Impacts of Climate Change on Wine Production: A Global Overview and Regional Assessment in the Douro Valley of Portugal

Gregory V. Jones[1,2] and Fernando Alves[2]

Abstract — Climate change has the potential to greatly impact nearly every form of agriculture. However, history has shown that the narrow climatic zones for growing winegrapes are especially prone to variations in climate and long-term climate change. 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. Projections of future warming at the global, continent, and wine region scales will likely continue to have both beneficial and detrimental impacts through opening new areas to viticulture and increasing viability, or severely challenging the ability to adequately grow grapes and produce quality wine. This paper will detail the observed and projected changes in wine regions worldwide and discuss the impacts on vine growth, fruit composition, yield, and wine quality. Furthermore, this paper will discuss the opportunities and challenges inherent in regional assessments of climate change with particular attention on the Douro Valley of Portugal.

Keywords — Climate Change, Portugal, Viticulture, Wine

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 optimum characteristics to produce a given wine style.

2 Global Overview

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 [1]. 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 [1].

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 [1]. These narrow niches for optimum quality and production put the cultivation of winegrapes at greater risk from both short-term climate variability and long-term climate changes than other more broadacre crops. 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. While grapevines respond to a

1. *The Department of Environmental Studies, Southern Oregon University, Ashland, Oregon 97520 USA. E-mail: gjones@sou.edu*
2. *The Association for the Development of Viticulture in the Douro Region (ADVID), Peso da Régua, 5050-106 Portugal. E-mail: fernando.alves@advid.pt*

myriad of climate influences, temperature is the most influential factor in the overall growth and productivity of winegrapes. 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 (Fig. 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 [1]. 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 Fig. 1 where large areas of eastern Europe, western Asia, China, the mid-western and eastern United States, southeastern Argentina, southeastern South Africa, and southern Australia fall within the 12-22°C thresholds. While many of these regions may have growing season temperatures conducive to growing

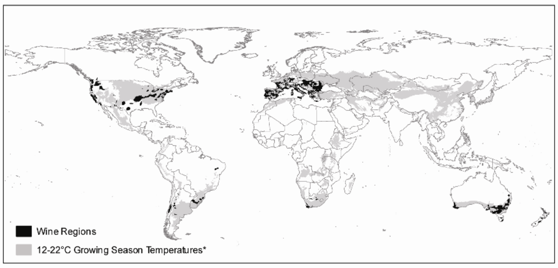

Fig. 1: Global wine regions and 12-22°C growing season temperature zones (Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the United States, Geographic Indicators in Australia 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).

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. 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 United States (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 raisons, and do not necessarily represent the average wine region.

Today our knowledge of the climate suitability for many of the world's most recognizable cultivars shows that high quality wine production is more realistically limited to 13-21°C average growing season temperatures (Fig. 2). The climate-maturity zoning in Fig. 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. While many of these cultivars are grown and produce wines outside of the bounds depicted in Fig. 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 [2]. 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 raisons (up to 24°C).

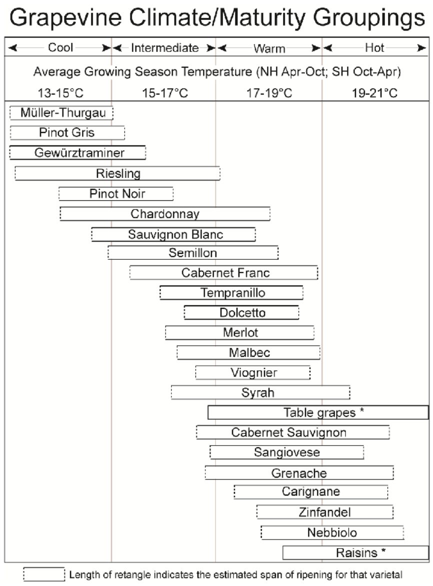

Fig. 2: Climate-maturity groupings based on relationships between phenological requirements and growing season average temperatures for high to premium quality wine production in the world's benchmark regions for many of the world's most common cultivars. The dashed line at the end of the bars indicates that some adjustments may occur as more data become available, but changes of more than +/- 0.2-0.5°C are highly unlikely [1].

An example of cool climate suitability is found with the widely recognized 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 recognized in the world. The spread of these two cultivars worldwide has produced an assortment of wine styles from quite diverse regions. Fig. 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.

Another example of both broad climate and wine styles diversification can be found with Chardonnay. As Chardonnay production expanded worldwide it was found to be one of the most flexible and forgiving cultivars, producing a range of wine styles. Chardonnay can be grown in relatively cool climates (~14-16°C) creating an elegant, crisp style that is flavored more by apple, pear, and fig while in warmer climates (~16-18°C) it produces a bolder style with more peach to honey notes that could be enhanced via the use of oak barrel ageing. Cultivar diversification within regions is also evident in Fig. 2 with two notable examples. The Piedmont region of Italy has become known for its red wines which are made from either Dolcetto or Nebbiolo. While both cultivars are grown over a relatively narrow climate range, Dolcetto does better in a slightly cooler climate (16.4-18.4°C) while Nebbiolo does better in a warmer climate (17.8-20.4°C) with a long growing season. The Piedmont region has therefore diversified its production and quality potential in that during cool years Dolcetto ripens best, during warm years Nebbiolo does better, and during average years they both do relatively well. Another example of cultivar-climate diversification is in Bordeaux where the average growing season temperatures of 16.8-17.8°C makes it ideal to Cabernet Franc, Cabernet Sauvignon, and Merlot, albeit with warmer years favoring higher Cabernet Sauvignon quality.

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 [2], [3], [4], [5]. For example, if a region currently experiences a ripening period that allows sugars to accumulate to favorable levels, maintains acid structure, and produces the optimum flavor 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 flavors 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 [6]. 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 and was highly correlated to significantly warmer ripening periods and earlier phenology. For Napa, average alcohol levels have risen from 12.5% to 14.8% from 1971-2001 while acid levels fell and the pH climbed. 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 higher alcohol levels is that wines 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 [6]. 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 flavor and aroma compounds) with the potential for greater fruit desiccation, without greater irrigation inputs.

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 [2]. 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, with 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 [2]. However, climate model projections by 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 with increasing area on the poleward fringe in the Northern Hemisphere (NH) and decreasing area in the Southern Hemisphere (SH) due to the lack of land mass (Fig. 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, 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 [6].

To place viticulture and wine production in the context of climate suitability and the potential impacts from climate change, Fig. 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.

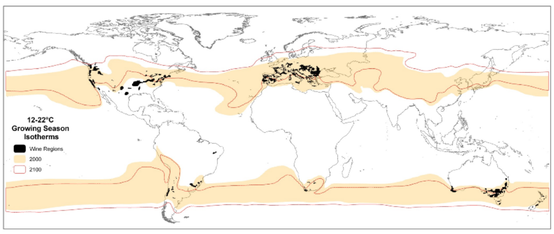

Fig. 3: Changes in general climate zones for viticulture from 2000 to 2100. Climate data is derived from the National Center for Atmospheric Research's Community Climate System Model (CCSM) for observed (2000) and an A1B (mid-range scenario). The wine regions are derived from governmentally defined boundaries (e.g., American Viticultural Areas in the United States, 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). The general climate zones are given by the 12-22°C growing season (Apr-Oct in the Northern Hemisphere and Oct-Apr in the Southern Hemisphere) average temperatures.

3 Douro wine region Observations and Projections

The climate of the Douro Demarcated Region (Douro – DDR; Fig. 4) is characterised by a strong inter-annual consistency of total insolation, temperature, and potential evapotranspiration and significant inter-annual variation in precipitation [7]. During the active growth stages of grapevines (April to September), the average rainfall varies between 121 and 310 mm, while it is only 34 to 90 mm during the ripening stage (from July to September). 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 (Fig. 4).

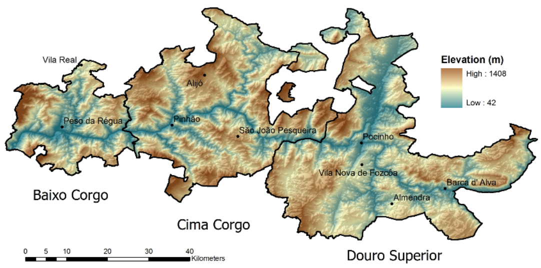

Fig. 4: Elevation of the Douro wine region and its three main regions – Baixo Corgo, Cima Corgo, Douro Superior.

A combination of numerous factors (climate, soil, varieties and technology) in the region has contributed to a significant fluctuation in inter-annual production (Fig. 5) and a low average vine yield of around 30 hl ha^{-1}, which can fluctuate between 20 and 40 hl ha^{-1} (not shown) [7]. These values are typically below the maximum amounts permitted for Porto and Douro controlled appellations (55 hl ha^{-1}).

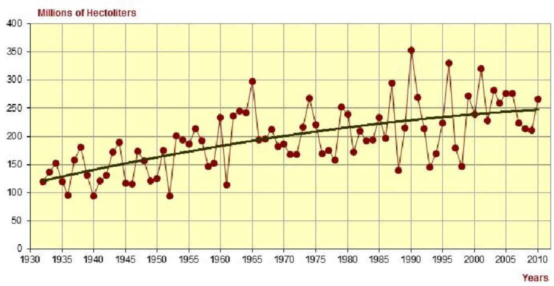

Fig. 5: Regional production trends between 1932 and 2007. Source: Martins (1990); Casa do Douro and IVDP.

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 [8]. 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 [9]. 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 700 mm – Fig. 6). In addition, the likelihood of experiencing a dry year is generally greater than that of years with above-average rainfall.

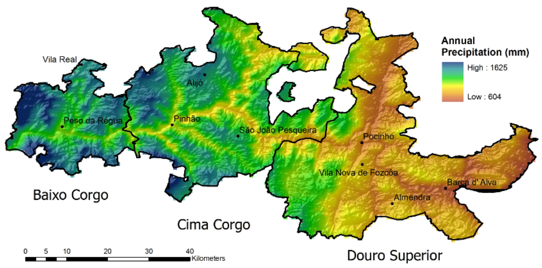

Fig. 6: Distribution of average annual precipitation in the Douro during 1950-2000, WorldClim Database [10].

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) [11]. 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 [12], [13], which in turn affected yield and quality.

According to [4] 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 [14].

As can be seen in Fig. 7, for the period 1950-2000, a significant part of the area of the Douro wine region was under the effects of an average growing season temperatures (Apr-Oct) for various locations that approached or exceeded optimum growing temperatures for some varieties compared with the reference temperatures presented [2] (Fig. 2). This is further shown in Fig. 8 where the average growing season temperatures during the second half of 1967-2010 are 1.3°C warmer than the first half of the period and now place Peso da Régua in the 'hot' climate suitability in Fig. 2. In addition, increasing trends in average temperatures during the growth period (Mar-Sept) and the whole year (Fig. 8) have been seen over a period of 40 years between 1967 and 2010. The trend for the growing period is more pronounced, increasing 2.9°C during this time period.

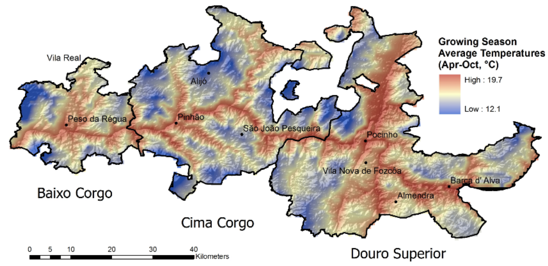

Fig. 7: Distribution of growing season average temperatures in the Douro during 1950-2000, WorldClim Database (Hijmans et al. 2005).

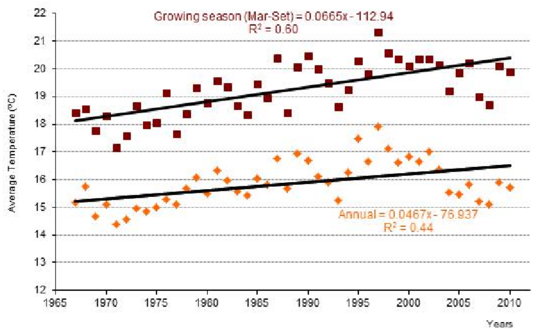

Fig. 8: Average annual temperature trends in the Douro wine region (Peso da Régua) between 1967 and 2010 [7].

Furthermore, the optimum photosynthetic response range for grapevines is for maximum daytime temperatures from 20 to 35°C, depending on the location and variety [15]. Above this temperature, the photosynthetic response is lowered, depending on a combination of other factors such as water availability. Temperatures above 40-45°C may cause irreversible losses, bypassing the grapevine's acclimation capacity that [16] and [17] has noted for varieties originating in warm regions.

It is important to note that the effect of climate on grapevine processes is conditional not only on the change in average values, but more importantly on the intensity and frequency of occurrence of extreme values. For example, [18] 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 and 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 water use efficiency suggest not only the occurrence of stomatal limitations but also of non-stomatal limitations in the decline in photosynthetic productivity.

For these reasons, viticulture in the Douro wine region is carried out over a considerable area of the land in very severe conditions, particularly when climate and topography are associated. Thus with projections of temperature changes over the next 50 years of 1.5-2.5ºC, combined with predictions of less rainfall and/or greater variability in the occurrence heat waves or intense rainfall events are realized, the stability of hillside vineyards and sustainability of entire operations will be challenged [2] and [4].

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 [2]. 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, technical management to be followed and the typicity and style of wine to be produced. Given these issues there is an urgent need to understand the vulnerability of the Douro wine region to changes in climate and maximize the adaptive capacity of the wine industry.

4 Douro Wine region Assessment

Currently, the concept of sustainable viticulture, including guidelines for integrated production of winegrapes, requires that the wine industry optimise available resources in order to guarantee environmentally responsible viticulture [19]. Thus mitigation of the effects of climate change should derive from a series of farming practices (land levelling, tillage, variety and rootstock, training system and late pruning and irrigation management when necessary), applying International Organization for Biological and Integrated Control (IOBC) Guidelines for Integrated Production in Viticulture, which guarantee the development of sustainable viticulture [20] (Fig. 9).

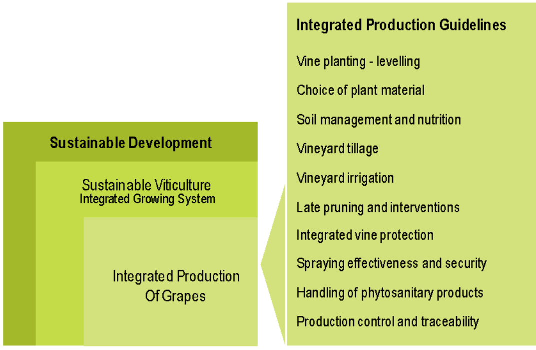

Fig . 9: Integration of Integrated Production components in sustainable viticulture ([20] - adapted from IOBC).

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), land levelling and resulting water efficiency, varieties, rootstock and training systems, the results obtained, although promising and giving some insights into strategies to be followed, lack greater robustness for sustained application in the Douro wine region's different ecological situations.

With regard to the region's potential, we must note the variety of meso- and micro-climate situations resulting from the region's morphology. In this respect, the existence of hillside viticulture enables wine growers to explore different options for the profiles of the wines intended.

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 varieties and their oenological performance [21]. Although the general characteristics and aptitude for drought resistance of rootstocks have been studied [20] and [22], 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 [23] and their different physiological responses [24]. These authors found in the varieties most commonly used in the Douro wine region a variable response with each cultivar studied. 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 (Table 3) [11].

To assess and plan for future climate change scenarios on the Douro wine region, growers and producers working with the Association for the Development of Viticulture in the Douro Region (ADVID) have developed a plan to increase our knowledge of the current situation, to develop models to simulate the impact of climate change on the region, and develop strategies for mitigation against and adaptation to the impacts. These proposals result from studies of our current knowledge on the subject, a compilation and processing of the information available, and contacts and working meetings at research centers 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, systematization, 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, when we seek an analysis over a longer time scale, there is a dearth of appropriate data. Typically there is only commercial criteria (valuation of premium wines such as in California; or grape prices as used in Australia), or qualitative criteria based on the rating attributed to the vintage on a regional basis [25], [26] and [27], using ratings from national institutes or institutes that manage the corresponding controlled appellations, or international institutes (e.g., Sotheby's or Wine Enthusiast) [2].

With regard to the Douro wine region, and following the same logic as for Champagne, [2] 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 2.5° x 2.5° grid that would represent all of Portugal or smaller grids of 0.5° x 0.5° grids, but which are still large and attempt to characterize a very heterogeneous area. To adequately represent a wine region such as the Douro, regional downscaled models are necessary [28] and [2], is required 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 (Fig. 10; e.g., DSSAT 4.0, STELLA 2.0 or the STICIS-Vigne model) which will be used 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.

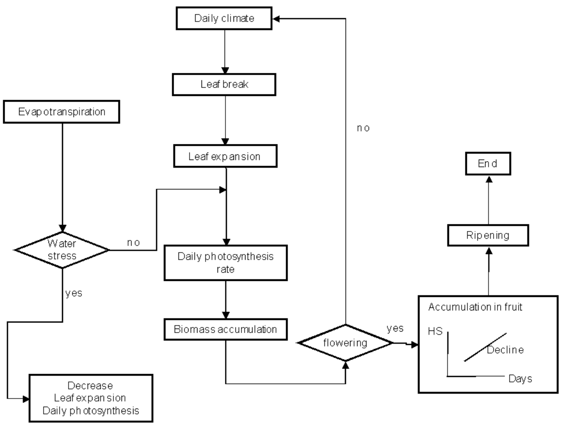

Fig. 10: Example of the layout of a potential yield model for the grapevine (Adapted from [29]).

F. Establishing zoning principles aimed at climate change issues.

Considering that one of the potentials of the Douro wine region for minimizing aspects related to climate change is its diversity of topography and plant material available, their correct evaluation and optimization will have to be an integral part of vineyard zoning in the region (Fig. 11). 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.

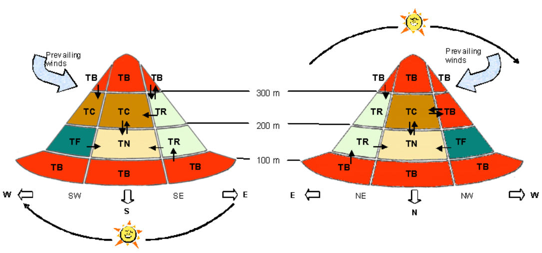

Fig.11: Simplified diagram for proposal of zoning varieties in the Douro wine region [30]. TN - Touriga Nacional; TF - Touriga Franca; TB - Tinta Barroca; TR - Tinta Roriz; TC - Tinto Cão.

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 acclimatization to higher temperatures and, most importantly, strategies for the rational management of water resources available to the plant.

4 Conclusions

Overall, winegrapes are a climatically sensitive crop whereby quality production is achieved across a fairly narrow geographic range [1] and [2]. 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 selections 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[31], including – 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[2]. 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, 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 a changing climate [7].

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