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CLIMATE CHANGE PROJECTIONS FOR THE PORTUGUESE VITICULTURE USING A MULTI-MODEL ENSEMBLE

PROJEÇÃO DAS ALTERAÇÕES CLIMÁTICAS PARA A VITICULTURA PORTUGUESA UTILIZANDO UM CONJUNTO DE MODELOS

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SUMMARY

Portuguese vitiviniculture represents an extremely important economic activity for the agricultural sector, particularly for some renowned winemaking regions, such as Alentejo, Dão, Douro, and Minho. Viticultural zoning allows tying the suitability of a given grapevine variety to the local soil and climatic conditions. Given the existing climate variability in the Portuguese territory and its likely changes in the future, this zoning is thus of utmost interest. In this study, the current viticultural zoning in Portugal is discussed, as well as changes induced by climate change in the period 2011-2070. For this purpose, daily temperatures and precipitation rates were used to calculate the Huglin, cool night, dryness and hydrothermal indices. A composite index based on the previous indices was also calculated. For the assessment of the recent past conditions (1961-2000), an observational dataset (E-OBS) was used, while for future climate projections, a dataset comprising 16 simulations of regional climate models (produced by the ENSEMBLES project) was considered. In the future climate, statistically significant increases in the thermal indices are projected to occur in the next decades, while for the precipitation-based indices decreases might be expected, particularly over the south and innermost regions of Portugal. A reshaping of the main Portuguese winemaking regions is likely to occur in the upcoming decades, therefore emphasizing the need for the development of appropriate measures for the adaptation to or mitigation of these climatic changes at the level of varieties and rootstocks used, as well as at the implemented cultural practices, keeping the typicity and wine styles.

RESUMO

A vitivinicultura portuguesa representa uma atividade económica de extrema importância para o sector agrícola nacional, nomeadamente para algumas regiões de renome, como as Regiões Demarcadas do Alentejo, Dão, Douro ou Vinhos Verdes. A zonagem vitícola permite avaliar a adaptabilidade de uma dada casta às condições climáticas locais. Dada a diversidade climática existente no território português, esta zonagem é assim de particular interesse para a fileira vitivinícola nacional. Sabe-se ainda que alterações no clima futuro poderão ter impactos importantes sobre essa zonagem. No presente estudo é discutida a zonagem vitícola atual em Portugal, bem como as variações induzidas pelas alterações climáticas no período 2011-2070. Para o efeito, a partir de temperaturas e precipitações diárias, foram calculados os índices de Huglin, de frescura das noites, de secura, um índice hidrotérmico e um índice composto, baseado nos índices anteriores. Para a avaliação das condições no passado-recente (1961-2000) foi utilizada uma base de dados observacionais (E-OBS), enquanto para as projeções climáticas foi considerada uma base de dados composta por 16 simulações de modelos climáticos (projeto ENSEMBLES). No clima futuro são projetados aumentos significativos nos índices térmicos, enquanto nos índices de base pluviométrica são projetadas diminuições, em particular sobre o interior sul de Portugal. Pelo exposto, é previsível que nas próximas décadas ocorra uma redistribuição das regiões vitivinícolas portuguesas, destacando-se, por conseguinte, a necessidade de desenvolver atempadamente medidas adequadas de adaptação/mitigação ao nível das castas e dos porta-enxertos recomendados, bem como ao nível das práticas culturais, para ajudar a manter a tipicidade dos vinhos.

Key words: climate change; Portuguese viticulture; climate models; viticultural zoning; bioclimatic indices.

Palavras-chave: alterações climáticas; viticultura portuguesa, modelos climáticos; zonagem vitícola; índices bioclimáticos.

INTRODUCTION

Climate is widely acknowledged as one of the major factors affecting vine physiology, phenology and wine parameters (Jones and Davis 2000; Santos *et al.*, 2011). In fact, the most worldwide renowned wine regions are located within relatively narrow latitude belts that provide very specific climatic conditions for high-quality wine production (Spellman 1999; Jones 2006). Although other factors, such as soils, winegrape varieties, agricultural and oenological practices might also play a crucial role on the entire winemaking process, climate and weather represent the most challenging factors (van Leeuwen *et al.*, 2004), as they cannot be directly controlled by producers (we can only predict them and take measures to adapt and/or mitigate their effects) and vary significantly on relatively short time scales. Hence, viticultural zoning based on climatic factors has been applied as a first approach to delineate areas where climate is (nearly) optimal to winegrape growing, thus allowing the development of a sustainable winemaking sector, providing that the other factors are also reasonably suitable.

Specialized bioclimatic indices can be used not only in evaluating the climatic suitability of a specified region to winegrape growth and wine production (Malheiro *et al.*, 2010), but also in assessing some wine quality parameters, such as the balance between acidity and alcoholic content (Huglin 1978; Magalhães 2008). The Huglin index (HI; Huglin 1978) is a degree day index that also accounts for day length during the vine growing season. It is used for assessing the basic thermal and radiative demands of the grapevine so as to complete its phenological stages, including full and adequate grape maturation. In fact, the HI classes show strong correlations with some grapevine phenological events (Jones *et al.*, 2005b), also linking a specific grapevine variety to a given climatic region. The Cool night index (Tonietto and Carbonneau 2004), another thermal index, accounts for night temperatures (minimum temperatures) during the maturation stage (September). Some studies argue that, at this stage, moderately low nocturnal temperatures combined with diurnal high temperatures tend to be advantageous for the production of high quality wines, promoting the synthesis of anthocyanins and other phenolic compounds (Kliewer and Torres 1972; Mori *et al.*, 2005).

Besides assessing the thermal conditions for grapevine development, it is also important to take into account the soil and atmospheric water conditions. The Hydrothermal index (HyI; Branas *et al.*, 1946) combines the effect of air humidity (using precipitation) and temperature during the growing season to assess the risk of grapevine exposure to certain diseases, such as downy mildew. On the other hand, the Dryness index (DI; Riou *et al.*, 1994) accounts for the soil water availability, thus providing information about the water stress conditions. The Composite index (CompI; Malheiro *et al.*, 2010) is useful in depicting regions with suitable climatic conditions for winegrape growth by combining critical thresholds in the previous indices. In this context, by allowing the assessment of climate suitability for winegrape growth, the bioclimatic indices are a widely used tool in viticultural zoning.

The awareness of a potential climate change is fundamental in order to raise adaptive capacity (Metzger *et al.*, 2008). Therefore, the assessment of regional climate projections is of high pertinence for the wine industry by enabling the development of adequate measures for both mitigating their impacts and adapting to the new climatic conditions. Under the A1B International Panel on Climate Change (IPCC) – Synthesis Report on Emission Scenarios (SRES) scenario include a global temperature rise within the range 2.2-5.1ºC (Nakićenović *et al.*, 2000). More specifically, climate in Portugal (typically Mediterranean, with temperature increasing and precipitation decreasing southwards and inwards) is expected to undergo some significant changes under anthropogenic forcing, including changes in temperature and precipitation (Meehl *et al.*, 2007), as well as in their extremes (Costa *et al.*, 2012).

Vineyards in Portugal are virtually grown over almost all of the country (globally about 238.000 ha for aprox. 6 millions hl of wine production; IVV 2011), which is divided in large wine regions throughout the country (Fig. 1). However, the most important winemaking regions are localized within legally bounded controlled appellations (e.g. from north to south: Vinhos Verdes, Douro, Dão and Alentejo). These winemaking areas are quite diverse in their climates, geomorphological features, soil characteristics, and grown grapevine varieties (Magalhães, 2008). As an illustration, while Alentejo (southeast) is mostly flatland with a relatively homogenous climate, the Douro Valley (northeast) is very mountainous and presents a large diversity of mesoclimates. Taking

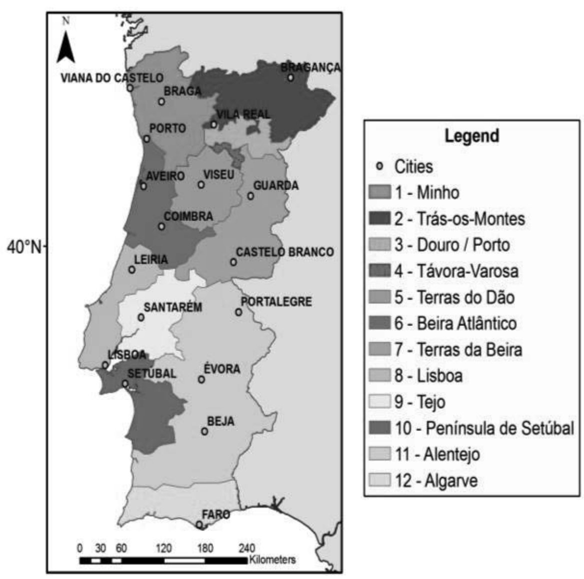

Figure 1 - The wine regions of mainland Portugal (IGP- Protected geographical indication).

Regiões vitícolas de Portugal continental (IGP – Indicação geográfica protegida).

into account the important incomes the winemaking sector brings to the Portuguese economy, amounting nearly 2% of the total national exportation revenue (IVV 2011), the present study is devoted to the understanding of the climatic viticultural zoning in Portugal and the future implication of the climate change in this sector. The current climatic zoning and its likely changes under future climates are discussed using the aforementioned five bioclimatic indices. As such, this study aims at contributing to a better planning of the measures that need to be taken by producers (grape-growers and winemakers), associations and organizations across the Portuguese wine industry in order to cope with climate change.

MATERIAL AND METHODS

Five bioclimatic indices, specifically 1) Huglin Index (HI), 2) Cool Night Index (CI), 3) Hydrothermic Index (HyI), 4) Dryness Index (DI) and 5) a Composite Index (CompI) were calculated over Portugal, using the mathematical definitions found in Table I. For assessing climate change impacts, two periods were considered in this study. The baseline period representing current-past condition (1961-2000) was calculated using data from an observational dataset (E-OBS, version-5, Haylock *et al.*, 2008), while for the future conditions (2041-2070) data from a 16-member ensemble, produced by the ENSEMBLES project (Table II), was considered. The future period (2041-2070) was chosen to better characterize mid-century climatic conditions under the A1B IPCC-SRES scenario, a moderate anthropogenic radiative forcing scenario, but with already high emission levels (Nakićenović *et al.*, 2000). Additionally, differences in the number of days with extreme temperatures (above 40ºC) and in the growing-season precipitations between future and current climates are also discussed.

TABLE I

List of all the bioclimatic indices used in this study, their definitions and references.

Lista dos índices bioclimáticos usados neste estudo, as suas definições e referências bibliográficas.

Bioclimatic Index	Definition	References
Composite index (CompI)	a: HI ≥ 900ºC; b: DI ≥ -100 mm; c: HyI ≤ 7500ºC.mm; d: T_{min} always > -17ºC	Adapted from (Malheiro *et al.*, 2010)
Cool Night Index (CI)	September average Tmin (ºC)	(Tonietto, 1999)
Dryness index (DI)	$\sum_{April}^{Sept.}(Wo + P - Tv - Es)$ Wo - Initial available soil water reserve (mm); P – Precipitation (mm); T_v - the potential transpiration in the vineyard (mm); E_s - Direct evaporation from the soil (mm)	(Riou *et al.*, 1994) (Tonietto and Carbonneau, 2004)
Huglin index (HI)	$\sum_{April}^{Sept.}\frac{(T-10)+(T_{max}-10)}{2}d$ T - Mean air temperature (ºC); T_{max} - Maximum air temperature (ºC); d - Length of day coefficient, ranging from 1.02 to 1.06	(Huglin, 1978)
Hydrothermic index (HyI)	$\sum_{April}^{Aug.}(T * P)$ T - Mean air temperature (ºC); P – Precipitation (mm)	(Branas *et al.*, 1946)

All data fields, from each model run, were bilinearly interpolated from their original resolution (Table II) onto a 0.25º × 0.25º grid, the same grid as in the observational dataset. This interpolation allowed applying a statistical error correction to the model-derived indices (model output statistics; MOS). The application of MOS to the calculated bioclimatic indices resulted in some losses of data along coastal areas of Portugal, where E-OBS grid-cells have missing data (cf. Fig. 2). Due to the low representativeness of these littoral areas to the national wine production, this is not an important shortcoming and no other statistical approach was thereby applied to estimate the indices in the blank cells (e.g. nearest neighbour with values).

TABLE II

Summary of all GCM / RCM model chains, original grid resolutions, institutions and references used in this study.

Resumo de todos os GCM / RCM usados neste estudo, as suas resoluções originais, instituições e referências bibliográficas.

GCM	RCM	Original grid	Institution	References
ARPEGE	HIRHAM	0.22ºx0.22º rotated	Danish Meteorological Institute	(Christensen *et al.*, 1996)
ARPEGE-RM5.1	Aladin	0.22ºx0.22º rotated	Centre National de Recherches Météorologiques	(Gibelin and Deque, 2003)
BCM	RCA	0.22ºx0.22º rotated	Sweden's Meteorological and Hydrological Institute	(Kjellström *et al.*, 2005) (Samuelsson *et al.*, 2011)
ECHAM5-r1	CLM-1	0.20ºx0.20º regular	Max Planck Institute	(Böhm *et al.*, 2006) (Steppeler *et al.*, 2003)
ECHAM5-r2	CLM-2	0.20ºx0.20º regular	Max Planck Institute	(Böhm *et al.*, 2006) (Steppeler *et al.*, 2003)
ECHAM5-r3	HIRHAM	0.22ºx0.22º rotated	Danish Meteorological Institute	(Christensen *et al.*, 1996)
ECHAM5-r3	RACMO	0.22ºx0.22º rotated	Koninklijk Nederlands Meteorologisch Instituut	(Lenderink *et al.*, 2003)
ECHAM5-r3	RCA	0.22ºx0.22º rotated	Sweden's Meteorological and Hydrological Institute	(Kjellström *et al.*, 2005) (Samuelsson *et al.*, 2011)
ECHAM5-r3	RegCM3	0.22ºx0.22º rotated	International Centre for Theoretical Physics	(Elguindi *et al.*, 2007) (Pal *et al.*, 2007)
ECHAM5-r3	REMO	0.22ºx0.22º rotated	Max Planck Institute	(Jacob and Podzun, 1997) (Jacob, 2001)
HadCM3Q16	RCA3	0.22ºx0.22º rotated	C4I Center	(Kjellström *et al.*, 2005) (Samuelsson *et al.*, 2011)
HadCM3Q3	RCA	0.22ºx0.22º rotated	Sweden's Meteorological and Hydrological Institute	(Kjellström *et al.*, 2005) (Samuelsson *et al.*, 2011)
HadRM3Q0	CLM	0.22ºx0.22º rotated	Eidgenössische Technische Hochschule Zürich	(Steppeler *et al.*, 2003) (Jaeger *et al.*, 2008)
HadRM3Q0	HadRM3Q0	0.22ºx0.22º rotated	Hadley Centre	(Collins *et al.*, 2011)
HadRM3Q16	HadRM3Q16	0.22ºx0.22º rotated	Hadley Centre	(Collins *et al.*, 2011)
HadRM3Q3	HadRM3Q3	0.22ºx0.22º rotated	Hadley Centre	(Collins *et al.*, 2011)

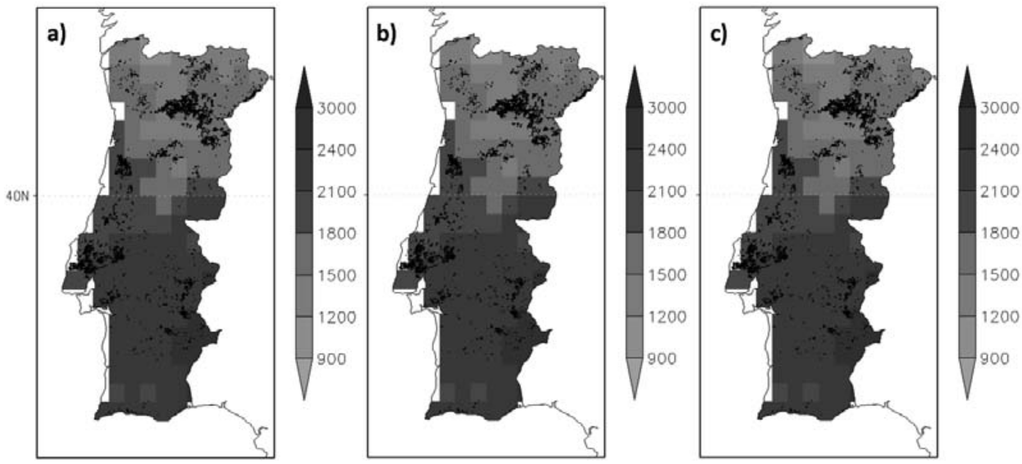

Figure 2 - Huglin Index (HI; in ºC) for a) the baseline period (1961-2000), b) the future time period (2041-2070), and c) overall differences in 2041-2070 minus 1961-2000 (under the A1B IPCC-SRES scenario). Black areas represent the current vineyard land cover.

Índice de Huglin (HI; em ºC) para a) o período de referência (1961-2000), b) o período futuro (2041-2070), e c) diferenças entre 2041-2070 menos 1961-2000 (sob o cenário A1B IPCC-SRES). Áreas a preto representam o atual coberto vegetal de vinha.

For the model calibration, since the calculated bioclimatic indices are normally distributed (according to the Lilliefors test; not shown), adjustments (transfer-functions) using multiple linear regressions were carried out. The same linear transformations were then applied to all future indices. This type of statistical model error correction has been used in previous studies (Alexandrov and Hoogenboom 2000) and can be used to provide reliable climate change scenarios (Jakob Themeßl *et al.*, 2011). The use of a 16-member ensemble in the assessment of viticultural zoning in the future is an innovative methodology, by taking into account model uncertainties. Due to the large amount of outcomes, the results shown in this study are only focused on the 16-member ensemble mean patterns.

In order to better analyse the spatial distribution of the resulting bioclimatic indices, an overlay of the current vineyard land cover was applied, using the Corine Land Cover Map (CLC 2000; EEA 2002; Büttner *et al.*, 2006). This dataset provides an inventory of the land cover over Europe and has proven to have high accuracy in representing the cartography over mainland Portugal (Caetano *et al.*, 2006)

RESULTS

The 16-member ensemble mean pattern of the HI (Fig. 2a), for the baseline period, shows relatively high values in the central and southern regions of Portugal (1800-3000ºC), while in the northern regions it reveals much lower values (900-1800ºC), which highlights the strong north-south contrast in the climatic conditions over Portugal. Similar results were reported by Magalhães (2008) using weather station data. For the future period (Fig. 2b), an overall increase in these values is expected (Fig. 2c), especially in the innermost regions, reaching values above 3000ºC (highest HI class). This pattern is in clear agreement with Malheiro *et al.*, (2010) in a study for Europe and using a single model (COSMO-CLM). In fact, these increases will indeed lead to shifts to higher classes in the HI throughout Portugal.

This warming is also apparent in the night temperatures, as is suggested by the CI patterns. The CI (Fig. 3a) mean ensemble pattern shows a clear difference between south and coastal regions (warmer nights) and north and innermost regions (cooler nights). The CI future pattern shows a clearer distinction between southern (>18ºC), central (16-18ºC) and northern (12-16ºC) Portugal (Fig. 3b); increases of 2-4ºC are expected to occur, particularly over inland Portugal (Fig. 3c). This overall warming is also attested by an increase in the frequency of occurrence of extreme temperatures in the future. In fact, for some regions of the Douro Valley and Alentejo, projected changes include a significant rise in the number of days with maximum daily temperature above or equal to 40ºC (up to 8 days, Fig. 4a).

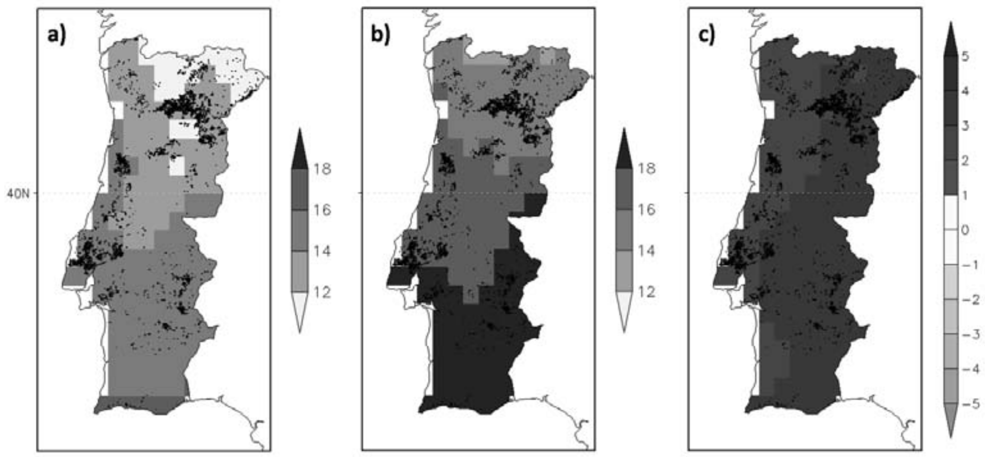

Figure 3 - Cool night Index (CI; in ºC) for a) the baseline period (1961-2000), b) the future time period (2041-2070), and c) overall differences in 2041-2070 minus 1961-2000 (under the A1B IPCC-SRES scenario). Black areas represent the current vineyard land cover.

Índice de frescura das noites (CI; em ºC) para a) o período de referência (1961-2000), b) o período futuro (2041-2070), e c) diferenças entre 2041-2070 menos 1961-2000 (sob o cenário A1B IPCC-SRES). Áreas a preto representam o atual coberto vegetal de vinha.

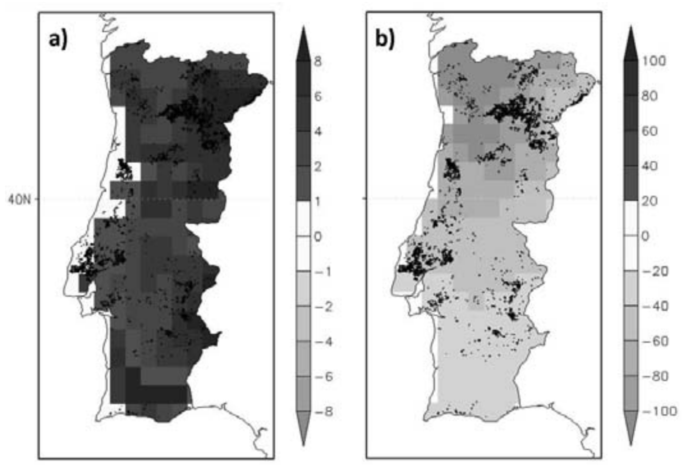

Figure 4 - a) Differences in the number of days with maximum daily temperature equal to or above 40ºC (2041-2070 minus 1961-2000). b) Differences in the precipitation totals (in mm) during the growing season (2041-2070 minus 1961-2000).

a) Diferença no número de dias com temperatura máxima diária igual a superior a 40ºC (2041-2070 menos 1961-2000). b) Diferenças no total de precipitação acumulada (em mm) durante a época de crescimento vegetativo (2041-2070 menos 1961-2000).

In addition to the overall warming in both the mean temperature and its extremes, a decrease in precipitation is also projected to occur, particularly in the northern and coastal areas (Fig. 4b). This drying leads to changes in the DI mean pattern (Fig. 5a), where southern Portugal already shows moderate dryness under current climatic conditions (-100 to -50 mm). Changes in this index thereby suggest an important threat or challenge to the viticultural sector owing to the severe dryness that is likely to occur in the future (Fig. 5b), particularly in the innermost southern regions (Fig. 5c). This excessive dryness is in effect considered unsuitable for winegrape growth without irrigation (Koundouras *et al.*, 1999). Conversely, the mean pattern of the HyI (Fig. 6a) for the baseline period shows low to moderate risk of downy mildew disease in most of the Portuguese mainland, and high risk in a small region in north-western Portugal (Alto Minho). The combined effect of the projected future warming and drying will yield a decrease in the HyI (Fig. 6b, c), leading to lower risks of crop contamination, which may have beneficial impacts on the sector.

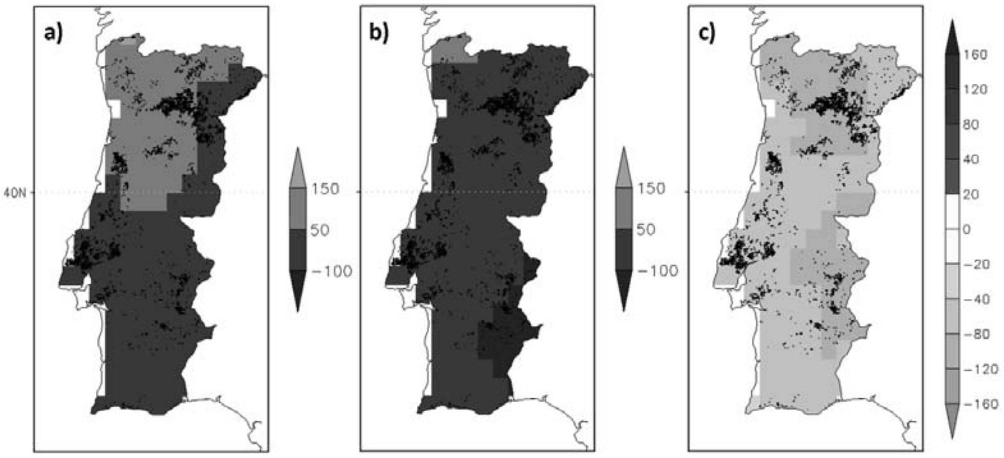

Figure 5 - Dryness Index (DI; in mm) for a) the baseline period (1961-2000), b) the future time period (2041-2070), and c) overall differences in 2041-2070 minus 1961-2000 (under the A1B IPCC-SRES scenario). Black areas represent the current vineyard land cover.

Índice de secura (DI; em mm) para a) o período de referência (1961-2000), b) o período futuro (2041-2070), e c) diferenças entre 2041-2070 menos 1961-2000 (sob o cenário A1B IPCC-SRES). Áreas a preto representam o atual coberto vegetal de vinha.

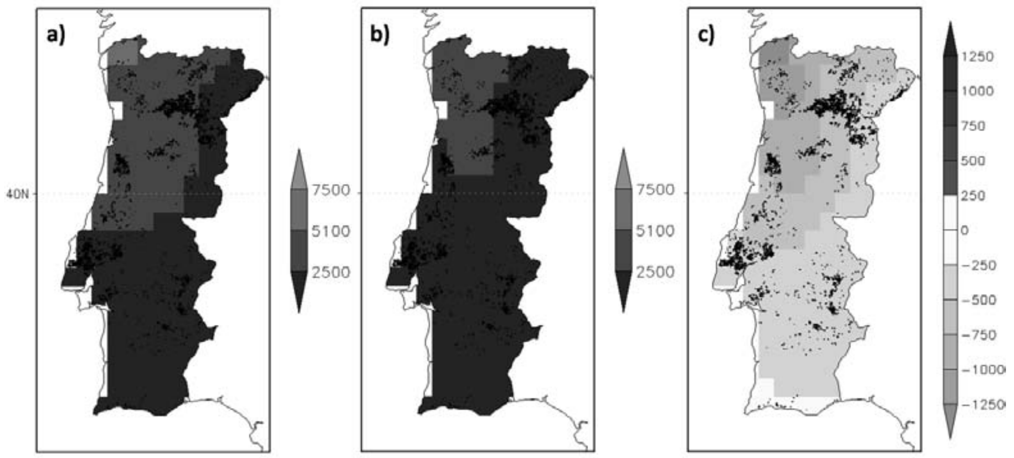

Figure 6 - Hydrothermal Index (HyI; in ºC.mm) for a) the baseline period (1961-2000), b) the future time period (2041-2070), and c) overall differences in 2041-2070 minus 1961-2000 (under the A1B IPCC-SRES scenario). Black areas represent the current vineyard land cover.

Índice hidrotérmico (HyI; em ºC.mm) para a) o período de referência (1961-2000), b) o período futuro (2041-2070), e c) diferenças entre 2041-2070 menos 1961-2000 (sob o cenário A1B IPCC-SRES). Áreas a preto representam o atual coberto vegetal de vinha.

The CompI has proven to be effective in detecting the most suitable European regions for winegrape growth and wine production (Santos *et al.*, 2012). For the baseline period, its mean pattern over Portugal highlights that most of Portugal has a very high suitability for viticulture (values above 0.99; Fig. 7a). However, in the future period, a tendency for lower values is depicted (Fig. 7b). In fact, the excessive dryness underlies this decrease (Fig. 7c) and may represent a detrimental impact on viticulture. Further, some regions in south-eastern Portugal (e.g. Alentejo) will have CompI values that suggest unsuitability for viticulture if mitigation measures (e.g. irrigation) are not implemented. From Fig. 8 it is clear that over most of Portugal (36-41 ºN) a decrease in the area of suitable climate (CompI above 0.5) is expected to occur in the future, while over north-western Portugal (polewards of 41ºN) small increases in suitability are projected instead.

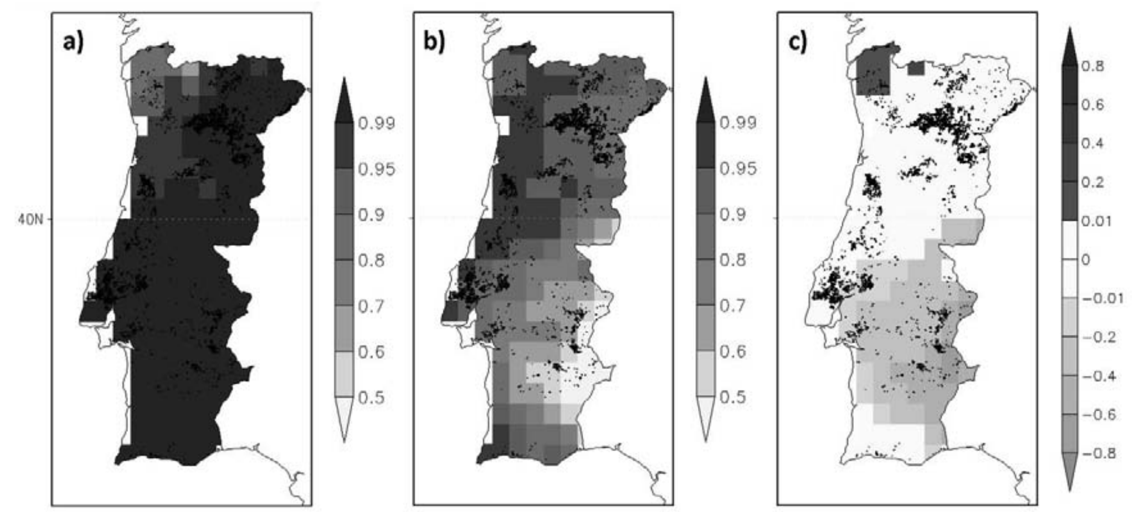

Figure 7 - Composite Index (CompI) for a) the baseline period (1961-2000), b) the future time period (2041-2070), and c) overall differences in 2041-2070 minus 1961-2000 (under the A1B IPCC-SRES scenario). Black areas represent the current vineyard land cover. Not statistically significant differences at the 99% confidence level are grey shaded.

Índice composto (CompI) para a) o período de referência (1961-2000), b) o período futuro (2041-2070), e c) diferenças entre 2041-2070 menos 1961-2000 (sob o cenário A1B IPCC-SRES). Áreas a preto representam o atual coberto vegetal de vinha. Diferenças estatisticamente não significativas, com um nível de confiança 99%, são marcadas a cinzento.

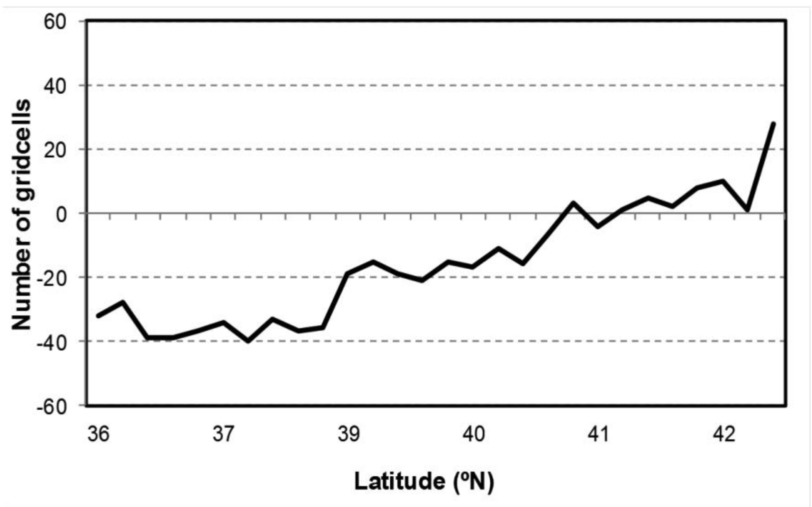

Figure 8 - Latitudinal differences between the periods 2041-2070 and 1961-2000 in the number of grid cells equal to or above 0.5 in the composite index (CompI).

Diferenças latitudinais entre os períodos 2041-2070 e 1961-2000 no número de pontos da grelha, com valor igual ou superior a 0.5 no índice composto (CompI).

DISCUSSION AND CONCLUSIONS

Aiming at analysing the climatic viticultural zoning in Portugal, five bioclimatic indices (HI, CI, HyI, DI and CompI) were computed and mapped over mainland Portugal. Their recent-past spatial patterns allow the isolation of the most suitable regions for winegrape growth and high-quality wine production. On the other hand, their changes under human-driven climate change (A1B SRES scenario) suggest a re-shaping of the suitability throughout the country in the next few decades (until 2070), shedding some light onto the measures that can be adopted to adapt to or mitigate climate change impacts on the Portuguese wine industry.

The HI pattern reveals a significant increase in the values of this index, particularly over the inland and southern areas of the country (Fig. 2). Increases in the HI have already been reported in other European countries, such as for Germany (Stock *et al.*, (2005); Neumann and Matzarakis (2011) and for France (Duchene and Schneider (2005). This is indeed a clear manifestation of the expected warming under the A1B emission scenario, which is more accentuated in continental rather than coastal areas (Meehl *et al.*, 2007; Knutti *et al.*, 2008). Since HI values are largely tied to grapevine thermal demands, including strong correlations with some phenological events which are projected to be brought forward into warmer periods of the year (Jones *et al.*, 2005b; Bock *et al.*, 2011), this shift may have important impacts on the Portuguese viticultural sector. A careful selection of the winegrape varieties to be grown at a given location in the future, based on the new HI classes, is certainly one important adaptation measure.

The CI pattern clearly shows a warming of the nights in September, which may have important implications on the wine quality that must be taken into full consideration, particularly in southern Portugal (e.g. Alentejo), where average minimum temperatures are currently already above 18ºC (Fig. 3). This projected night-time warming is also supported by previous findings of Malheiro and Santos (2011; for the Iberian Peninsula) and expected to yield altered negatively wine typicity and quality (Bock *et al.*, 2011). Furthermore, the CI values should be even higher in regions where the harvest is usually done in August (e.g. Alentejo). Additionally, the frequencies of occurrence of extremely high maximum temperatures (over 40ºC) will also increase (Fig. 4), which enhance thermal stresses and may eventually result in severe damages or even sunburns in leaves and berries. Grape harvest dates may also be affected by these extreme heat events, resulting from the high sensitivity of this crop to summer temperatures (Chuine *et al.*, 2004; Menzel *et al.*, 2011).

Despite the changes in the thermal conditions, changes in rainfall patterns can also strongly impact on the winegrapes. In particular, the overall decrease in the growing season precipitation, mainly in the northern half of Portugal (e.g. Douro Wine Region, Vinhos Verdes Wine Region), may substantially increase water stress symptoms (Fig. 4). In effect, the lack of rain may require compensation measures through irrigation. This idea is supported by the DI pattern that displays values below the minimum threshold of -100 mm over south-eastern Portugal (Fig. 5). Such decrease in the DI values can thus lead to great reductions in grapevine productivity, caused by damaging water stress (Moutinho-Pereira *et al.*, 2004). In contrast, the decrease in the HyI values, accompanied by the lowering of the rainfall during the growing season, mainly in north-western Portugal (Vinhos Verdes controlled appellation), suggests a weakening of the risks of some pests and diseases in the vineyards, such as the downy mildew disease, among others (Fig. 6).

The CompI summarizes the main changes in the previous indices and shows high agreement with the current distribution of the wine types in Portugal (Fig. 7 and Fig. 8). In the current climate, most of mainland Portugal tends to present optimal conditions for winegrape growth, whereas in the future large areas of south-eastern (e.g. Alentejo) will become less suitable. This outcome is supported by previous findings (Jones *et al.*, 2005a; Stock *et al.*, 2005; Malheiro *et al.*, 2010). This climatic unsuitability is largely tied to the excessively dryness that can, however, be widely overcome by implementing both short and long term measures. Amongst the short term measures, it is worth highlighting agronomic practices such as soil (e.g. cover cropping and minimum tillage), organic fertilization and irrigation management and use of chemical sunscreens for leaf protection. With respect to the long term measures, just to mention, adjustments in the training systems (e.g. by optimizing canopy geometry), changes in the altitude or solar exposure of the vineyards (vineyard microclimatic conditions), rootstocks and winegrape varieties of each region and genetic breeding of new varieties, necessarily less sensitive to water and thermal stresses, can be carried out. Furthermore, it is also important to emphasize the genetic pool given by a vast range of autochthonous/indigenous and international varieties (341 legally used varieties; Veloso *et al.*, 2010), which can provide a key tool for climate change adaptation. These measures need to be thoroughly evaluated for each specific region, since some can be more easily implemented in southern Portugal (plain areas more prone to irrigation) and others in northern Portugal (e.g. changes in altitude and solar exposure). Altogether, these measures can effectively mitigate the potentially adverse impacts of climate change on the wine production sector in Portugal and can decisively contribute to its sustainable development in the next decades. Hence, the present study provides some insight into future strategies for the maintenance of a highly competitive wine industry despite climate change threats.

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