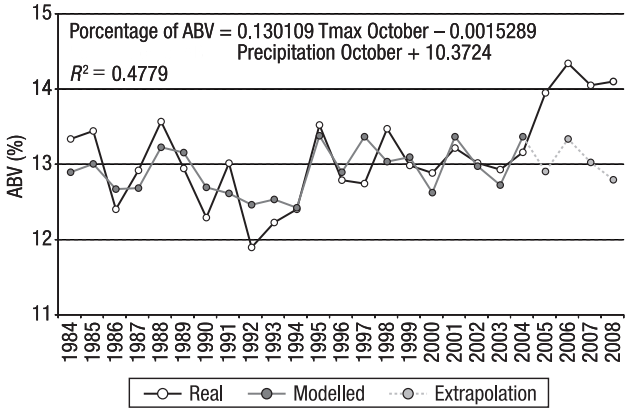

Figure 3. Evolution of the real percentage of ABV of red wines from the Montsant DO and the modelled percentage of ABV by means of maximum temperature (Tmax) and precipitation in October throughout the 1984-2008 study period. The equation of the multiple regression and the R^2 value are shown.

and 23.3°C of Tmax, respectively) (Fig. 4a) and very dry (23.2 mm and 5.7 mm, respectively) (Fig. 4b). On the other hand, October months were cool and humid along the 1990-1994 period; for instance, October 1992 was the coldest October month of the series (Tmax 17.4°C) and October 1994 was the second most humid October month (287.0 mm), and red wines obtained a low alcohol content in 1992 and 1994, 11.91% and 12.42%, respectively.

On the other hand, fast changes were detected in the landscape of the Montsant DO at the beginning of the 21st century (Table 1). In 2006, vineyards represented almost 25% of total croplands in the Montsant DO while it was under 20% in 2002. Moreover, the number of cellars in the Montsant DO ranged from 10 in 1990, to 28 in 2002, and to 54 in 2010 (Montsant DO Council, *pers. comm.*). The main concentration of vineyards is in the southern region of the study area, where new vineyards have recently appeared in a short period of time, above all, in the Marçà municipality (Fig. 1). Some towns in the north (Cornudella, Margalef and Ulldemolins) have even partially converted their traditional croplands to vineyards.

The plant material has also undergone a transformation in the last decade. The varietal percentage of Carignan presents a big reduction in the last years, while Grenache noir percentage remains similar (Table 4). New red grape varieties have been recently introduced (Tempranillo, Cabernet Sauvignon, Merlot, and Syrah).

Discussion

We satisfactorily constructed a 25-year (1984-2008) series of percentage of ABV of the red wines in the Montsant DO, which is a long series of percentage of ABV to our knowledge. We can find long series of alcohol content from other DOs in Catalonia (NE Spain), but they are usually referred to probable alcoholic degree in grapes. Bohigas Condal (2000) analysed a longer series (more than 40 years) of percentage of ABV in the Conca de Barberà DO (Province of Tarragona, Catalonia). The lack of wine official series may be related to the secrecy of wine private enterprises. We are aware of the limitations of the source data to construct this percentage of ABV series, but the large amount of wine samples considered and the coherent results we have obtained make this data series reliable enough. Obviously, further research is required to improve and extend our series of percentage of ABV in the future.

Red wines in the Montsant DO have an average of 13.12% of ABV for the 1984-2008 period, and we detect an overall increase of 1% (by volume) in the last four years, which constitute an anomalous subperiod.

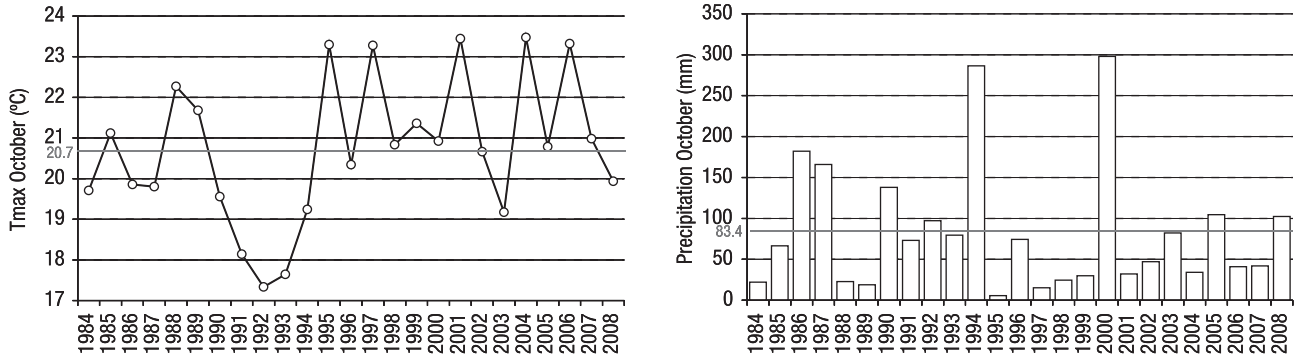

Figure 4. Evolution of the Tmax in October (a) and the precipitation (b) in the Montsant DO along the 1984-2008 study period. The Tmax and precipitation means in October for the whole study period is drawn as grey lines.

Table 4. Vineyard varietal composition in the Montsant DO (1978, 1993, 2010)

Varieties	1978 (%)	1993 (%)	2010 (%)
Carignan	50	55	29
Grenache noir	32	28	33
Macabeu	7	6	2
Grenache Blanc	5	4	2
Esquitxagós	3	3	0
Parellada	1	1	0
Grenache peluda	1	1	0
Pool of white cultivars	1	1	0
Pool of red cultivars	0	1	0
Tempranillo	0	0	12
Merlot	0	0	8
Syrah	0	0	7
Cabernet Sauvignon	0	0	7

Other wine regions worldwide have also shown an increase of the percentage of ABV in their wines (Jones, 2007); for instance, Napa Valley (California, USA) (Vierra, 2004) and Alsace (NE France) (Duchêne & Schneider, 2005). Wines with a high percentage of ABV (14-15%) are highly scored by the wine experts and sommeliers according to the Wine Spectator magazine (http://www.winespectator.com) and the Decanter magazine (http://www.decanter.com). Top and premium wines usually contain high levels of alcohol and they often represent the image marketing of a wine trademark. On the other hand, it could be a potential problem in the wine market since such high alcohol content makes wine too hot for meals (Jones & Alves, 2012). The consequences of the increase of sugar accumulation and obtaining wines with levels over 15% of ABV are to be out of scale from their classification such as dry wines by the current regulations of the Montsant DO Council (DOGC, 2005). Wines having more than 15% of ABV are grouped in the special wines class (finos, sherry, sweet wines, etc.). Moreover, society is more used to consume wines about 13% of ABV, which are easier to commercialise and become popular. We detected a maximum alcohol level of 14.35% (by volume) in red wines of the Montsant DO in 2006 (Fig. 2).

The potential influence of climate on alcohol levels observed in autumn would be coherent, as berries finish the ripening process at this time, a few weeks or days before the harvest; in the Montsant DO, the vintage takes place from the beginning of September to mid-October, approximately. According to our results, warm temperatures and low precipitation around the date of the harvest might increase the percentage of ABV in red wines in the Montsant DO. Duchêne & Schneider (2005) attributed the increase of potential alcohol levels of Riesling in Alsace to warmer temperatures at ripening moment. Dry conditions would concentrate sugar content during berry ripening due to drought stress (Nadal & Lampreave, 2007). Moreover, under water deficit conditions a noticeable reduction of grape yield and quality has been observed in some wine regions in Catalonia (Ramos *et al*., 2008; Camps & Ramos, 2012). It is an unexpected result having detected the largest influence of climate in October because the vintage ends in mid-October; however, October is the rainiest month in the Priorat County and in the rest of the littoral and pre-littoral ranges of Catalonia (Martín-Vide *et al*., 2008). Torrential rainfall events are frequent in October in eastern Iberian Peninsula, above all, during the first fortnight October (Lopez-Bustins, 2007). Intense precipitation few days before the harvest or during the harvest might dilute sugar concentration and increase acidity in grapes or, even, grapes might get rotted leading to a poor vintage. Under these circumstances, wine growers usually delay harvest in order to minimize this dilution effect and improve pulp and skin ripeness (Nadal & Lampreave, 2007).

There has been an overall warming in the Montsant DO along the last decades which is such an important issue with regard to water availability for vegetation. This sharp increase of annual temperature in the Montsant DO had been already detected throughout Catalonia (NE Spain) by other studies (Brunet *et al*., 2007; Ribas *et al*., 2010). Nevertheless, in the last four years of the study period we did not observe October months to be either anomalously warm or very dry to justify the high alcohol levels detected in red wines in the Montsant DO. Therefore, the recent increase in the percentage of ABV in the Montsant DO cannot be attributed to climate change. Climate could account for variability in alcohol content in most part of the study period, but not for the high increase detected in the last years. The changes observed in the last years may be attributable to, and explained by, other factors, such as agronomic techniques. Nevertheless, a recent study has detected a strong increase in the global solar radiation throughout Spain since 2005 (Sanchez-Lorenzo *et al.,* 2013), which coincides with the sudden increase in the percentage of ABV in the Montsant DO; further research about the relationship between

viticulture and exposure to sun, among other key factors, is crucial to improve wine quality (Conde *et al*., 2007).

Since the 1990s, the study area has been undergoing drastic changes in the varietal percentages and the viticultural practices. The biggest changes involved modification from bushed grapevines to trellis systems with vertical shoot positioning. In some cases, grapevine growers extended terraces over a wider area in order to facilitate mechanisation of cultivation. In this sense, the big change in soil uses and cultivars must be taken into account (Savé *et al*., 2008; De Herralde *et al*., 2012). Viticulture has had an important role in the Priorat County along the last decade for reactivating the local economy, as it is proven with the sudden increase of the area dedicated to vineyards between 2002 and 2006 in the Montsant DO (Fig. 1 and Table 1). These agronomic changes involve a variation in geomorphologic characteristics (Ramos *et al*., 2007), biological fertility (Calvet *et al*., 2007), slope and hydrological characteristics (Cots-Folch *et al*., 2006), and irrigation implementation (Girona *et al*., 2009).

These modifications of plant material and the influence of viticultural techniques would have notably increased the percentage of ABV in the wine. On the one hand, we could highlight the increase in yield per hectare in the new plantations of young grapevines where the trellis system has been implemented (in some parcels with limited support irrigation) (Nadal & Lampreave, 2007). On the other hand, the number of new plantations of the Grenache noir has increased and new plantations of the Carignan has fallen to practically zero (Nadal, 2002). Grenache is one of the Mediterranean grape varieties which are characterised by a high accumulation of sugar in berries during the ripening process and, subsequently, a great alcoholic yield in wines (Andrés-de-Prado *et al*., 2007). The alcohol content these wines reach is much higher than in Carignan varieties. The newly introduced red grape varieties from the Atlantic region, Cabernet Sauvignon and Merlot (Table 4), also produce a high sugar percentage in grapes (Nadal, 2002). Consequently, the greater wine production of Grenache noir and the introduction of new red grape varieties during the last years would have together contributed to the increase in the alcohol levels of the red wines in the Montsant DO.

All these changes might be explained by the foundation of the Montsant DO in August 2001 as a new trade that replaced the old and more extended Tarragona DO in the Priorat County; afterwards new cellars and rural business investments were settled down in the study area (Nadal & Sánchez-Ortiz, 2011). The requirements of the Montsant DO Council specify the high percentage of ABV that the red wine must attain (12.5-15.0%), and the fashion for red wines, aimed at achieving a level of quality demanded by the market, with a high concentration of phenolic compounds, would have determined a delay in the vintage. In recent years, influenced by the scores awarded to premium wines, customers would have preferred red wines characterised by a rich colour, a good tannin structure and high complexity. Currently, nearly all wine growers of the Montsant DO would delay the harvest date in order to obtain the best level of phenolic maturity. They would usually extend the maturity by one or two weeks, even when the level of sugars would have already reached the expected 14% of ABV (Nadal *et al*., 2008). All these new wine concepts might have led to economic development of viticulture over the study area. This would explain the conversion and noteworthy increase that we detected in vineyards (Fig. 1) and cellars over a short period, despite of the reduction of the cropland area in the Montsant DO (Table 1).

Global change would be the most likely explanation of why the Montsant DO red wines shows a drastic increase in alcohol levels in the last years of the study period. There have been big changes in land cover in the Montsant DO during the last two decades, where vineyard cultivation has shown an increase at the expense of other crops in general. Some viticulture practices, such as vine training systems and plant material, have been greatly modified. There have been new plantations of the autochthonous Grenache noir grape and Atlantic red grape varieties have been introduced, which would have reached much higher alcohol levels in their wines than the relegated autochthonous Carignan grape. Furthermore, the yield per hectare in the new plantations would have been higher due to the implementation of the trellis system. Although climate change can partially explain this recent rise in alcohol levels in the Montsant DO red wines, general human-related changes in the last decade could better justify it. The new requirements resulting from the foundation of the Montsant DO in 2001 might appear to constitute a relevant factor. Our results indicate that, despite climate change, the main changes may be attributable to agricultural techniques, and reducing the vulnerability of the sector would be therefore in our hands.

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