ORIGINAL ARTICLE

Very high resolution bioclimatic zoning of Portuguese wine regions: present and future scenarios

H. Fraga · A. C. Malheiro · J. Moutinho-Pereira ·
G. V. Jones · F. Alves · J. G. Pinto ·
J. A. Santos

Abstract Wine production is strongly affected by weather and climate and thus highly vulnerable to climate change. In Portugal, viticulture and wine production are an important economic activity. In the present study, current bioclimatic zoning in Portugal (1950–2000) and its projected changes under future climate conditions (2041–2070) are assessed through the analysis of an aggregated, categorized bioclimatic index (CatI) at a very high spatial resolution (near 1 km). CatI incorporates the most relevant bioclimatic characteristics of a given region, thus allowing the direct comparison between different regions. Future viticultural zoning is achieved using data from 13 climate model transient experiments following the A1B emission scenario. These data are downscaled using a two-step method of spatial pattern downscaling. This downscaling approach allows characterizing mesoclimatic influences on viticulture throughout Portugal. Results for the recent past depict the current spatial variability of Portuguese viticultural regions. Under future climate conditions, the current viticultural zoning is projected to undergo significant changes, which may represent important challenges for the Portuguese winemaking sector. The changes are quite robust across the different climate models. A lower bioclimatic diversity is also projected, resulting from a more homogeneous warm and dry climate in most of the wine regions. This will lead to changes in varietal suitability and wine characteristics of each region.

H. Fraga (✉) · A. C. Malheiro · J. Moutinho-Pereira ·
J. A. Santos
Centre for the Research and Technology of Agro-Environmental and Biological Sciences, University of Trás-os-Montes e Alto Douro, P. O. Box 1013, 5001-801 Vila Real, Portugal
e-mail: hfraga@utad.pt

G. V. Jones
Department of Environmental Studies, Southern Oregon University, 1250 Siskiyou Boulevard, Ashland, OR 97520, USA

F. Alves
ADVID Associação para o Desenvolvimento da Viticultura Duriense, Qta. St. Maria, APT 137, 5050-106 Godim, Portugal

J. G. Pinto
Institute for Geophysics and Meteorology, University of Cologne, 50923 Cologne, Germany

J. G. Pinto
Department of Meteorology, University of Reading, Reading RG6 6BB, UK

Introduction

The study of possible climatic impacts on natural and agricultural ecosystems is of major importance for a wide range of socioeconomic activities (IPCC 2001). More specifically, the viticultural sector is strongly controlled by weather and climate and is thereby highly vulnerable to climate change (Fraga et al. 2012a; Kenny and Harrison 1992). In Portugal, this sector plays an important role in economic stability and growth. Its importance is evident with vineyards being grown over most of the country (Fig. 1a), covering an area of nearly 240,000 ha (3 % of global vineyard surface area) and producing approximately 6×10^6 hl of wine (2 % of world production) each year (OIV 2012). Roughly, half of this production is exported,
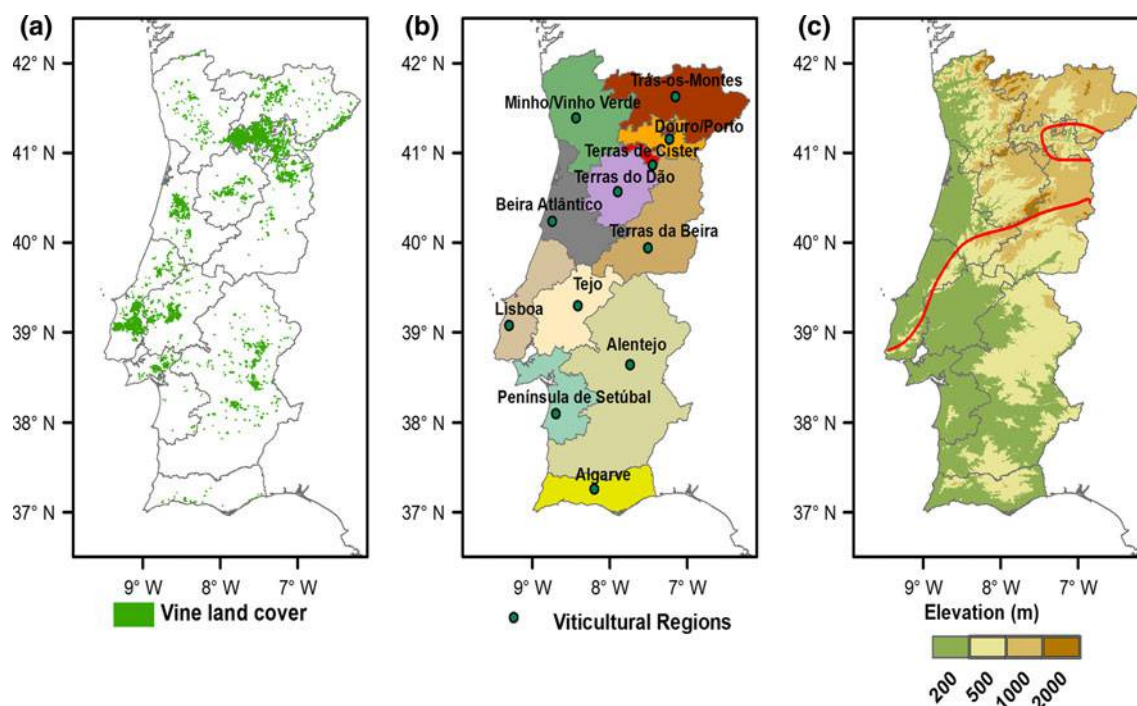
Fig. 1 a Vineyard land cover over mainland Portugal using Corine Land Cover (EEA 2002). **b** Winemaking regions in Portugal (IVV 2011). **c** Elevation in meters using the GTOPO30 digital elevation model (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo 30_info), the *red line* differentiates the Atlantic/Mediterranean climatic zones

corresponding to more than €670 × 10⁶ (OIV 2012) and representing approximately 2 % of national export revenues (IVV 2011). In 2011, Portugal was the eleventh or tenth largest wine producer/exporter in the world (OIV 2012). Mainland Portugal is divided into 12 winemaking regions (Fig. 1b), many of which are world renowned such as the Douro/Porto, Minho and Alentejo. The Douro/Porto region, renowned for its Port Wine, is the oldest Demarcated Region in the world to be regulated by law and was designated World Heritage by UNESCO since 2001, which has obvious implications in tourism and other economic-stimulating activities.

Viticultural microclimatic and mesoclimatic characteristics are key factors in determining varietal suitability and wine types of a given region (Carbonneau 2003; Jones 2006). Portuguese viticultural regions are in fact very distinct regarding their climatic characteristics (Fraga et al. 2012b). As an example, Alentejo (in southern Portugal) is mostly flatland (Fig. 1a, c), with a relatively homogenous warm and dry climate, while Douro/Porto (in northern Portugal) is a very mountainous region, characterized by the steep slopes of the Douro Valley. Furthermore, the Douro Valley contains a significant part of the country's vineyard land cover (Fig. 1a) and comprises a large diversity of mesoclimates (Santos et al. 2013). Another climatically distinct viticultural region is Minho (in

northwestern Portugal), which is characterized by relatively high annual precipitation (above 1,200 mm) and relatively mild summers. These climatic features provide distinct viticultural characteristics in each winemaking region (Magalhães 2008). The combination of favorable climatic conditions, geomorphological aspects, experienced management decisions and numerous native wine-grape varieties (e.g., Castelão, Touriga Nacional, Touriga Franca, Tinta Barroca) result in unique wine types (Jones 2012).

Spatially interpolated climate datasets have been a valuable tool to study recent-past climate and to assess possible climate change impacts, particularly in terms of environmental and agricultural changes (IPCC 2001). The use of high spatial resolution datasets is of significant importance for viticulture, since it is necessary to properly capture environmental variability within and between regions. This is particularly relevant for regions with steep climate gradients, where low resolution datasets cannot truly represent vineyard mesoclimates. Furthermore, as vineyards are usually dependent on slope, aspect and other yield-influencing elements of the landscape, the complexity of the Portuguese topography (cf. Fig. 1c) is also an important factor controlling both development and spatial distribution of this crop throughout the country. The diverse climatic conditions and large spatial

variability in which vineyards are grown in Portugal must be taken into account in order to produce a valuable viticultural zoning. Several previous studies used weather station data (Blanco-Ward et al. 2007; Jones and Goodrich 2008); other studies used Global Climate Model (GCM) data with spatial resolutions of about 100–250 km, and, more recently, Regional Climate Model (RCM) data with higher spatial resolutions of about 25 km (Fraga et al. 2012b, 2013; Malheiro et al. 2010). Although these studies represent a valuable tool for climatic characterization of viticultural regions, the data used may not entirely reflect the vineyard climate. Therefore, the use of high-resolution data (1 km or less) has proven to be an important advance for regional/local scale assessments (Hall and Jones 2010; Anderson et al. 2012; Jones et al. 2010).

Bioclimatic indices are useful metrics for assessing climatic influences on viticulture and thus can be used in viticultural zoning applications. One of the most widely used climatic indicators in viticultural zoning is the concept of degree-day for a base temperature of 10 °C (Amerine and Winkler 1944). Using a degree-day approach, the Huglin Index (HI; Huglin 1978) allows assessing the thermal potential of a given region and links the thermal demands for the ripening of each variety, reflecting the potential grape sugar content. The Dryness index (DI; Riou et al. 1994) evaluates soil water availability for vine development, by estimating soil water reserves, precipitation and potential evapotranspiration (potential water balance). This is also a good indicator for winegrape growth, as water availability can influence yield and quality (Hardie and Martin 2000). The Cool Night Index (CI; Tonietto and Carbonneau 2004) accounts for minimum temperatures during September, providing a coarse estimate of the ripening stage, as large temperature ranges during ripening tend to be favorable to high-quality wines. Furthermore, by combining these bioclimatic aspects of heat accumulation (HI), dryness (DI), and ripening conditions (CI), it is possible to determine optimum viticulture suitability and direct comparison between regions.

The present study aims to improve the current knowledge concerning the bioclimatic conditions of the Portuguese viticultural regions, also focusing on future implications of climate change in the sustainability of this agribusiness. As such, the objectives of this study are three-fold: (1) to provide a high-resolution viticultural climatic zoning and comparison of bioclimatic indices over mainland Portugal; (2) to develop an aggregated categorized index that provides combined information regarding the bioclimatic characteristics of each region; and (3) to discuss the impacts of climate change on this zoning.

Materials and methods

Bioclimatic zoning

A very high resolution climate dataset, produced by the WorldClim project (Hijmans et al. 2005), is used over the baseline period (1950–2000) for index computations. This gridded dataset provides monthly climatic normals of precipitation, minimum, maximum and mean temperatures over a $0.008° \times 0.008°$ latitude–longitude grid (~ 1 km). The above-mentioned variables are extracted over the Portuguese mainland (649×865 grid cells). Using the WorldClim data, three bioclimatic indices CI, DI and HI are calculated over mainland Portugal (cf. Table S1 in supplementary material). For validation purposes, differences between the indices calculated using this dataset and the E-OBS observational data (~ 25 km spatial resolution; Haylock et al. 2008) are computed, revealing an overall good agreement (Fig. S1). Differences can be mostly explained by the predominant location of the E-OBS stations at low-elevations, leading to slightly warmer and drier conditions in E-OBS than in WorldClim. Although other bioclimatic indices are also calculated (Table S1), their spatial patterns provide overlapping information (Pearson correlation coefficients ≥ 0.95 with the previous three indices, Table S2) and are thus not presented here.

To assess the impacts of climate change on future viticultural suitability in Portugal, the period 2041–2070 under the *Intergovernmental Panel on Climate Change Special Report on Emission Scenarios* A1B scenario is considered (Nakićenović et al. 2000). An ensemble of 13 RCM simulations driven by 3 different GCMs (Table S3) produced by the ENSEMBLES project (van der Linden and Mitchell 2009) is used for this purpose.

Spatial pattern downscaling

As raw RCM datasets are available on a $0.22° \times 0.22°$ latitude–longitude grid (~ 25 km), which is a coarse grid when compared to the baseline pattern (BP; <1 km), a two-step downscaling of the RCM-derived indices is undertaken. First, the climate change signal (CCS) for each index, that is, the difference pattern between its 13-member ensemble means for 2041–2070 and 1951–2000 ('deltas' or anomalies), is bi-cubically interpolated for the same grid as in BP. Second, the interpolated climate change signal of each index is then added to BP, resulting in an index future pattern (FP) at a very high resolution. Therefore, the entire procedure for each index is as follows: CCS → interpolated CCS + BP = FP. This approach, also called pattern downscaling or 'delta method', relies on the assumption that the CCS presents high spatial correlations within a 25 km cell (RCM resolution). This is indeed a very

reasonable assumption and does not present a significant limitation in the methodology. In fact, similar methodologies have been used in previous studies (Ramirez-Villegas and Jarvis 2010; Hay et al. 2000), but using GCM data (significantly lower resolutions than herein). Besides the very high resolution of the downscaled fields, this approach has the important advantage of maintaining the original baseline dataset independent variables (longitude, latitude and elevation). Another important advantage of this methodology is that it does not require model output statistics, since the CCS itself is independent of these corrections.

Categorized Index

Lastly, an aggregated categorization is developed that integrates the CI, DI, and HI into a Categorized Index (CatI hereafter). This single, multipurpose index provides combined information regarding regional bioclimatic characteristics. The combination of classes is indeed similar to the multi-criteria climatic classification (MCC) by Tonietto

and Carbonneau (2004). However, CatI includes only 17 different categories (Table 1), instead of 96 classes in the MCC, which simplifies mapping over large areas and allows an easier regional comparison. Also, the CatI includes limiting thresholds for viticultural suitability, namely $DI > -100$ mm and $HI > 900\ °C$ (Fraga et al. 2013). Area-average minima, maxima and means of the CatI composing indices (HI, DI and CI) are also summarized for the 12 wine regions in Table S4.

Results

Regional climatic zoning

For the different wine regions in mainland Portugal, the patterns of CatI (Table 1) are depicted in Figs. 2, 3, 4 and 5 (cf. CI, DI and HI patterns in Figs. S2–S4). High correspondences between CatI and MCC are found for Portugal (Table S5), with the classes showing a Spearman rank correlation coefficient of 0.81 (the MCC nominal scale is

Table 1 Categories of CatI, along with the corresponding classes of the combined indices: Huglin, Dryness and Cool Night indices

Category	Huglin Index (°C units) (Huglin 1978)	Dryness Index (mm) (Riou et al. 1994)	Cool Night Index (°C units) (Tonietto and Carbonneau 2004)	Description
0	<900	<−100		Unsuitably cold or excessively dry
1	900–1,500	−100 to 50	<14	Cool, dry with cool nights
2			>14	Cool, dry with warm nights
3		> 50	<14	Cool, humid with cool nights
4			>14	Cool, humid with warm nights
5	1,500–2,100	−100 to 50	<14	Temperate, dry with cool nights
6			>14	Temperate, dry with warm nights
7		>50	<14	Temperate, humid with cool nights
8			>14	Temperate, humid with warm nights
9	2,100–2,700	−100 to 50	<14	Warm, dry with cool nights
10			>14	Warm, dry with warm nights
11		>50	<14	Warm, humid with cool nights
12			>14	Warm, humid with warm nights
13	>2,700	−100 to 50	<14	Very warm, dry with cool nights
14			>14	Very warm, dry with warm nights
15		>50	<14	Very warm, humid with cool nights
16			>14	Very warm, humid with warm nights

A short description of the each category is also provided

converted into an equivalent ordinal scale for computing this correlation). For Minho (Fig. 2a, b), CatI is projected to undergo changes that are mainly from category 3 to 6 and from 7 or 8 to 10. This is the most humid wine region in Portugal under current conditions and will likely retain the maximum DI local value in the future (Table S4). The Trás-os-Montes region (Fig. 2c, d) is characterized by a strong bioclimatic heterogeneity, with warm and dry climates coexisting with cool and humid climates due to

elevation differences over the region (Fig. 1c). In the future, contrary to the results seen for other regions, where a homogenization of the climate categories is projected, this region is expected to retain strong regional contrasts. In fact, some areas that are currently too cold are projected to become suitable (changes from category 0 to 1 or 3). Other areas will likely see changes from category 3 to 6, 6 to 14 and 7 to 9 or 10. It is also important to note that Trás-os-Montes exhibits the lowest minimum CI and HI in both

Fig. 2 CatI for the winemaking regions of **a**, **b** Minho, **c**, **d** Trás-os-Montes and **e**, **f** Douro/Porto for (*left panel*) 1950–2000 and (*right panel*) 2041–2070 under the A1B scenario. The current vineyard land cover is shown in *dark stipple*. See Table 1 for class structure for the CatI
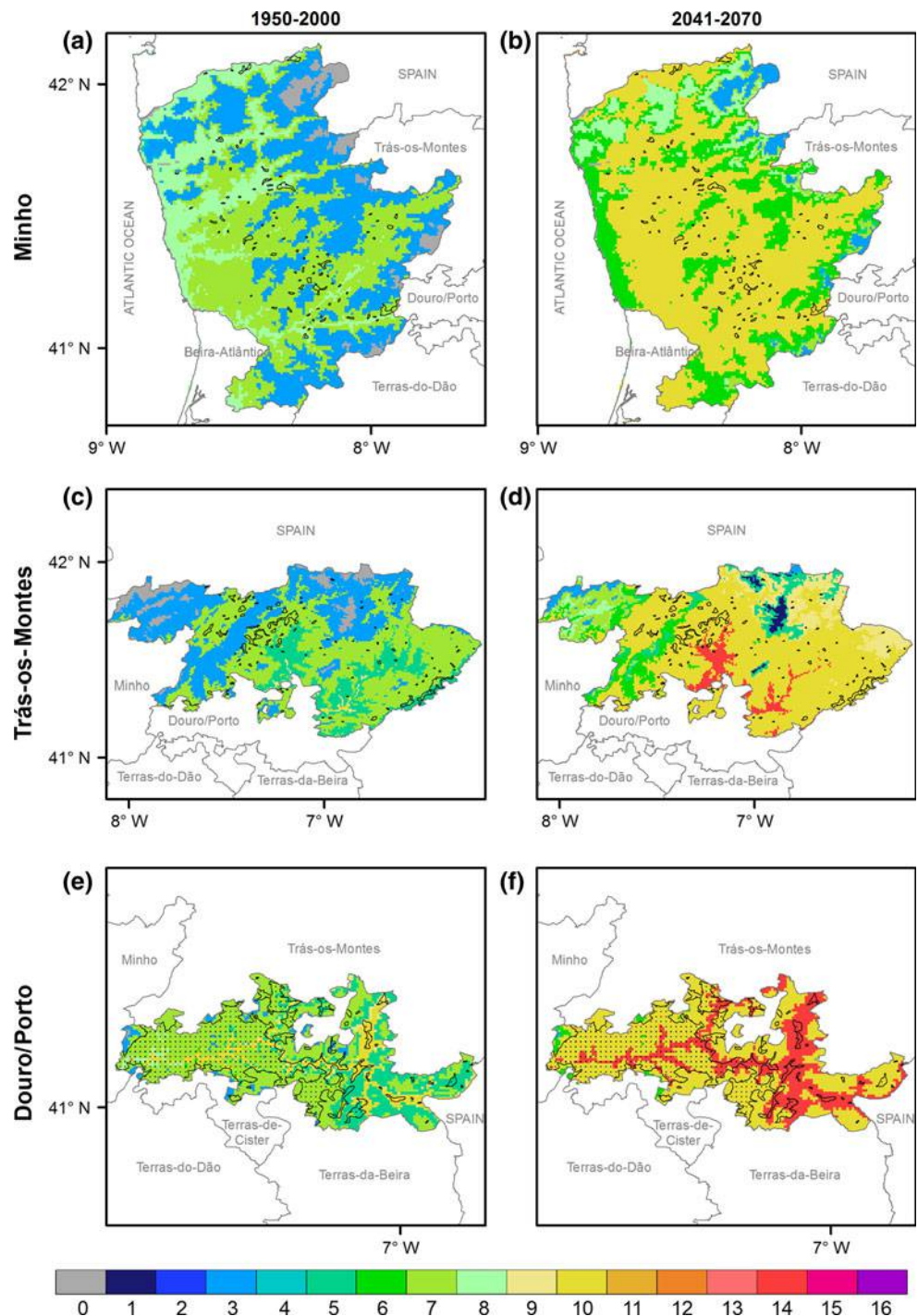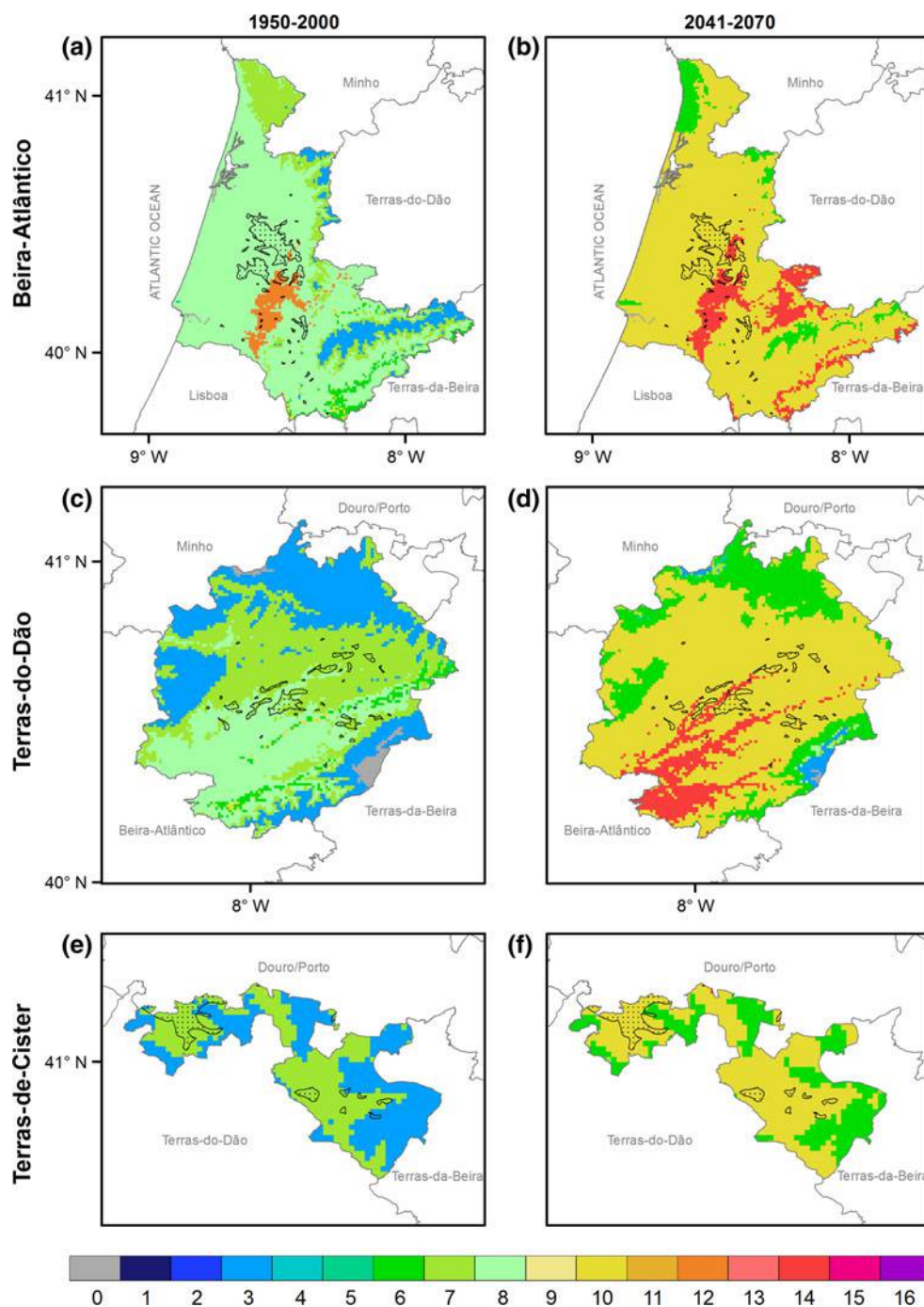
Fig. 3 CatI for the winemaking regions of **a**, **b** Beira-Atlântico, **c**, **d** Terras-do-Dão and **e**, **f** Terras-de-Cister for (*left panel*) 1950–2000 and (*right panel*) 2041–2070 under the A1B scenario. The current vineyard land cover is shown in *dark stipple*. See Table 1 for class structure for the CatI

present and future periods for the whole of Portugal (Table S4). The Douro/Porto region (Fig. 2e, f) presents a high diversity of bioclimatic regions due to the complex topography of the Douro Valley. In low elevation areas, categories 9 or 10 are projected to change to category 14, whereas categories 6 (in eastern areas) and 7 (in central and western areas) are projected to change to category 10.

The Beira-Atlântico region (Fig. 3a, b) shows a large diversity of distinct bioclimatic categories, which can be largely explained by orographic forcing inland from the

coast. Most of the region is currently in category 8, while more northern areas are category 7 (cooler nights) and some higher elevation areas are in category 3 (due to generally cooler climate). In the future, however, large areas of the region are projected to change to category 10, with the exception of some higher elevation and northern areas that will likely change to category 6. Currently, this region is the only showing category 12, combining a warm and humid climate with warm nights. In the future, this area will likely change to category 14, as a result of

Fig. 4 CatI for the winemaking regions of **a**, **b** Terras-da-Beira, **c**, **d** Lisboa and **e**, **f** Tejo for (*left panel*) 1950–2000 and (*right panel*) 2041–2070 under the A1B scenario. The current vineyard land cover is shown in *dark stipple*. See Table 1 for class structure for the CatI
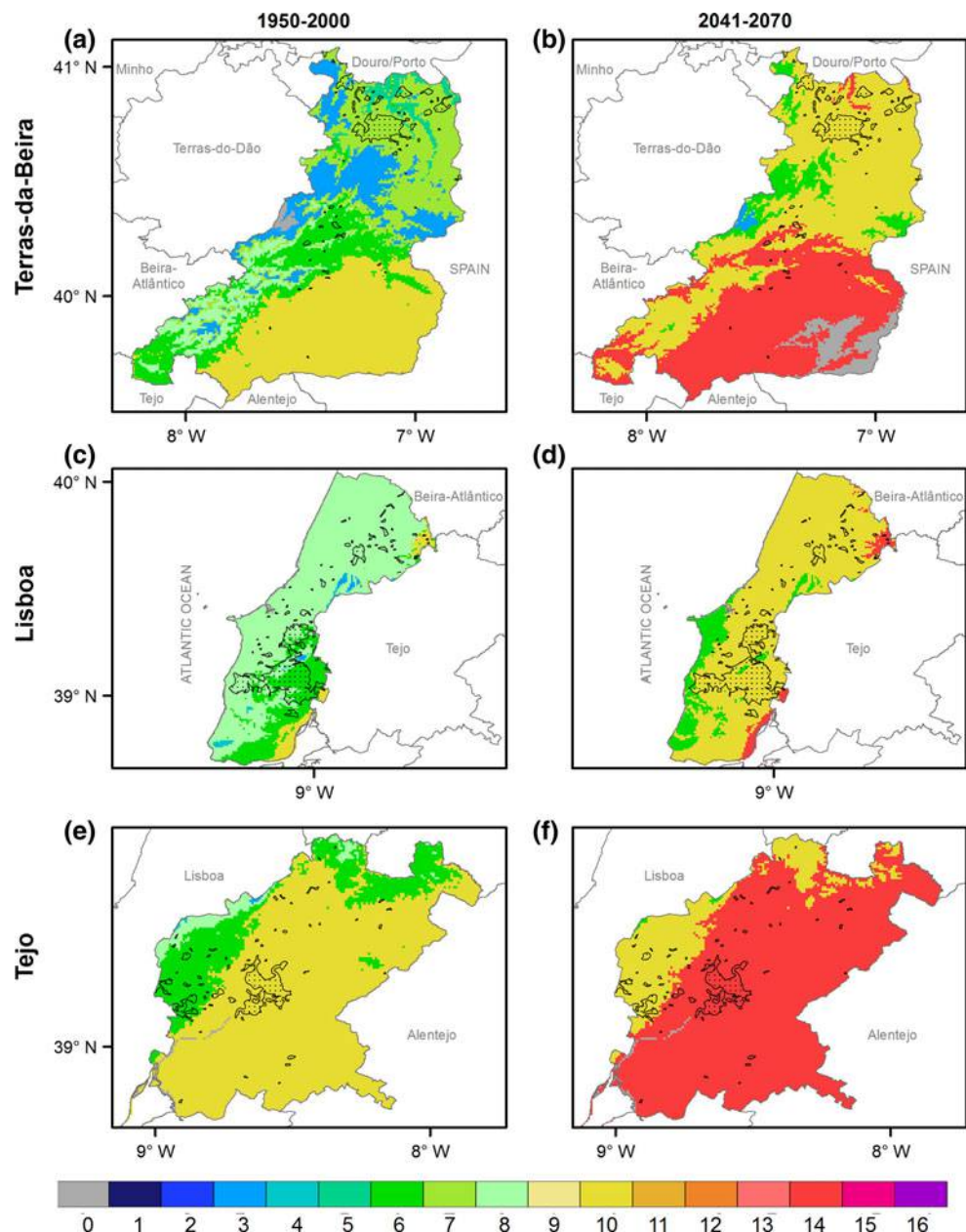

warming and increased dryness. Regarding Terras-do-Dão (Fig. 3c, d), shifts mainly occur from categories 3, 7 and 8 to 6, 10 and 14. The small region of Terras-de-Cister (Fig. 3e, f) undergoes changes from categories 3 and 7 to 6 and 10. In the future, according to HI and DI, this region will likely become the coolest and least dry region (less affected by the overall drying trend) in the whole country (Table S4).

For Terras-da-Beira (Fig. 4a, b), CatI clearly shows two distinct areas that either reflect the dominance of Atlantic (north) or Mediterranean (south) influences on climate. Southeastern areas are in category 10, with a warmer climate, while northern areas present temperate (CatI 7) or even cool (CatI 3) climates. Intermediate areas, between these climatically distinct zones, present CatI 6 or 8 (dry or humid temperate climates with warmer nights; Table 1). In the future, the Mediterranean area is projected to change to categories 14 or 0, being the last transition always due to excessive dryness. In the more Atlantic areas, changes are projected to be mostly to categories 6 and 10. The Lisboa region (Fig. 4c, d) is mostly characterized by categories 6 and 8 (western coastal areas), which is projected to change to category 10, though category 6 will likely remain in some coastal areas and category 14 is likely to be residual at some easternmost locations. For Tejo (Fig. 4e, f), changes are projected to be mostly from categories 6 and 10 to 10 and 14, respectively.

Fig. 5 CatI for the winemaking regions of **a**, **b** Península-de-Setúbal, **c**, **d** Alentejo and **e**, **f** Algarve for (*left panel*) 1950–2000 and (*right panel*) 2041–2070 under the A1B scenario. The current vineyard land cover is shown in *dark stipple*. See Table 1 for class structure for the CatI
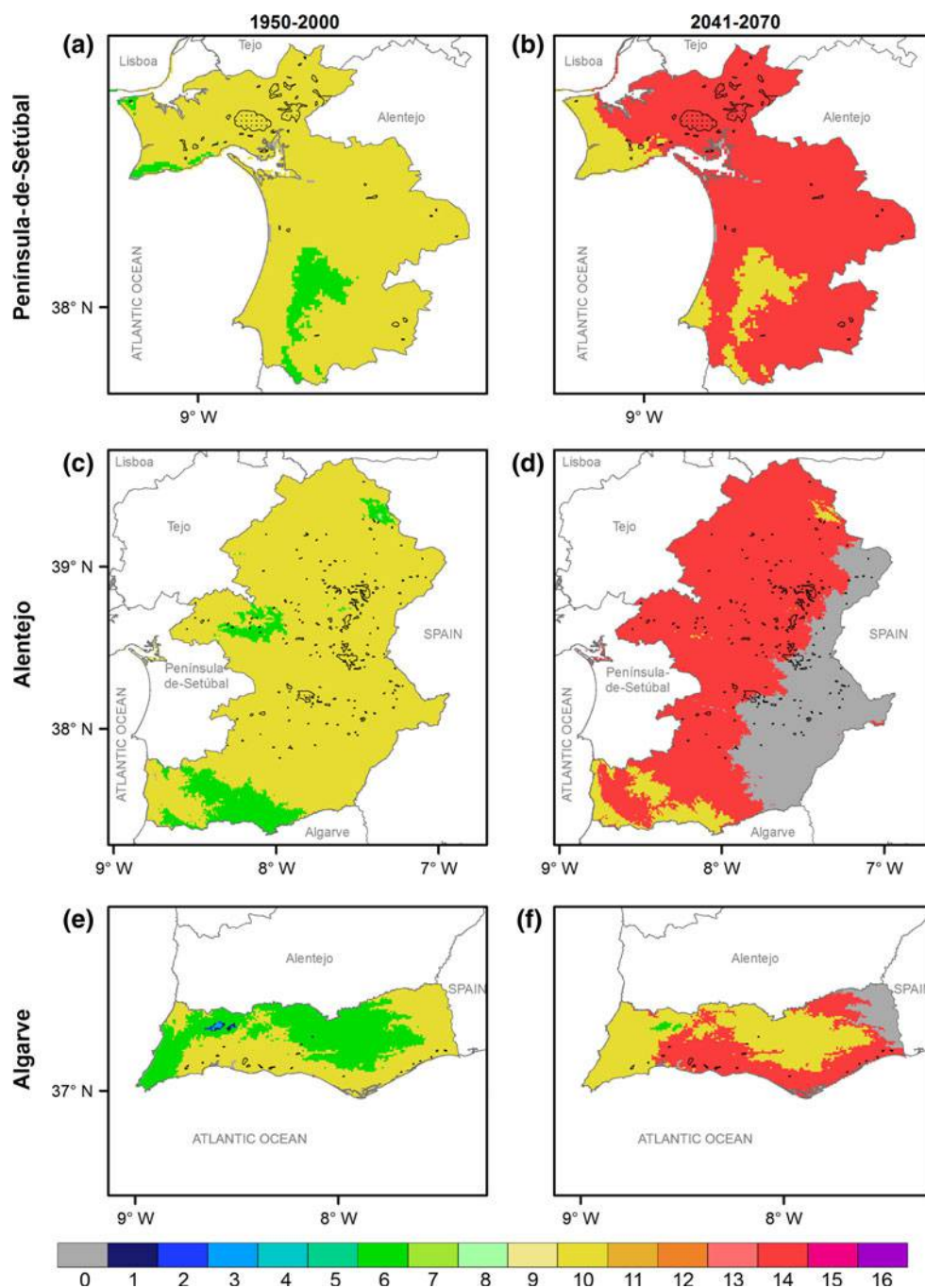
For the Península-de-Setúbal (Fig. 5a, b) region, projected changes are expected to be similar to the Tejo region with categories 6 and 10 changing to 10 and 14, respectively. However, it is worth noting that Península-de-Setúbal is expected to have the highest CI in the future (Table S4). For the Alentejo (Fig. 5c, d), CatI shows that most of the region is projected to transition from category 10 to 14, resulting in a future with a dry and very warm climate with warm nights, or even category 0, where viticulture is constrained, in this case due to excessive dryness (Fig. S3). In the future, Alentejo will not only likely experience the highest area-mean HI in Portugal, but will also keep the absolute nationwide maximum. Furthermore, the lowest DI value over Portugal is also projected to be found in this region (-127 mm), where its area-mean value is near the suitability limit of -100 mm (Table S4). Although some areas will likely change from category 6 to 10, they currently show relatively low vineyard coverage. Lastly, in the Algarve wine region (Fig. 5e, f), similar future changes are visible, which is not totally surprising due to the proximity between these two regions. In fact, most of category 10 areas are projected to change to either

category 14 or 0 (mainly in the Guadiana river basin, eastern Algarve), while category 6 areas (high elevation or northwestern Algarve) will likely change to category 10. Algarve, in both present conditions and future projections, shows the highest CI values in Portugal (Table S4).

Projected category transitions

Overall, CatI transitions will mainly occur to higher categories (Fig. S5), while opposite changes will cumulatively account for less than 1 % (transitions to category 0 not included). It is visible that most changes are from category 10 to 14 (33 % of all grid boxes). This outcome is largely influenced by changes depicted in vast areas of southern Portugal. Changes from category 5, 6, 7 or 8 to 10 are also frequent (2, 7, 17 and 12 %, respectively), especially in the coastal regions. Most of the changes to category 0 (with viticultural unsuitability) come from current category 10 (8 %), mainly occurring in the innermost regions of southern Portugal, as other transitions to category 0 are residual. Category 3 areas will mostly change to categories 6 and 10 (5 and 3 %) in the north. Moreover, remarkable climate anomalies, depicting changes from temperate to very warm climates, are visible from category 6 to 14 (3 %). Conversely, positive CatI changes from category 0 to others, account for 1 % of the total transitions over the Portuguese mainland, due to changes from very cool to

cool or temperate climates in some high-elevation areas in the northern half of Portugal.

Ensemble variability

The ensemble variability in the projected CatI transitions reveals low model spread for each region. Although other categories occur within each region, only the future dominant categories (with the highest spatial coverage) are considered here for the sake of succinctness (Table 2). The highest agreement between models is found for Lisboa, with all models projecting the same future category as in the ensemble mean (CatI 10; Fig. 4d), whereas for Terras-de-Cister, only 7 from 13 models (53.8 %) show the same dominant category as in the ensemble mean (CatI 10; Fig. 3f).

Discussion and conclusions

In the present study, a high-resolution current viticultural bioclimatic zoning over mainland Portugal is produced using an aggregated index that combines aspects of heat accumulation, dryness and ripening conditions (CatI) allowing for direct comparison between regions. The new CatI also provides an easier and more practical integration with high-resolution climatic dataset than other indices, such as the MCC, by using fewer classes more adapted to the Portuguese climate (17 instead of 96). The index computation is based on a very high resolution dataset (WorldClim Project) for a baseline period (1950–2000). Climate change projections are carried out by using a 13-member GCM/RCM ensemble of transient model experiments over 2041–2070 and following the A1B scenario. These data are downscaled to a near 1-km grid spacing, through a two-step method of spatial pattern downscaling, allowing the characterization of mesoclimatic influences in viticulture. Although a moderate emission scenario is selected, the variability in the climate change projections associated with more/less severe scenarios are commonly of the same magnitude as the variability across a model ensemble (IPCC 2001).

The viticultural zoning clearly depicts an Atlantic/Mediterranean climatic contrast over Portugal (roughly delineated by the red line Fig. 1c), highlighting not only significant spatial variability throughout the country, but also in each winemaking region. The current vineyard land cover in mainland Portugal takes advantage of the current bioclimatic diversity, explaining the relatively high number of wine regions and sub-regions with Denomination of Origin (Jones and Alves 2012b), specialized in the production of very specific wines made from a large number of grapevine varieties grown all across the country (Lopes

Table 2 Wine regions with the corresponding dominant category (with the highest spatial coverage) in the ensemble-mean CatI for the future period (2041–2070; cf. Figs. 2, 3, 4, 5)

Region	Ensemble-mean dominant category (CatI)	Single-model dominant categories (CatI–%)
Alentejo	14	**14–76.9 %**; 0–23.1 %
Algarve	14	**14–69.2 %**; 0–15.4 %; 10–15.4 %
Beira-Atlântico	10	**10–84.6 %**; 14–15.4 %
Douro/Porto	10	**10–84.6 %**; 14–15.4 %
Lisboa	10	**10–100 %**
Minho	10	**10–92.3 %**; 14–7.7 %
Península-de-Setúbal	14	**14–92.3 %**; 0–7.7 %
Tejo	14	**14–76.9 %**; 10–23.1 %
Terras-da-Beira	10	**10–69.2 %**; 14–23.1 %; 0–7.7 %
Terras-de-Cister	10	**10–53.8 %**; 6–38.5 %; 14–7.7 %
Terras-do-Dão	10	**10–84.6 %**; 14–15.4 %
Trás-os-Montes	10	**10–84.6 %**; 14–7.7 %; 0–7.7 %

The respective single-model dominant categories are also listed, along with the percentages of occurrence across the 13-model ensemble (ensemble-mean dominant category in bold)

et al. 2008). Current grapevine-growing areas are not only determined by climate, but also by historic factors, soil and varietal characteristics, land-use limitations and food politics (e.g., other crop priorities). Despite the importance of all these factors, the very high resolution maps of the bioclimatic indices provided herein represent an important tool for better understanding viticultural zoning in Portugal, especially if interpreted in conjunction with these factors.

Under human-induced climate change, however, the current viticultural zoning is projected to undergo remarkable changes that can represent important challenges to the Portuguese winemaking sector. Future shifts in the CatI to higher classes are expected, which are in close agreement with recent and current warming reported in several European countries (Orlandini et al. 2009; Neumann and Matzarakis 2011; Duchene and Schneider 2005; Lorenzo et al. 2012). This may also lead to earlier phenological events throughout the country (Jones et al. 2005; Webb et al. 2012; Jones and Davis 2000). Future CatI spatial characteristics may imply a lower diversity of bioclimatic categories, resulting in a more homogeneous warm and dry climate throughout the country (mostly CatI 10 and 14), with the exception of Trás-os-Montes, where this warming will result in more heterogeneity. A more homogeneous climate undoubtedly will lead to changes in varietal selection and wine characteristics of each region.

In particular, in the more Mediterranean-like climatic regions (Alentejo, Algarve, Península-de-Setúbal, Tejo, southern half of Terras-da-Beira and innermost part of Douro/Porto), where CatI categories such as 10 characterize the current conditions, the projected increase in HI (warmer climates) may threaten less adapted cultivars. Moreover, in these regions, projected severe dryness (DI; Fig. S3) may lead to poor yields or even to unsuitable conditions for viticulture wherever irrigation is not feasible. In fact, the combined effect of increased warming and drying may cause damaging stresses to grapevines and grapes at biochemical and physiological levels (Moutinho-Pereira et al. 2004; Chaves et al. 2010). Nocturnal warming and decreased diurnal thermal amplitude (CI; Fig. S2) in the last stages of development may also reduce wine quality (Tonietto and Carbonneau 2004). Although not covered by CatI, extreme high summertime temperatures may substantially increase water demands, which, when unmitigated, may cause physiological issues (e.g., leaves and berries sunburn, dehydration). Other weather extremes (e.g., hailstorms and late frosts) can also play a key role, but are not taken into account herein. All these changes can ultimately result in negative impacts on wine characteristics and/or quality.

On the other hand, northern and coastal regions of Portugal (Minho, Trás-os-Montes, Lisboa, Terras-do-Dão,

Terras-de-Cister and Beira-Atlântico), which are more exposed to Atlantic air masses, where lower CatI categories are found, the results herein suggest some beneficial impacts of climate change. While projections for HI (Fig. S4) in these regions also give evidence for strong warming trends in the growing season, changes in these regions will likely enable changes to late maturing varieties, different wine styles and potentially better quality. However, increased dryness in these regions, although neither excessive nor limiting for grapevine development, may have impacts on yield and quality regularity. To a certain extent, the overall drying in future climates can be advantageous, since lower humidity levels in vineyard microclimates, should reduce the risk of diseases (e.g., downy mildew) potentially requiring less chemical control measures in vineyards.

The results from this study indicate that climate change adaptation measures should be focused on regions that are currently in category 10 (CatI; Fig. S5), as they are projected to change to category 14 or 0 (unsuitable conditions). The excessive dryness in these regions will likely require improved grapevine water use efficiency (Flexas et al. 2010). Furthermore, changes in some traditionally developed training systems may need to be applied (Pieri and Gaudillere 2003) to deal with lower water availability. In addition, proper selection of scion and rootstock will become more essential under increasingly warm and dry climate regimes (Harbertson and Keller 2012). Exploring irrigation management techniques, such as deficit irrigation strategies (Ferreira et al. 2012; Alves et al. 2012), should also be considered to provide an optimum yield/cost ratio. Solar radiation interception is also a major factor that can influence grapevine physiology. In the future, the optimization of canopy geometry and row orientation, or even employing shading materials, will likely be key measures that should be considered. Changes in soil management practices (e.g., cover cropping) should also be included in a broader adaptation strategy (Lopes et al. 2011). Furthermore, the beneficial effect of the enhanced atmospheric CO_2 concentrations in grapevine physiology may also play an important role in future viticulture (Moutinho-Pereira et al. 2009).

In the future, warmer and dryer climates will challenge Portuguese viticulture, but may also represent an opportunity for a more sustainable sector. Although the current study focuses on a single future scenario (A1B), it provides robust and comprehensive projections using a multi-model ensemble. Previous studies have established the importance of viticultural zoning (e.g., Jones et al. 2010; Santos et al. 2012; Webb et al. 2011; Jones and Alves 2012a) and also emphasized the relevance of various bioclimatic factors in the geographical distribution of winegrapes, phenological developmental stages and varietal suitability. However,

until the present, due to the lack of a high-resolution climatic zoning in Portugal, direct comparisons between the winemaking regions have been based on large-scale assessments or weather station data, which may overestimate the climatic structure in a given wine region (Hall and Jones 2010; Jones and Alves 2012a). Although the country has a large number of legally authorized varieties (341; Veloso et al. 2010), most of them autochthonous, only a few studies have been devoted to their optimum suitability in some specific Portuguese wine regions (e.g., Lopes et al. 2008). By depicting bioclimatic conditions at a very high resolution for both current and future climates in Portugal, along with advances in understanding the optimal requirements of the traditionally grown or autochthonous winegrape varieties, a better understanding of adaptation strategies to climate change impacts can be fostered within this key sector of the Portuguese economy.

References

Alves F, Costa J, Costa P, Correia CM, Gonçalves BM, Soares R, Moutinho-Pereira J (2012) Influence of climate and deficit irrigation on grapevine physiology, yield and quality attributes, of the cv. Touriga Nacional at Douro Region. In: Proceeding of the IX international Terroirs congress, 25–29 June, Dijon-Reims, France

Amerine MA, Winkler AJ (1944) Composition and quality of musts and wines of California grapes. Hilgardia 15:493–675

Anderson JD, Jones GV, Tait A, Hall A, Trought MCT (2012) Analysis of viticulture region climate structure and suitability in New Zealand. Journal International des Sciences de la Vigne et du Vin 46(3):149–165

Blanco-Ward D, Queijeiro JMG, Jones GV (2007) Spatial climate variability and viticulture in the Mino River Valley of Spain. Vitis 46(2):63–70

Carbonneau A (2003) Ecophysiologie de la vigne et terroir. In: Terroir, zonazione, viticoltura. Trattato internazionale. Phytoline, pp 61–102

Chaves MM, Zarrouk O, Francisco R, Costa JM, Santos T, Regalado AP, Rodrigues ML, Lopes CM (2010) Grapevine under deficit irrigation: hints from physiological and molecular data. Ann Bot 105(5):661–676. doi:10.1093/aob/mcq030

Duchene E, Schneider C (2005) Grapevine and climatic changes: a glance at the situation in Alsace. Agron Sustain Dev 25(1):93–99. doi:10.1051/Agro:2004057

EEA (2002) CORINE land cover update, I&CLC2000 project, Technical guidelines

Ferreira MI, Silvestre J, Conceição N, Malheiro AC (2012) Crop and stress coefficients in rainfed and deficit irrigation vineyards using sap flow techniques. Irrig Sci 30(5):433–447. doi:10.1007/s00271-012-0352-2

Flexas J, Galmes J, Galle A, Gulias J, Pou A, Ribas-Carbo M, Tomas M, Medrano H (2010) Improving water use efficiency in grapevines: potential physiological targets for biotechnological improvement. Aust J Grape Wine Res 16:106–121. doi:10.1111/j.1755-0238.2009.00057.x

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2012a) An overview of climate change impacts on European viticulture. Food Energy Secur 1(2):94–110. doi:10.1002/fes3.14

Fraga H, Santos JA, Malheiro AC, Moutinho-Pereira J (2012b) Climate change projections for the portuguese viticulture using a multi-model ensemble. Ciência Téc Vitiv 27(1):39–48

Fraga H, Malheiro AC, Moutinho-Pereira J, Santos JA (2013) Future scenarios for viticultural zoning in Europe: ensemble projections and uncertainties. Int J Biometeorol 1–17. doi:10.1007/s00484-012-0617-8

Hall A, Jones GV (2010) Spatial analysis of climate in winegrape-growing regions in Australia. Aust J Grape Wine Res 16(3):389–404. doi:10.1111/j.1755-0238.2010.00100.x

Harbertson JF, Keller M (2012) Rootstock effects on deficit-irrigated winegrapes in a dry climate: grape and wine composition. Am J Enol Vitic 63(1):40–48. doi:10.5344/ajev.2011.11079

Hardie WJ, Martin SR (2000) Shoot growth on de-fruited grapevines: a physiological indicator for irrigation scheduling. Aust J Grape Wine Res 6(1):52–58. doi:10.1111/j.1755-0238.2000.tb00162.x

Hay LE, Wilby RJL, Leavesley GH (2000) A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. J Am Water Resour Assoc 36(2):387–397. doi:10.1111/j.1752-1688.2000.tb04276.x

Haylock MR, Hofstra N, Klein Tank AMG, Klok EJ, Jones PD, New M (2008) A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J Geophys Res 113(D20):D20119. doi:10.1029/2008jd010201

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25(15):1965–1978. doi:10.1002/joc.1276

Huglin P (1978) Nouveau mode d'évaluation des possibilités hélio-thermiques d'un milieu viticole. Comptes Rendus de l'Académie d'Agriculture. Académie d'agriculture de France 64(13):1117–1126

IPCC (2001) Climate change 2001: synthesis report. In: Watson RT, The Core Team (eds) A contribution of working groups I, II, III to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, 398 pp

IVV (2011) Vinhos e Aguardentes de Portugal, Anuário 2010/2011. Ministério da Agricultura, do Desenvolvimento Rural e das Pescas: Instituto da Vinha e do Vinho, Lisboa

Jones GV (2006) Climate and terroir: impacts of climate variability and change on wine in fine wine and terroir—the geoscience perspective. In: Macqueen RW, Meinert LD (eds) Geoscience Canada, Geological Association of Canada, St. John's, Newfoundland, Canada, Geoscience Canada

Jones GV (2012) A climate assessment for the Douro Wine Region: an examination for the past. Present and future conditions for wine production. ADVID, Peso da Régua

Jones GV, Alves F (2012a) Impact of climate change on wine production: a global overview and regional assessment in the Douro Valley of Portugal. Int J Glob Warming 4(3/4):383–406

Jones GV, Alves F (2012b) Spatial analysis of climate in winegrape growing regions in Portugal. In: Proceedings of the 9th international Terroir congress, vol 3, pp 1–4, 25–29 June, 2012, Burgundy and Champagne, France

Jones GV, Davis RE (2000) Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. Am J Enol Vitic 51(3):249–261

Jones GV, Goodrich GB (2008) Influence of climate variability on wine regions in the western USA and on wine quality in the Napa Valley. Clim Res 35(3):241–254. doi:10.3354/cr00708

Jones GV, White MA, Cooper OR, Storchmann K (2005) Climate change and global wine quality. Clim Change 73(3):319–343. doi:10.1007/s10584-005-4704-2

Jones GV, Duff AA, Hall A, Myers JW (2010) Spatial analysis of climate in winegrape growing regions in the Western United States. Am J Enol Vitic 61(3):313–326

Kenny GJ, Harrison PA (1992) The effects of climate variability and change on grape suitability in Europe. J Wine Res 3(3):163–183. doi:10.1080/09571269208717931

Lopes J, Eiras-Dias JE, Abreu F, Climaco P, Cunha JP, Silvestre J (2008) Thermal requirements, duration and precocity of phenological stages of grapevine cultivars of the Portuguese collection. Ciencia E Tecnica Vitivinicola 23(1):61–71

Lopes CM, Santos TP, Monteiro A, Rodrigues ML, Costa JM, Chaves MM (2011) Combining cover cropping with deficit irrigation in a Mediterranean low vigor vineyard. Sci Hortic-Amsterdam 129(4):603–612. doi:10.1016/j.scienta.2011.04.033

Lorenzo MN, Taboada JJ, Lorenzo JF, Ramos AM (2012) Influence of climate on grape production and wine quality in the Rías Baixas, north-western Spain. Reg Environ Change 1–10. doi:10.1007/s10113-012-0387-1

Magalhães N (2008) Tratado de viticultura: a videira, a vinha e o terroir. Chaves Ferreira, Lisboa

Malheiro AC, Santos JA, Fraga H, Pinto JG (2010) Climate change scenarios applied to viticultural zoning in Europe. Clim Res 43(3):163–177. doi:10.3354/cr00918

Moutinho-Pereira JM, Correia CM, Goncalves BM, Bacelar EA, Torres-Pereira JM (2004) Leaf gas exchange and water relations of grapevines grown in three different conditions. Photosynthetica 42(1):81–86

Moutinho-Pereira J, Goncalves B, Bacelar E, Cunha JB, Coutinho J, Correia CM (2009) Effects of elevated CO_2 on grapevine (Vitis vinifera L.): physiological and yield attributes. Vitis 48(4):159–165

Nakićenović N, Alcamo J, Davis G, de Vries HJM, Fenhann J, Gaffin S, Gregory K, Grubler A, Jung TY, Kram T, La Rovere EL, Michaelis L, Mori S, Morita T, Papper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen S, Victor N, Dadi Z (2000) Emissions scenarios. A special report of working group III of the Intergovernmental Panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Neumann PA, Matzarakis A (2011) Viticulture in southwest Germany under climate change conditions. Clim Res 47(3):161–169. doi:10.3354/cr01000

OIV (2012) Statistical report on world vitiviniculture. OIV, Paris, France, 32 pp

Orlandini S, Di Stefano V, Lucchesini P, Puglisi A, Bartolini G (2009) Current trends of agroclimatic indices applied to grapevine in Tuscany (Central Italy). Idojaras 113(1–2):69–78

Pieri P, Gaudillere JP (2003) Sensitivity to training system parameters and soil surface albedo of solar radiation intercepted by vine rows. Vitis 42(2):77–82

Ramirez-Villegas J, Jarvis A (2010) Downscaling global circulation model outputs: The Delta method; decision and policy analysis working paper no 1: CIAT-CGIAR

Riou C, Carbonneau A, Becker N, Caló A, Costacurta A, Castro R, Pinto PA, Carneiro LC, Lopes C, Clímaco P, Panagiotou MM, Sotez V, Beaumond HC, Burril A, Maes J, Vossen P (1994) Le determinisme climatique de la maturation du raisin: application au zonage de la teneur en sucre dans la Communauté Européenne. Office des Publications Officielles des Communautés Européennes, Luxembourg

Santos JA, Malheiro AC, Pinto JG, Jones GV (2012) Macroclimate and viticultural zoning in Europe: observed trends and atmospheric forcing. Clim Res 51(1):89–103. doi:10.3354/Cr01056

Santos JA, Grätsch SD, Karremann MK, Jones GV, Pinto JG (2013) Ensemble projections for wine production in the Douro Valley of Portugal. Clim Change 117(1–2):211–225. doi:10.1007/s10584-012-0538-x

Tonietto J, Carbonneau A (2004) A multicriteria climatic classification system for grape-growing regions worldwide. Agric For Meteorol 124(1–2):81–97. doi:10.1016/j.agrformet.2003.06.001

van der Linden P, Mitchell JFB (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3 PB, UK, 166 pp

Veloso MM, Almandanim MC, Baleiras-Couto M, Pereira HS, Carneiro LC, Fevereiro P, Eiras-Dias J (2010) Microsatellite database of grapevine (Vitis vinifera L.) cultivars used for wine production in Portugal. Ciência e Técnica Vitivinicola 25(2):53–61

Webb LB, Whetton PH, Barlow EWR (2011) Observed trends in winegrape maturity in Australia. Glob Change Biol 17(8):2707–2719. doi:10.1111/j.1365-2486.2011.02434.x

Webb LB, Whetton PH, Bhend J, Darbyshire R, Briggs PR, Barlow EWR (2012) Earlier wine-grape ripening driven by climatic warming and drying and management practices. Nat Clim Change 2(4):259–264. doi:10.1038/Nclimate1417