Impact of climate change on wine production: a global overview and regional assessment in the Douro Valley of Portugal

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Abstract: This paper examines the nature of climate change, viticulture and wine at the global scale and details changes and projections in the historic Douro wine region of Portugal. Overall, the observed warming over the last fifty years in wine regions worldwide has benefited some by creating more suitable conditions, while others have been challenged by increased heat and water stress. The projected future warming at the global, continent and wine region scales will likely continue to have both beneficial and detrimental impacts by opening up new areas with increasing viability to viticulture, or by severely challenging the ability to adequately grow grapes and produce quality wine. Observations from the Douro region reveal higher growing season temperatures, increases in extreme temperatures, fewer cold events that are not as cold as before, more and higher heat stress events and a lower diurnal temperature range. Projections indicate that further warming may range from 0.8–6.6°C by 2020 to 2080, while precipitation during the growing season is projected to decline by up to 7–22% over the same time period. Continued research and understanding is needed to decrease vulnerability and enhance the adaptive capacity of both the Douro and the global wine industries.

Keywords: climate change; Portugal; Douro Valley; viticulture; wine.

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1 Introduction

Climate is a pervasive factor in the success of all agricultural systems, influencing whether a crop is suitable to a given region, largely controlling crop production and quality and ultimately driving economic sustainability. Climate's influence on agribusiness is never more evident than with viticulture and wine production, where overall it is arguably the most critical aspect in ripening fruit to the optimum characteristics that produce a given wine style (Tate, 2001; Bisson et al., 2002; Schultz and Jones, 2010).

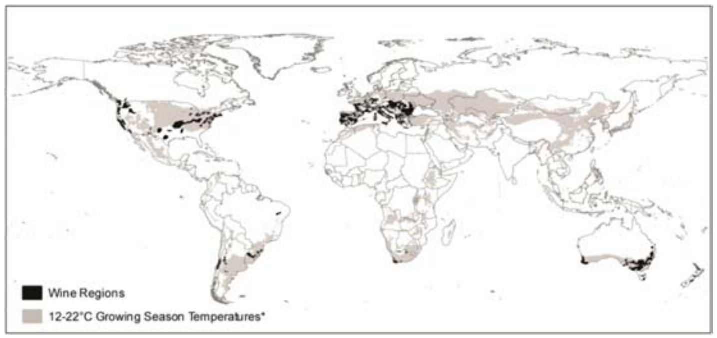
History has shown that winegrape growing regions developed when the climate was most conducive and that shifts in viable wine-producing regions have occurred due to climate changes in the past (Le Roy Ladurie, 1971; Pfister, 1988; Jones, 2006). In Europe, records of dates of harvest and yield have been kept for nearly a thousand years, revealing periods with more beneficial growing season temperatures, greater productivity and arguably better quality in some regions. Other evidence has shown that vineyards were planted as far north as the coastal zones of the Baltic Sea and southern England during the medieval 'Little Optimum' period (roughly 900–1300 AD) when temperatures were up to 1°C warmer. During the High Middle Ages (12th and 13th centuries) harvesting occurred in early September, as compared to late September to early October in the recent past and growing season temperatures must have been at least as warm as those experienced today. However, during the 14th century dramatic temperature declines lead to the 'Little Ice Age' (extending into the late 19th century), which resulted in most of the northern vineyards dying out and growing seasons so short that harvesting grapes in much of the rest of Europe was difficult (Pfister, 1988).

2 Geographical and climatic zones

As in the past, today's wine production occurs over relatively narrow geographical and climatic ranges. Winegrapes also have relatively large cultivar differences in climate suitability, further limiting some winegrapes to even smaller areas that are appropriate for their cultivation (Gladstones, 1992; Jones, 2006). These narrow niches for optimum quality and production put the cultivation of winegrapes at greater risk from both short-term climate variability (vintage to vintage or decadal scale) and long-term climate changes (multi-decadal or longer) than other more broad acre crops (Jones and Webb, 2010). As one of the natural components encompassing the notion of 'terroir', climate arguably exerts the most profound effect on the ability of a region or site to produce quality grapes and therefore, wine. Worldwide, average climatic conditions in wine regions determine to a large degree the grape varieties that can be grown there, while wine production and quality are chiefly influenced by site-specific factors, husbandry decisions and short-term climate variability (Gladstones, 1992). While grapevines respond to a myriad of climate influences, temperature is the most influential factor in the overall growth and productivity of winegrapes (Mullins et al., 1992). At the global scale, the general bounds on climate suitability for viticulture are found between 12–22°C for the growing season in each hemisphere (Figure 1). The 12–22°C climate bounds depict a largely mid-latitude suitability for winegrape production; however, many sub-tropical to tropical areas at higher elevations also fall within these climate zones (Jones et al., 2012). Furthermore, any general depiction of average temperatures will also include large areas that have not been typically associated with winegrape production. This is evident in Figure 1, where large areas of eastern Europe, western Asia, China, the mid-western and eastern US, southeastern Argentina, southeastern South Africa and southern Australia fall within the 12–22°C thresholds. While many of these regions may have seasonal temperatures conducive to growing winegrapes, other limiting factors such as winter minimum temperatures, spring and fall frosts, short growing seasons and water availability would limit much of the areas mapped to the average conditions (Gladstones, 1992). Furthermore, while the vast majority of the world's wine regions are found within these average growing season climate zones, there are some exceptions. For example, there are defined winegrape growing areas in the US (Texas, Oklahoma and the Mississippi delta region), Brazil (São Francisco Valley) and South Africa (Lower Orange River in the Northern Cape) that are warmer than 22°C during their respective growing seasons. However, these regions have different climate risks, have developed viticultural practices to deal with the warmer climates (e.g., two crops per year, irrigation, etc.), or produce table grapes or raisins and do not necessarily represent the average wine region.

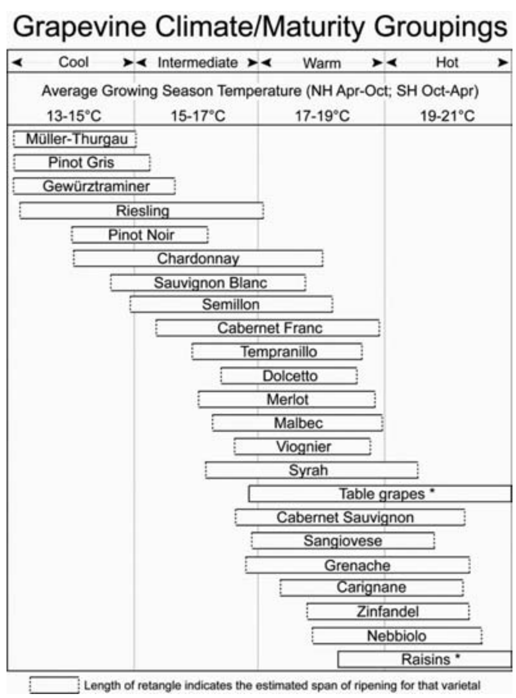
Today, our knowledge of the climate suitability for many of the world's most recognisable cultivars shows that high quality wine production is more realistically limited to 13–21°C average growing season temperatures (Figure 2). The climate-maturity zoning in Figure 2 was developed based upon both climate and plant growth for many cultivars grown in cool to hot regions throughout the world's benchmark areas for those winegrapes (Jones, 2006). While many of these cultivars are grown and produce wines outside of the bounds depicted in Figure 2, these are more bulk wine (high yielding) for the lower end market and do not typically attain the typicity or quality for those same cultivars in their ideal climate. Furthermore, growing season average temperatures below 13°C are typically limited to hybrids or very early ripening cultivars that do not necessarily have large-scale commercial appeal (Jones et al., 2005). At the upper limits of climate, some production can also be found with growing season average temperatures greater than 21°C, although it is mostly limited to fortified wines, table grapes and raisins (up to 24°C).

Figure 1 Global wine regions and 12–22°C growing season temperature zones (April–October in the Northern Hemisphere and October–April in the Southern Hemisphere). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the US, Geographic Indicators in Australia and Brazil and Wine of Origin Wards in South Africa) or areas under winegrape cultivation identified with remote sensing (e.g., Corine Land Cover for Europe) or aerial imagery (e.g., Canada, Chile, Argentina and New Zealand)



Source: Jones et al. (2012)

Figure 2 Climate-maturity groupings based on relationships between phenological requirements and growing season average temperatures for high to premium quality wine production in the world's benchmark regions for many of the world's most common cultivars. The dashed line at the end of the bars indicates that some adjustments may occur as more data become available, but changes of more than ± 0.2 – 0.5°C are highly unlikely



Source: Jones (2006)

An example of cool climate suitability is found with the widely recognised Pinot Noir variety, which is typically grown in regions that span from cool to lower intermediate climates with growing seasons that range from roughly 14.0–16.0°C (e.g., Burgundy or Northern Oregon). The coolest of these is the Tamar Valley of Tasmania, while the warmest is the Russian River Valley of California. Across this 2°C climate niche, Pinot Noir produces the broad style for which is it known, with the cooler zones producing lighter, elegant wines and the warmer zones producing more full-bodied, fruit-driven wines. While Pinot Noir can be grown outside the 14.0–16.0°C growing season average temperature bounds, it typically is unripe or overripe and does not obtain or readily loses its typicity. As examples of intermediate to warmer climate cultivars, the noble winegrapes Cabernet Franc and Cabernet Sauvignon are clearly two of the most widely recognised in the world. The spread of these two cultivars worldwide has produced an assortment of wine styles from quite diverse regions. Figure 2 shows this wide diversity with both Cabernet Franc and Cabernet Sauvignon having roughly 3.5°C climate ranges, nearly double that of Pinot Noir. Cabernet Franc can be grown in intermediate to warm climates (15.4–19.8°C), as evidenced by its quality production in the Loire Valley of France. Cabernet Sauvignon, on the other hand is grown in regions that span from intermediate to hot climates with growing seasons that range from roughly 16.8–20.2°C (e.g., Bordeaux or Napa). The lower climate limit for Cabernet Sauvignon suitability is found in Hawke's Bay, New Zealand, while the upper climate limit is found in Robertson, South Africa.

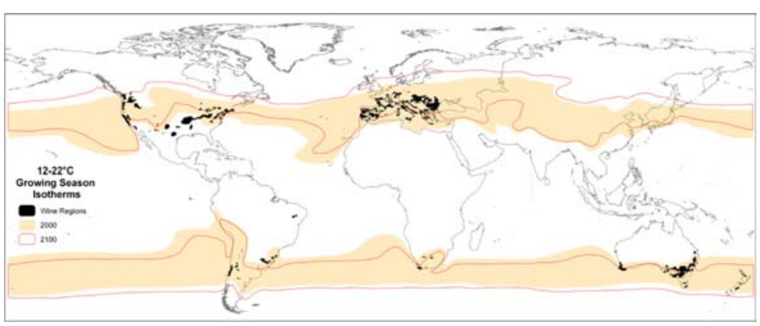
3 Viticulture and wine impacts

Wine quality impacts and challenges related to climate change and shifts in climate maturity potential have been and will likely continue to be evidenced mostly through more rapid plant growth and out of balance ripening profiles (Bindi et al., 1996; Schultz, 2000; Jones et al., 2005; Webb et al., 2008). For example, if a region currently experiences a ripening period that allows sugars to accumulate to favourable levels, maintains acid structure and produces the optimum flavour profile for that variety, then balanced wines result. In a warmer than ideal environment, the grapevine goes through its phenological events more rapidly, resulting in earlier and likely higher sugar ripeness and while the grower or winemaker is waiting for flavours to develop, the acidity is lost through respiration, resulting in unbalanced wines without greater after-harvest inputs or adjustments in the winery. As a result of warming conditions to date, higher alcohol levels have been observed in many regions (Jones, 2007). For example, research has found that potential alcohol levels of Riesling at harvest in Alsace have increased by 2.5% (by volume) over the last 30 years; this was highly correlated to significantly warmer ripening periods and earlier phenology (Duchêne and Schneider, 2005). For Napa, average alcohol levels have risen from 12.5% to 14.8% from 1971–2001, while acid levels fell and the pH climbed (Vierra, 2004). While higher alcohol can be viewed by some as a good thing, alcohol makes wine 'hotter' and less food friendly. One of the additional issues related to wines with higher alcohol levels is that they typically will not age as well or as long as wines with lower alcohol levels. While many may argue that this trend is due to the tendency for bigger, bolder wines driven by wine critics and the economics of vintage rating systems, research has shown that that climate variability and change are responsible for over 50% of the trend in alcohol levels (Jones, 2007). Furthermore, the climates of wine regions today allow growers to hang the fruit on the vine longer – this could not be done in the climates of as little as 30–50 years ago when earlier fall frosts occurred. Finally, harvests that occur earlier in the summer, in a warmer part of the growing season (e.g., August or

September instead of October in the Northern Hemisphere) will result in hotter fruit being harvested (which readily loses flavour and aroma compounds), with the potential for greater fruit desiccation, without greater irrigation inputs (Schultz and Jones, 2010).

At the global scale, trends in wine region climates have resulted in warmer growing seasons that have allowed many regions to produce better wine, while future climate projections indicate more benefits for some regions and challenges for others (Kenny and Harrison, 1992; Jones et al., 2005). The observed growing season warming rates for numerous wine regions across the globe during 1950–2000 averaged 1.3°C, with the warming driven mostly by changes in minimum temperatures, accompanied by greater heat accumulation, a decline in frost frequency that is most significant in the dormant period and spring, earlier last spring frosts, later first fall frosts and longer frost-free periods (Jones et al., 2005). However, climate model projections through to 2100 predict growing season warming of an additional 2.0–4.5°C on average, with spatial analyses showing the potential for relatively large latitudinal shifts in viable viticulture zones, indicating increasing areas on the poleward fringe in the Northern Hemisphere (NH) and decreasing areas in the Southern Hemisphere (SH) due to the lack of land mass (Figure 3). Within regions, spatial shifts are projected to be toward the coast, up in elevation and to the north (NH) or south (SH). Furthermore, climate variability analyses have shown evidence of increased frequency of extreme events in many regions (Jones et al,. 2012), while climate models predict a continued increase in variability globally. In addition, phenological changes observed over the last 50 years for numerous locations and varieties globally indicate that grapevines have responded to the observed warming with earlier events (bud break, bloom, véraison and harvest) and shorter intervals between events that range from 6–17 days, depending on variety and location (Jones, 2007; Tomasi et al., 2011).

Figure 3 Changes in general climate zones for viticulture from 2000 to 2100. Climate data is derived from the National Center for Atmospheric Research's Community Climate System Model (CCSM) for observed (2000) and an A1B (mid-range scenario). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the US, Geographic Indicators in Australia and Brazil and Wine of Origin Wards in South Africa) or areas under winegrape cultivation identified with remote sensing (e.g., Corine Land Cover for Europe) or aerial imagery (e.g., Canada, Chile, Argentina and New Zealand) (Jones et al., 2012). The general climate zones are given by the 12–22°C growing season (April–October in the Northern Hemisphere and October–April in the Southern Hemisphere) average temperatures (see online version for colours)



To place viticulture and wine production in the context of climate suitability and the potential impacts from climate change, Figure 2 provides the framework for examining today's climate-maturity ripening potential for premium quality wine varieties grown in cool, intermediate, warm and hot climates. From the general bounds that cool to hot climate suitability places on high quality wine production, it is clear that the impacts of climate change are not likely to be uniform across all varieties and regions, but are more likely to be related to climatic thresholds, whereby any continued warming would push a region outside the ability to produce quality wine with existing varieties. For example, if a region has an average growing season temperature of 15°C and the climate warms by 1°C, then that region is climatically more conducive to ripening some varieties, while potentially less so for others. If the magnitude of the warming is 2°C or larger, then a region may potentially shift into another climate maturity type (e.g., from intermediate to warm). While the range of potential varieties that a region can ripen will expand in many cases, if a region is a hot climate maturity type and warms beyond what is considered viable, then grape growing becomes challenging and maybe even impossible.

4 Douro wine region climate observations

Understanding the climate structure in wine regions helps define/understand cultivar suitability, along with wine style, production and quality potential. However, a complete region-wide assessment is difficult due to station density and areas where climate station location is generally not representative of vineyard locations. However, interpolation of stations using topography, known horizontal and vertical atmospheric patterns and latitude and longitude can generate tremendous improvement in spatial climate data and understanding. Today, many new spatial climate data products are now available, or being developed, at resolutions that are useful for viticulture. This assessment uses the WorldClim database (Hijmans et al., 2005). WorldClim consists of monthly averages of climate parameters, as measured at weather stations from a large number of global, regional, national and local sources for 1950–2000, that are interpolated using the thin-plate smoothing spline algorithm implemented in ANUSPLIN. The data have a 30 arc second spatial resolution (0.86 km^2 at the equator, ~1 km for the mid-latitudes) and have undergone strong cross validation and uncertainty assessments (Hijmans et al., 2005).

4a Precipitation

The climate of the Douro wine region (Figure 4) is characterised by a strong inter-annual consistency of total insolation, temperature and potential evapotranspiration and significant inter-annual variation in precipitation (ADVID, 2007). A combination of numerous factors (climate, soil, varieties and technology) in the region has contributed to a significant fluctuation in inter-annual production (Figure 5) and a low average vine yield of around 30 hl ha^{-1}, which can fluctuate between 21 (Douro Superior) and 35 hl ha^{-1}(Baixo Corgo) (ADVID, 2007). Several authors have shown that production variability in the region is largely driven by variations in late winter and early spring precipitation and temperatures during spring (Santos et al., 2011; Gouveia et al., 2011), but that production models also need dynamic updating as the season progresses (Cunha and Richter, 2011) and take into account the adaptive capacity of the grapevines, for example, to variations in the CO_2 atmospheric concentration (Moutinho-Pereira et al., 2009; Gonçalves et al., 2010). On examination of the annual precipitation during 1950–2000, it is found that the Douro wine region averaged 950 mm over the entire region, but ranged from a low of 643 mm in the driest locations in the Douro Superior to a high of 1,625 mm in the wettest areas in the upper elevations in the Baixo Corgo (Table 1, Figure 6). Winter precipitation amounts (November through March) are approximately 60–65% of the annual total, while growing season precipitation is roughly 35–40% (not shown). During the active growth stages of grapevines (April to September), the average rainfall varies between 189 and 326 mm, while it is only 50 to 85 mm during the ripening stage (from July to September) during the 1950–2000 time period (not shown). The low precipitation during these periods along with significant temperature and radiation availability give rise to situations of intense summer plant-soil-water stress, particularly in the Cima Corgo and Douro Superior sub-regions (Figure 4).

Figure 4 Elevation of the Douro wine region and its three main sub-regions, the Baixo Corgo, Cima Corgo and Douro Superior (see online version for colours)

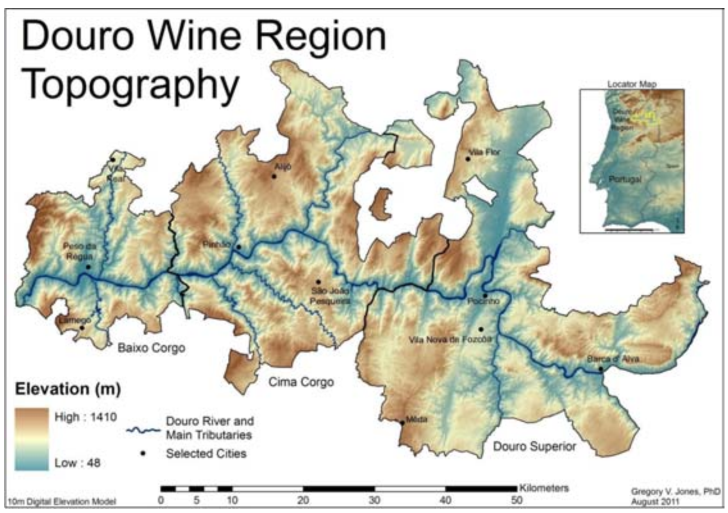
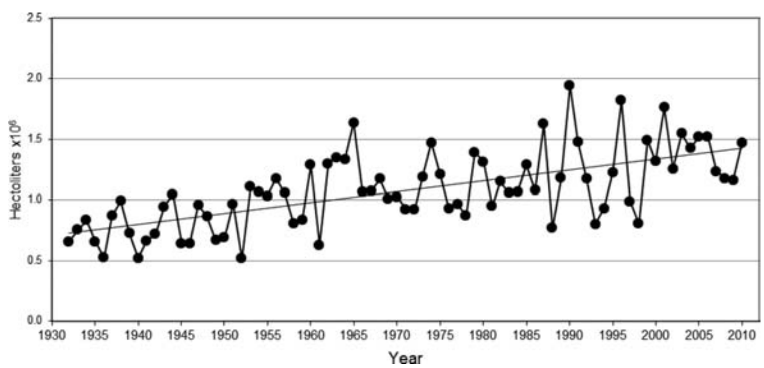


Figure 5 Regional production trends between 1932 and 2010



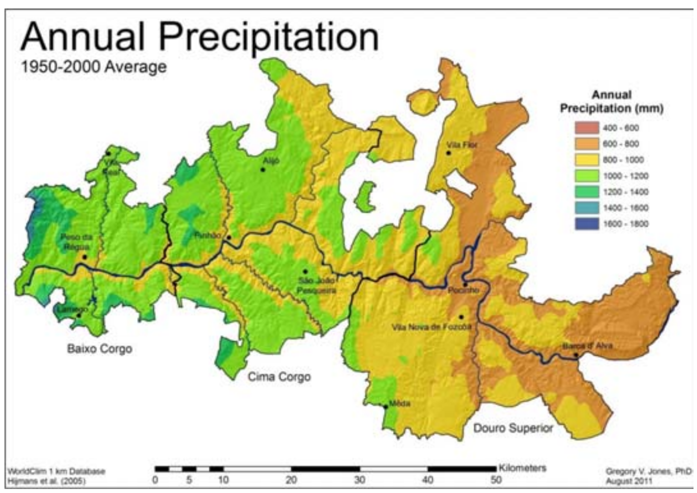
Source: Martins (1990); Casa do Douro and IVDP

Table 1 Quartile statistics for annual precipitation (mm) and growing season average temperatures (°C, April–October) for the three sub-regions of the Douro wine region. The values represent the spatial statistics of each variable; absolute minimum, 25%, median, 75% and absolute maximum.

Region	*Minimum*	*25%*	*Median*	*75%*	*Maximum*
Annual Precipitation (mm)					
Baixo Corgo	971	1128	1190	1282	1625
Cima Corgo	778	938	1026	1089	1314
Douro Superior	643	776	832	927	1123
Growing Season Average Temperature (°C)					
Baixo Corgo	12.1	16.5	17.5	17.9	19.2
Cima Corgo	14.9	16.8	17.5	18.3	19.7
Douro Superior	15.6	17.1	18.0	18.6	19.7

Data Source: WorldClim Database Hijmans et al. (2005)

Figure 6 Distribution of average annual precipitation in the Douro wine region during 1950–2000, WorldClim Database (see online version for colours)



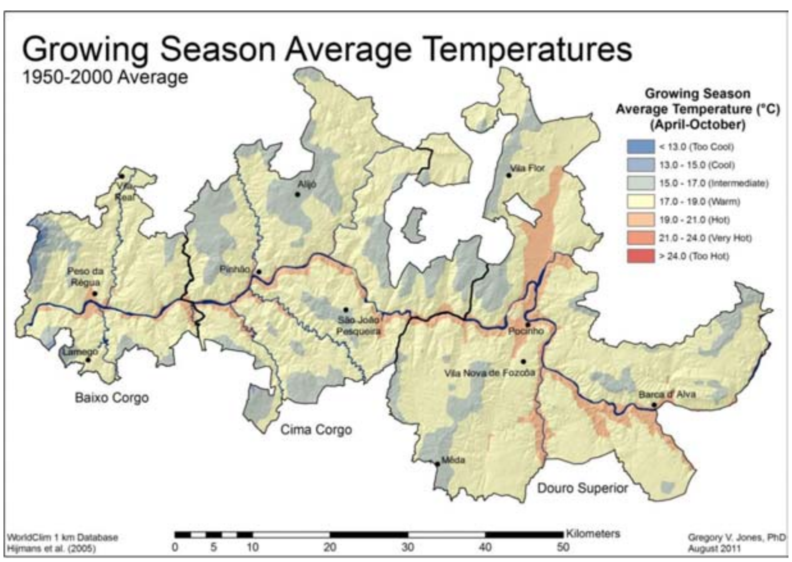
Source: Hijmans et al. (2005)

In the Douro wine region, as in most regions with a Mediterranean climate, the high variability in precipitation along with high evapotranspiration during the summer period is normally one of the major factors limiting grapevine development and production and quality of the harvest (Sotés, 2001). In the case of the Douro wine region, grapevines are subject to a high potential water deficit whereby the difference between evapotranspiration and precipitation can be as high as 730–750 mm throughout the bud break to harvest period (Malheiro et al., 2007). However, it should be noted that an important part of the geographic area of the Douro is subject to low precipitation regimes (33% of the area has less than 600 mm – Figure 6). In addition, the likelihood of experiencing a dry year is generally greater than that of years with above-average rainfall. The most efficient methods for assessing plant water status include measuring water potential before dawn, which reflects the plant water energy status and is an accurate diagnosis of the net CO_2 assimilation, of stomatal conductance and intrinsic Water Use Efficiency (WUE) (Moutinho-Pereira et al., 2007). Recent observations show that years with high water deficit such as 2002, 2004 and 2005 led to water potential incompatible with the normal physiological processes of the grapevine (Deloire et al., 2005; Alves et al., 2006a, 2006b; Alves and Costa, 2011), which in turn affected yield and quality. According to Schultz (2000), this limitation may be aggravated in the future, given that climate change scenarios show a potential reduction of soil moisture conditions of up to 70%, which would likely reduce yield in countries in southern Europe, particularly the Iberian Peninsula (Stigliani and Salomons, 1992).

4b Temperature

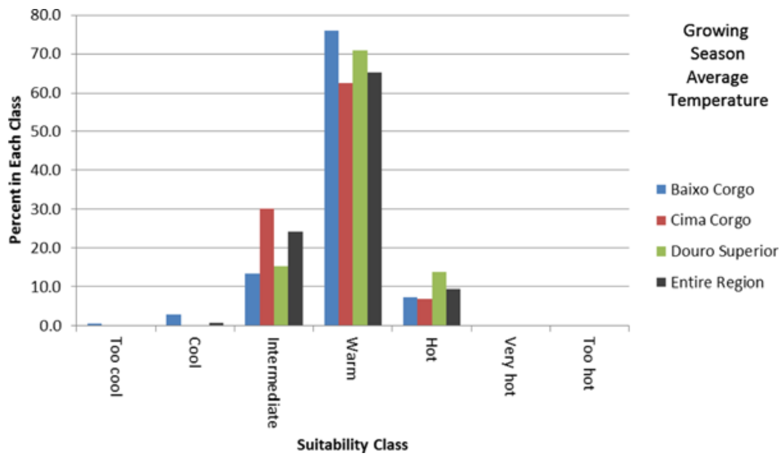
Growing season temperatures (April–October) in the region for the period 1950–2000 averaged 17.8°C over the entire region, but ranged from a low of 12.1°C in the upper elevations in the Baixo Corgo to 19.7°C in the warmest areas in the Douro Superior (Table 1; Figure 7). Overall, the region is 65% an Intermediate climate, 24% a warm climate and nearly 10% a 'Hot' climate type (Figure 8). By sub-region, each area is predominately a warm climate type with 76, 63 and 71% of the area in the Baixo Corgo, the Cima Corgo and the Douro Superior, respectively. The Cima Corgo has more area as an Intermediate climate type than the other two regions, while the Douro Superior has twice the area in a 'Hot' climate type as the other two regions and approaches or exceeds optimum growing temperatures for some varieties (Jones et al., 2005). In addition, increasing trends during the growing season in both maximum and minimum temperatures have been seen for the three main climate stations between 1967 and 2010 (Figure 9). During this 43-year period, minimum temperatures have increased 2.6°C on average, almost double the increase in maximum temperatures (1.4°C). Furthermore, the trend shows that average growing season temperatures during the second half of 1967–2010 are 1.3ºC warmer than the first half of the period, which now places Régua in the 'Hot' climate suitability in Figure 2.

Figure 7 Distribution of growing season average temperatures in the Douro wine region during 1950–2000, WorldClim Database (see online version for colours)



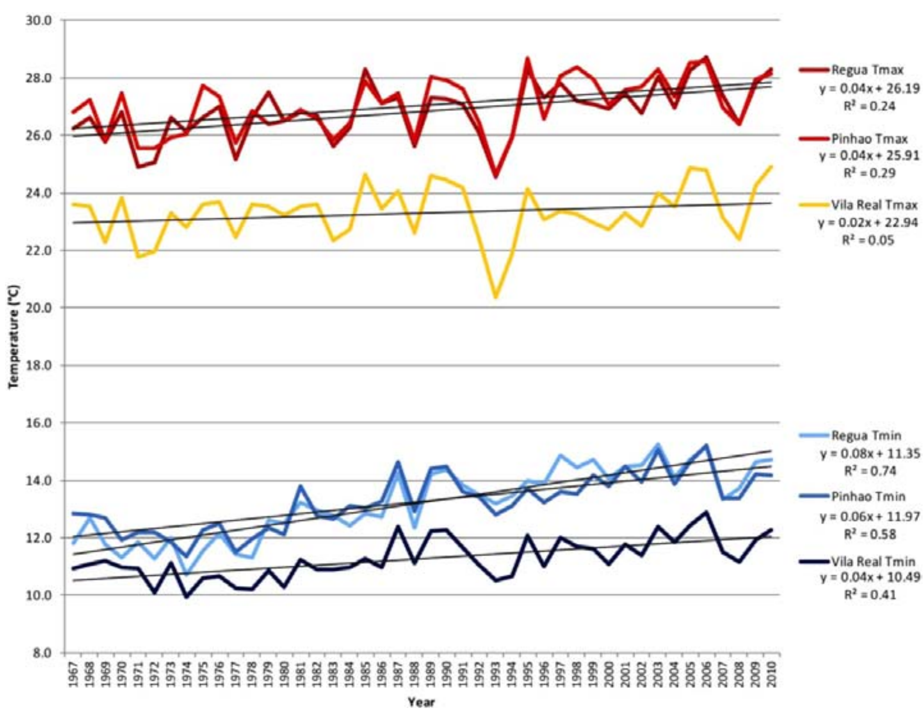
Source: Hijmans et al. (2005)

Figure 8 Percentage of the Douro wine region and the three sub-regions in each class of the growing season average temperature index during 1950–2000. Data Source: WorldClim Database (see online version for colours)



DataSource: WorldClim Database Hijmans et al. (2005)

Figure 9 Growing season average temperature (April–October) trends for the climate stations from Régua, Pinhão and Vila Real in the Douro wine region between 1967 and 2010 (see online version for colours)



Source: (ADVID, 2007)

4c Climate extremes

It is important to note that the effect of climate on grapevine processes is conditional not only on the changes in average values, but more importantly, on the intensity and frequency of occurrence of extreme values. For example, Moutinho-Pereira et al. (2004) compared the physiological performance of Touriga Nacional in three locations with different mesoclimates in the Douro (Vila Real, Pinhão and Almendra with 1000, 650 and 450 mm of rainfall per year, respectively) and found that photosynthetic productivity fell from Vila Real to Pinhão, was due to a significant increase in stomatal limitations. However, when grapevines were subject to more severe water stress, as is the case in Almendra, seasonal and daily net CO_2 assimilation, stomatal conductance, CO_2 concentration in intercellular spaces and intrinsic WUE suggest not only the occurrence of stomatal limitations but also of non-stomatal limitations in the decline in photosynthetic productivity. Furthermore, the optimum photosynthetic response range for grapevines is for maximum daytime temperatures from 20 to 35ºC, depending on the location and variety (Carbonneau et al., 1992). Above this temperature, the photosynthetic response is lowered, depending on a combination of other factors such as water availability. Temperatures above 40–45ºC may cause irreversible losses, bypassing the grapevine's acclimation capacity that Chaves et al. (1987) and Chaves and Rodrigues (1987) have noted for varieties originating in warm regions.

To assess climate extreme characteristics and trends in the Douro wine region, this research uses the CCl/CLIVAR/JCOMM Expert Team (ET) on the Climate Change Detection and Indices (ETCCDI) tool. The main goals of the tool are to check for data homogeneity and the quality control of outliers (unrealistic values, bad data points, etc.) and to provide a suite of indices for understanding the behaviour of climate at a given station. The aim of climate data homogenisation is to adjust observations, if necessary, so that temporal variations in the adjusted data are caused only by climate processes. In terms of station climate assessment, ETCCDI developed a suite of 27 core indices which provide a common framework using which the frequency or severity of extreme climate events can be assessed worldwide. For a review on climate data homogenisation and the ETCCDI tool, can see Peterson et al. (1998) and Peterson (2005). Therefore, the 27 indices are calculated for Vila Real, Régua and Pinhão after data quality control and homogenisation were properly assessed. The results show a generally coherent pattern in trends across a sub-set of 12 of the 27 indices (Table 2). However, Régua and Pinhão, which are located in the heart of the Douro wine region (Figure 4), trended at a higher rate and over each of the 12 indices, compared to Vila Real, which is near the periphery of the region and at a higher elevation (Table 2). Over 1967–2010, numerous cold extremes have changed, with frost days ($T < 0°C$) declining 15 days on average; the cold spell duration indicator (annual count of days with at least 6 consecutive days when the minimum temperature is below the 10th percentile) declining 14 days on average and the extreme cold nights declining 13 days on average. For warm extremes, the number of summer days ($T > 25°C$) has increased by 23 days on average; the number of heat stress events ($T > 35°C$) has increased by 17 days on average; days with maximum temperatures above the 90th percentile have increased by 7 and the absolute maximum temperature during the summer has gone up by 2.30°C (Table 2). Additionally, significant changes in minimum temperatures are evident, with tropical nights ($T > 20°C$) increasing by 10 days; warm nights when the minimum temperature is above the 90th percentile increasing by 7; and both absolute maximum and absolute minimum temperatures going up by 3.5 and 1.8°C, respectively. Finally, given the greater warming in minimum compared with maximum temperatures, the diurnal temperature range has declined by 1.2°C on average (Table 2).

Table 2 Sub-set of 12 of the 27 core climate extremes indices calculated with the ETCCDI tool. All trends listed are significant at the 0.05 level

Indicator name	*Units*	*Régua trend*	*Vila Real trend*	*Pinhão trend*	*Average trend*
Frost days	Days	–18.7		–11.4	–15.1
Cold spell duration indicator	Days	–16.8		–10.5	–13.6
Summer days (>25°C)	Days	25.6		20.7	23.1
Heat Stress days (>35°C)	Days	18.6		16.1	17.3
Tropical nights (>20°C)	Days	13.4	6.1	9.5	9.7
Cool nights (Tmin10p)	Days	–19.8	–5.8	–13.4	–13.0
Warm nights (Tmin90p)	Days	18.9	9.3	12.0	13.4
Warm days (Tmax90p)	Days	7.9		6.5	7.2
Maximum Tmax	°C	2.2		2.5	2.3
Maximum Tmin	°C	4.3	2.9	3.3	3.5
Minimum Tmin	°C	1.9	1.2	2.2	1.8
Diurnal Temperature Range	°C	–1.9	–0.6	–1.0	–1.2

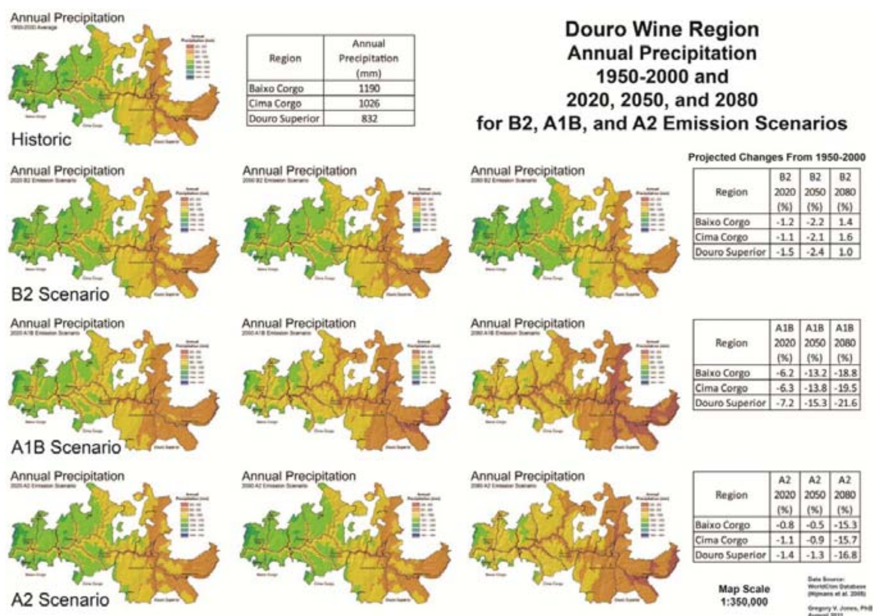
5 Douro wine region climate projections

To examine the potential future climate structure in the Douro wine region and have it be complementary to the spatial data discussed above, this research used downscaled data developed in the Decision and Policy Analysis (DAPA) programme in the International Centre for Tropical Agriculture (CIAT). The data were originally obtained from the IPCC data portal and re-processed using a spline interpolation algorithm of the anomalies and the current distribution of climates from the WorldClim database developed by Hijmans et al. (2005). All GCMs in this database come from the fourth IPCC Assessment Reports (IPCC, 2007). The process assumes that the geographies of changes in climates do not vary too much at regional scales and that the relationships between the different variables will remain basically the same in the future (Ramirez and Jarvis, 2010). As such, the data surfaces are generated using an empirical downscaling approach instead of remodelling the climate patterns using an Regional Climate Model (RCM). For the assessment of the Douro wine region, the research used downscaled GCM output from the HADCM3 climate model (Gordon et al., 2002) at the same 1 km resolution of the WorldClim data, for three future emission scenarios: B2 (lower energy requirements), A1B (high emissions, but balance across sources) and A2 (higher energy requirements) for three time slices centred on 2020, 2050 and 2080. It is important to note that global CO_2 levels are following the A2 emission scenario and that new Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) being developed in the IPCC 5th Assessment Report will provide updates to these climate models.

5.1 Precipitation

Projections for annual precipitation averaged over the sub-regions indicate a 1–7% decrease by 2020, a 1–15% decrease by 2050 and a 1–22% decrease by 2080 (Figure 10). For each time period, the A1B scenario shows the greatest potential decrease in annual precipitation from the base period. Winter precipitation projections are mixed, with the B2 scenario indicating increases of 7–17% from 2020 to 2080, the A1B scenario specifying slight decreases of 1–7% and the A2 scenario indicating increase of up to 9% by 2050 and decreases of 2–3% by 2080 (not shown). Growing season precipitation, on the other hand, is projected to decrease across all scenarios and time slices with decreases of 40% across all sub-regions by 2080 (not shown). The greatest decline in precipitation over all seasons is shown to occur in the Douro Superior, which is already the driest in the region (Figure 6).

Figure 10 Average annual precipitation for the Douro wine region. The upper row is the historic conditions during 1950–2000, with the lower rows representing the B2, A1B and A2 SRES emission scenarios for three future time slices (2020, 2050 and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo and Douro Superior) and the projected changes in % from the 1950–2000 base period. (see online version for colours)

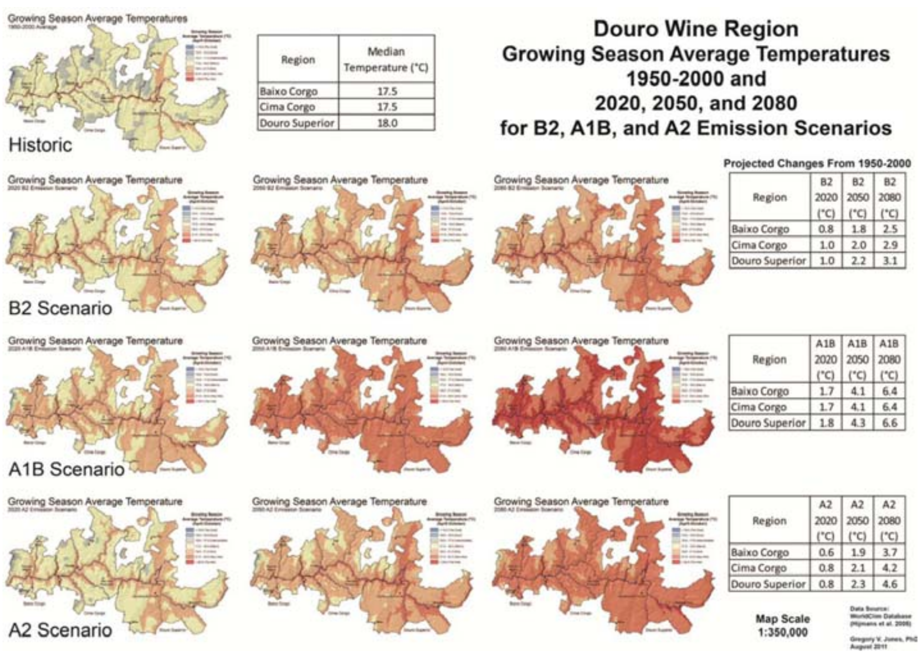


Data Source: Ramirez and Jarvis (2010) and the WorldClim Database Hijmans et al. (2005)

5.2 *Temperature*

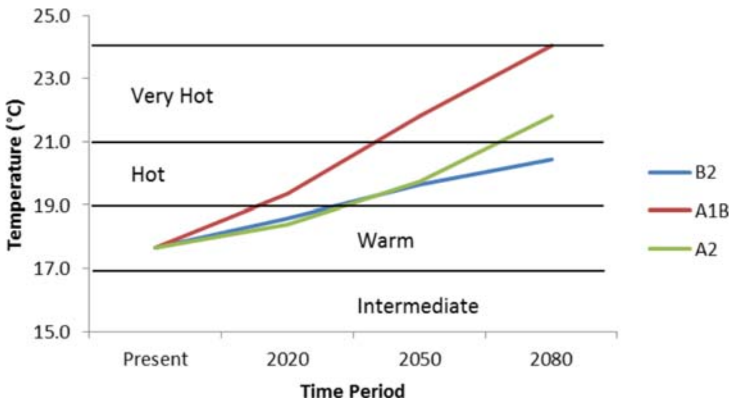
For annual temperatures, the projections from the base period, averaged over the sub-regions, indicate a warming of 0.5 to 1.4°C by 2020, a 1.4 to 3.3°C warming by 2050 and a 2.1 to 5.1°C warming by 2080 (not shown). During the growing season, average temperatures are projected to warm by 0.6 to 1.8°C by 2020, with the A1B scenario indicating the greatest warming (Figure 11). Projections for 2050 indicate further warming ranging from 1.8 to 4.3°C, while those increases for 2080 are projected to be 2.5 to 6.6°C over the base period. Average growing season increases of these magnitudes have the potential to change the suitability of the Douro wine region to certain varieties, as indicated by Figure 11. Projected warming by 2020, in terms of the overall situation, may result in a region wide shift from average to the upper range of warm climate suitability and even potentially Hot climate suitability with the A1B scenario. By 2050, the region on average is projected to become a hot climate suitability region, or potentially in the Very Hot class in the A1B scenario (Figure 12). By 2080, further projected temperature increases indicate that the Douro wine region has the potential to be mostly a Very Hot climate for wine production (A2 and A1B scenarios) or Hot, as seen with the B2 scenario. Projections for maximum and minimum temperatures during the growing season both show increases over the base period, but with maximum temperatures warming to a higher degree than minimum temperatures (not shown). For example, maximum temperatures are projected to increase by 2.1–3.0°C by 2050 in the B2 scenario, while minimum temperatures are projected to increase by 1.3–1.7°C (results are similar in the other scenarios and time slices). In addition, projected increases in the winter, in both maximum and minimum temperatures, are roughly half the projections during the growing season (not shown). Similar to the precipitation projections, the results for temperatures indicate greater increases in the Douro Superior, which is already the warmest in the region (Figure 7).

Figure 11 Growing season average temperatures (April through October) for the Douro wine region. The upper row is the historic conditions during 1950–2000, with the lower rows representing the B2, A1B and A2 SRES emission scenarios for three future time slices (2020, 2050 and 2080). The tables represent the median values across the three sub-regions (Baixo Corgo, Cima Corgo and Douro Superior) and the projected changes in °C from the 1950-2000 base period. (see online version for colours)



Data Source: Ramirez and Jarvis (2010) and the WorldClim Database Hijmans et al. (2005)

Figure 12 Growing season average temperatures (April through October)) spatially averaged over the entire Douro wine region for the present (1950–2000), 2020, 2050 and 2080 time slices and the B2, A1B and A2 SRES emission scenarios. The horizontal gridlines represent the climate-maturity classes in Figure 2. (see online version for colours)



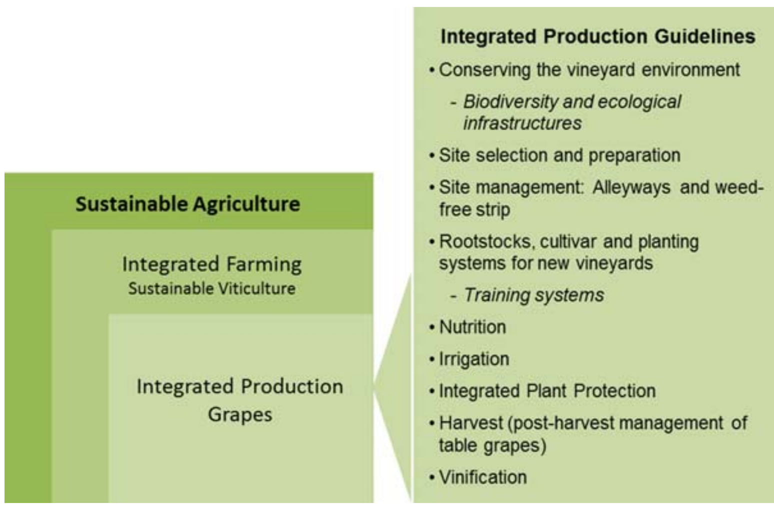
Data Source: Ramirez and Jarvis (2010) and the WorldClim Database Hijmans et al. (2005)

6 Discussion and future work

Overall, winegrapes are a climatically sensitive crop, whereby quality production is achieved across a fairly narrow geographic range (Jones et al., 2005; Jones, 2006). In addition, winegrapes are grown largely in mid-latitude regions that are prone to high climatic variability that drive relatively large vintage differences in quality and productivity. However, while understanding the climate structure and variability in wine regions worldwide provides more exacting cultivar selection and vintage to vintage production management, the projected rate and magnitude of future climate change will likely bring about numerous potential impacts for the wine industry (Bisson et al., 2002). These impacts include added pressure on increasingly scarce water supplies, additional changes in grapevine phenological timing, further disruption or alteration of balanced composition in grapes and wine, regionally-specific needs to change the types of varieties grown, necessary shifts in regional wine styles and spatial changes in viable grape growing regions (Jones et al., 2005). While winegrapes may seem like a frivolous crop to worry about, the plant's extraordinary sensitivity to temperature makes the industry a strong early-warning system for problems that all food crops will likely confront as climates continue to change. In *vino veritas*, the Romans said: In wine, there is truth. The truth now is that the earth's climate is changing much faster than the wine business and virtually every other business on earth, is preparing for. While uncertainty exists in the exact rate and magnitude of climate change in the future, it would be advantageous for the wine industry to be proactive in assessing the impacts, invest in appropriate plant breeding and genetic research, be ready to adopt suitable adaptation strategies, be willing to alter varieties and management practices or controls, or mitigate wine quality differences by developing new technologies.

To help address these issues in the Douro wine region, the Association for the Development of Viticulture in the Douro Region (ADVID) is helping growers and producers by conducting important data collection, analysis and discussion on the best strategies to reduce vulnerability and increase adaptive capacity in the face of changing climate (ADVID, 2007). Currently, the concept of sustainable viticulture, including guidelines for integrated production of winegrapes, requires that the wine industry optimise available resources to guarantee environmentally responsible viticulture (Malavolta and Boller, 1999). Thus mitigation of the effects of climate change should derive from a series of farming practices (e.g., land levelling, tillage, variety and rootstock, training system and late pruning and irrigation management when necessary) and applying the International Organization for Biological and Integrated Control's (IOBC) Guidelines for Integrated Production in Viticulture, which guarantee the development of sustainable viticulture (Alves and Magalhães, 2001) (Figure 13).

Figure 13 Integration of Integrated Production components in sustainable viticulture (see online version for colours)



Source: Alves and Magalhães (2001), adapted from the IOBC

The Douro wine region is rich in landscape and plant characteristics that may help mitigate the deleterious effects of climate change. First of all, the region's geomorphology and relief contribute to multiple meso- and micro-climate situations, which may provide some spatial adaptation strategies. Furthermore, the landscape provides growers with choices in cultivation techniques to manage the ecophysiological dimension of the environment. One characteristic that will be very important is how growers can adapt the landscape and vineyards to help balance global photosynthetic activity of the grapevine and water loss by transpiration. Although some of these techniques have been studied, such as mulching (essential for future management of the added risks of erosion resulting from the projected increase in extreme rainfall events), others, such as land levelling, WUE, the use of other varieties, rootstocks and training systems need to be studied more to better understand the relationships and how they can be applied in a sustainable manner in the Douro wine region's different ecological situations.

A highly significant factor in the management of changes that may be required due to climate change is the genetic heritage of the plant material, particularly the myriad varieties used in the region and their oenological performance (Almeida, 1998). Although the general characteristics and aptitude for drought resistance of rootstocks have been studied (Sousa et al., 1998; Alves and Magalhães, 2001, Alves et al., 2011), it is above all the vast heritage of varieties grown in the Douro wine region that will provide some of the most useful tools for wine growers, both through the different thermal requirements of varieties and the elasticity of their phenological behaviour (Lopes et al., 2007) and their different physiological responses (Brito et al., 2004). These authors found that the most commonly used varieties in the Douro wine region show a variable response to environmental stresses such as soil water availability. For instance, for cultivars such as Touriga Franca and Tinta Barroca, the most negative water potential was associated with lower photosynthetic rates than other cultivars, such as Touriga Nacional and Tinto Cão. For Tinto Cão, despite the chlorotic appearance of its leaves, they observed that the greater assimilation activity was related to greater cell wall rigidity and a photosynthetic apparatus better adapted to high summer stress conditions (Moutinho-Pereira et al., 2007). Recently, Costa et al. (2011) found that the variety Touriga Nacional is well adapted to warmer climate conditions when water is not limited, due to its higher capacity for heat dissipation via evaporative cooling.

To assess and plan for future climate change scenarios on the Douro wine region, growers and producers working with ADVID have developed a plan to increase common knowledge of the current situation, to further develop models to simulate the impact of climate change on the region and develop strategies for mitigation of and adaptation to the impacts. These proposals result from studies of the current knowledge on the subject, a compilation and processing of the information available and contacts and working meetings at research centres dedicated to this issue. They include the following components:

A. Information collection and structuring reference data for the Douro wine region

Despite a long history of observation and data collection, this region lacks a comprehensive compilation, systematisation, reanalysis and interpretation of both data from experimental studies and observational networks (e.g., climate data). ADVID is undertaking this process through an exhaustive collection of data and analysis of trends in production characteristics and their relationship with general climate situations, as well as information on winegrape harvest dates, phenology and phytosanitary use in the Douro wine region.

B Structuring a reference index for harvest quality and to help validate the climate effect

A literature review has shown that although harvest quality can be evaluated using different parameters, there is a dearth of appropriate data for analyses over longer time scales. Typically, there is only commercial criteria (valuation of premium wines such as in California or grape prices as in Australia), or qualitative criteria based on the rating attributed to the vintage on a regional basis (Esteves and Orgaz, 2001; Orlandini et al., 2005; Grifoni et al., 2006). This last approach uses ratings from national institutes or institutes that manage the corresponding controlled appellations, or international institutes (e.g., Sotheby's or Wine Enthusiast) (Jones et al., 2005). With regard to the Douro wine region and following the same logic as for Champagne, (Jones et al., 2005) noted that the discontinuity of ratings (Sotheby's) may be the source of the difficulty in relating them to climate. Thus, the proposal for this work includes, besides the analysis of ratings available (IVV and vintage declarations), the creation of a harvest assessment index, which can include different references, using for more recent years data from the annual vintage tasting by ADVID and questionnaires to entities in the sector.

C. Increasing the resolution of observed and projected climate data

Large-scale climate data, while very useful for general approaches, may present limitations for more precise interpretations of the effects of climate and future scenarios on wine quality, especially in a region with such topographic variation as the Douro wine region.

Future climate model data is normally available from many sources (e.g., the Hadley Centre in England), but typically cover a single 2.5º × 2.5º grid that would represent all of Portugal or smaller grids of 0.5º × 0.5º that are still large and attempt to characterise a very heterogeneous area. To adequately represent a wine region such as the Douro, regional downscaled models are necessary (Moriondo and Bindi, 2004; Jones et al., 2005). It is necessary to enable assessments at scales of 25–50 km or less. However, to conduct appropriate regional downscaling requires a sound observational network to validate the models. In the Douro wine region, the data network is scattered and has time period gaps. As part of the assessment, ADVID will collect, validate and collate all available climate data sources to improve the observational data network and facilitate the downscaling of climate model output appropriate for the Douro wine region.

D. Study of the impact on the Douro wine region of global and regional atmospheric circulation influences on production and quality of Douro wine

Knowing that global to regional atmospheric circulation characteristics influence local scale climatic conditions, this work will also examine relationships between the North Atlantic Oscillation (NAO) and other circulation mechanisms and harvest production and quality. Given that many of the global to regional climate variability mechanisms have their most dominant influence in the winter and spring, it is, therefore, possible to also establish estimates of production and quality for the current vintage.

E. Modelling climate change on the growth of grapevines based on growth simulation models:

To better understand potential impacts from climate variability and change in the Douro wine region, ADVID will employ crop growth simulation models, also known as mechanistic models (e.g., DSSAT 4.0, STELLA 2.0 or the STICIS-Vigne model, which is used by the SIAMVITI project at the national and regional levels), to help model the grapevine system in the region. These models allow for incorporating the influences of climate and edaphic characteristics, along with the integration of different technical management strategies to be used for estimates of potential crop yield, phenological development, physiological growth, nitrogen and water cycles, for example.

F. Establishing zoning principles aimed at climate change issues:

Considering that one of the potentials of the Douro wine region for minimising aspects related to climate change is its diversity of topography and plant material available, their correct evaluation and optimisation will have to be an integral part of vineyard zoning in the region (Oliveira et al., 2000). In this respect, ADVID is working with various institutions to develop a region-wide vineyard zoning proposal that will incorporate landscape and soil variations, with cultivar potential and climate change concerns.

G. Drawing up a handbook with a technical itinerary to adapt the growing of vines to the impact of climate change:

To transfer information and innovation relative to adaptation to climate change to the Douro wine industry, ADVID will produce a handbook with reference practices for viticulture. This handbook will cover aspects of crop adaptation and acclimatisation to higher temperatures and most importantly, strategies for the rational management of water resources available to the plant.

7 Conclusions

Climate exerts a dominant influence on wine production, driving baseline suitability, largely controlling crop production and quality and ultimately driving economic sustainability. The global assessment of wine production and climate change presented in this paper details the sensitivity of the crop to climate and the narrow ranges in which winegrapes are grown today. Given these issues, small changes in climate have the potential to bring about significant changes in the management of existing vineyards and changes in the varieties planted in wine regions worldwide and drive potential shifts in suitable zones for viticulture with some regions becoming too warm all together, while others become more viable.

The Douro wine region has a long history of quality wine production, which is conducted over a complex landscape with steep slopes and in generally warm and dry conditions. The results from this work indicate that general station trends in the region show higher minimum and maximum temperatures, increases in extreme temperatures, fewer cold events that are not as cold as before, more and higher heat stress events and a lower diurnal temperature range. Future projections over three different emission scenarios indicate a range of growing season warming from 1950–2000 of 0.8–1.8°C by 2020, 1.8–4.3°C by 2050 and 2.5–6.6°C by 2080. In addition, growing season temperatures are projected to increase more than winter temperatures and maximum temperatures are projected to increase at nearly twice the rate of minimum temperatures. The region is also projected to see a range of annual precipitation changes from the 1950–2000 base period of slight increases to decreases of up to 7% by 2020, 15% by 2050 and 22% by 2080. The model projections also indicate a greater reduction in precipitation during the growing season than during the winter. Furthermore, the decreases in precipitation and warming temperatures projected for the region are greatest in the driest and warmest areas of the Douro Superior.

The Douro wine region is already a warm and dry wine growing region with heat and water stress in most years and small changes in climate may push regional climate thresholds sooner than other regions. Given the observations and if projections of temperature changes, combined with predictions of less rainfall or greater variability in the occurrence heat waves or intense rainfall events are realised, the stability of hillside vineyards and sustainability of entire operations will be challenged (Schultz, 2000; Jones et al., 2005). However, the Douro wine region has large genetic potential and adaptive capacity, which combined with an even larger landscape potential and adaptive capacity, should provide numerous mechanisms for growers and producers to enhance sustainability. Future work in the region needs to continue to develop the understanding of the spatial climate structure and the range of observed and projected changes, while further developing plant, production and quality models to better understand the relationships between climate change and wine, with the goal of reducing vulnerability and increasing adaptive capacity.

Based on work carried out in other regions, the impact of climate change scenarios on wine production and quality will have different outcomes depending on the characteristics of each sub-region/location and the capacity of grape varieties and growers/producers to adapt (Jones et al., 2005). It may be beneficial for some regions that traditionally produce white wines, or it may allow them to be produced in areas where grapevines are not traditionally grown, but the changes could create constraints in regions where red wines with high quality potential are traditionally produced. The evolution of these scenarios will condition decision-making on vineyard locations, selection of plant material, the technical management to be followed and the typicity and style of wine to be produced. Given these issues, there is an urgent need to further the understanding of the vulnerability of the Douro wine region to changes in climate and to maximise the adaptive capacity of the wine industry.

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