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RESEARCH ARTICLE

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Bioclimatic conditions of the Portuguese wine denominations of origin under changing climates

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Abstract

Wine production and quality are highly sensitive to local weather variability and climatic conditions. To assess these characteristics, this research examines high-resolution bioclimatic zoning over 50 protected denominations of origin (DOs)/sub-regions in mainland Portugal through the analysis of two selected bioclimatic indices (dryness and Huglin indices). The analysis is based on a new very high-resolution dataset over mainland Portugal and for a baseline period (1981–2015). Climate change projections are also assessed for two scenarios (RCP4.5 and RCP8.5) and using a 5-member climate model ensemble over the future periods of 2041–2070 and 2071–2100. A principal component analysis was applied to the time mean spatial patterns of the two selected bioclimatic indices, for the baseline period (1981–2015) and only over the planted vineyard cover areas in each region, isolating a new optimized combined index which was used for subsequent analysis. The results for the present conditions highlight the spatial variability of Portuguese DO/sub-regions. This study also shows that for the future periods, and regardless of the scenario, the wine sector in Portugal will likely see important bioclimatic changes across most DOs. Increases in the growing-season mean temperatures in all the Portuguese winemaking DO/sub-regions, accompanied by increasing severe dryness, are projected in future climates, mainly in south-eastern Portugal and along the upper Douro Valley (Douro Superior) in north-eastern Portugal. These DO/sub-regions are projected to become much drier than currently so that irrigation or the introduction of new varieties are likely adaptation measures to maintain the viability and sustainability of regional viticulture in future decades.

KEYWORDS

climate change, dryness index, EURO-CORDEX, Huglin index, Portugal, protected denominations of origin

1 | INTRODUCTION

The weather and climate conditions of a given region play a significant role in the productivity of vineyards and the quality of its winegrapes, thus being a key element of the terroir concept. As such, viticulture is very susceptible to atmospheric conditions over a wide range of timescales, from short-duration weather events (e.g., wind gusts, hail or frost) to medium-range episodes (e.g., droughts or floods) and to long-term trends in climate (from decades to centuries). In effect, grapevine suitability and growth are largely dependent on weather conditions during the growing season (Jones and Davis, 2000; Urhausen *et al*., 2011; Santos *et al*., 2013), ultimately driving variations in wine production and quality, which together drive economics across the whole winemaking sector.

Grapevines are influenced by air temperature throughout their vegetative cycle (Jones, 2006; Keller, 2015). Excessively low temperatures during the winter can kill or severely limit viability (Keller, 2015) and during the growing season may have detrimental impacts on grapevine development and on berry parameters (Cyr *et al*., 2010). Frost and hail occurrences during the vegetative period are also major threats in viticulture (Spellman, 1999). Although grapevines require heat accumulation (thermal forcing) for their growth and physiological development, temperatures far beyond a cultivar-specific optimum (Brisson *et al*., 2008; Lopes *et al*., 2008; Jones and Alves, 2012a) may also have negative implications on these processes and commonly lead to unbalanced ripening and potential shifts in harvest timing (Duchêne and Schneider, 2005). The optimum photosynthetic response range for grapevines is for maximum daytime temperatures from 20 to 35°C (Jones and Alves, 2012a). Furthermore, temperatures greater than 35°C may affect grape secondary metabolism and alter sugar accumulation and acid concentration (Mori *et al*., 2007), while photosynthetic activity is also impaired with temperatures above 40°C (Luo *et al*., 2011).

In addition, precipitation is a key factor in controlling soil water balance and plant water status, particularly in rainfed vineyards (without irrigation). Excessively dry climates will very likely require irrigation in vineyards. Excessive precipitation in late spring can impact flowering and fruit set and in summer can adversely affect berry quality parameters and may also trigger increases in disease pressure in vineyards (Cyr *et al*., 2010). On the other hand, severe dryness, particularly during the early stages of grapevine annual growth cycle, may also cause adverse effects on grapevine growth, development and yields (Fraga *et al*., 2013; Koufos *et al*., 2018). Even though other atmospheric parameters are also important for grapevines, such as solar radiation, wind and air humidity levels, temperature and precipitation are the leading forcing variables in rainfed, temperate climate viticulture. Therefore, the spatial and temporal variability in temperature and precipitation, as well the frequency of occurrence and intensity of extreme events (e.g., heat waves or droughts), play a critical role in governing canopy microclimatic conditions in vineyards and are thereby critical to viticulture and to the entire winemaking sector (Santos *et al*., 2003; Gouveia *et al*., 2011).

According to the last report of the International Panel on Climate Change, global temperatures are expected to rise from 1 to 5°C by the end of the 21st century (IPCC, 2014). Moreover, heat waves, droughts and heavy precipitation events are expected to become more frequent and intense in many areas worldwide. In this context, anticipated changes in climate will likely play a key role in the productivity and even viability of the wine sector in the future (Fraga *et al*., 2016a). Although the impacts of climate change on grapevines will likely be highly heterogeneous across varieties and regions, any change can impact grape yield and wine quality (Jones *et al*., 2005b). For Europe overall, climate change impacts on viticulture have been described in several previous studies (Jones *et al*., 2005a; Malheiro *et al*., 2010; Caffarra *et al*., 2012; Santos *et al*., 2012; Fraga *et al*., 2016a). Other studies for specific European wine areas have also been carried out, such as; Bordeaux (Jones and Davis, 2000) and Alsace (Duchêne and Schneider, 2005) in France, Nobile di Montepulciano (Dalla Marta *et al*., 2010) in Italy, north-eastern (Ramos and Martínez-Casasnovas, 2009) and north-western Spain (Lorenzo *et al*., 2013), and for the Portuguese Douro/Port wine region (Gouveia *et al*., 2011; Jones and Alves, 2012a; Santos *et al*., 2013), among several others.

More specifically for mainland Portugal, which is predominately a Mediterranean climate but also has Atlantic and continental influences due to elevation and proximity to the ocean, important warming and drying trends are projected over the next decades (Fraga *et al*., 2014; Melo-Gonçalves *et al*., 2016). While there are some uncertainties inherent to the climate change projections, particularly for precipitation, most of the country is projected to become drier. Additionally, some significant changes in temperature and precipitation extremes are also very likely in the future (Andrade *et al*., 2014; Santos *et al*., 2018). Annual mean precipitation is projected to decrease up to 400 mm by the mid-21st century, mostly in spring, summer and autumn (Melo-Gonçalves *et al*., 2016). This widening of the dry season will inexorably decrease growing season water availability and the overall available water resources in the future. In addition, drier and warmer climates, with strengthened evapotranspiration and soil water deficits, will likely trigger severe water stress in vineyards, thus requiring irrigation where it is not now practiced (Fraga *et al*., 2017). Hence, a combination of lower water availability with higher water demand is a noteworthy challenge to the Portuguese winemaking sector under a changing climate.

Portugal is the 11th largest wine producing country in the world (OIV, 2018), despite its relatively small area, with wine production ~6,738,772 hL (2% of world production) in 2018 (Instituto do Vinho e da Vinha [IVV], 2018). The mainland portion of the country comprises 12 broad wine producing regions (Figure 1a; for example, Vinhos Verdes, Alentejo, Tejo, Douro, Dão and Bairrada) and 50 protected denominations of origin (DOs) or sub-regions (Figure 1b; e.g., Douro/Port, Minho and Alentejo) (Fraga *et al*., 2014). In 2018 the Douro/Port wine region produced ~22% of the total national wine production, while the Lisboa wine region produced nearly 18% (IVV, 2018). As a result of the heterogeneity of climates in Portugal, these wine regions present clearly differentiated climatic characteristics (Fraga *et al*., 2012). While several previous studies have characterized the climates of the wine regions in Portugal (e.g., Fraga *et al*., 2012; 2014; Jones and Alves, 2012b; Blanco-Ward *et al*., 2017), the use of improved high-quality data at high spatial resolution is crucial for an accurate assessment of current and future bioclimatic conditions (Hall and Jones, 2010; Anderson *et al*., 2012; Fraga *et al*., 2014). In addition, analysing the variability between DO/sub-regions is important for a more detailed understanding of regional bioclimatic susceptibility (Fraga *et al*., 2014). Considering the high value of the winemaking sector for the Portuguese economy, further research on the potential implications of climate change on Portuguese viticulture is of foremost relevance.

The goal of the present study is to assess the bioclimatic conditions of the Portuguese DOs under present and future

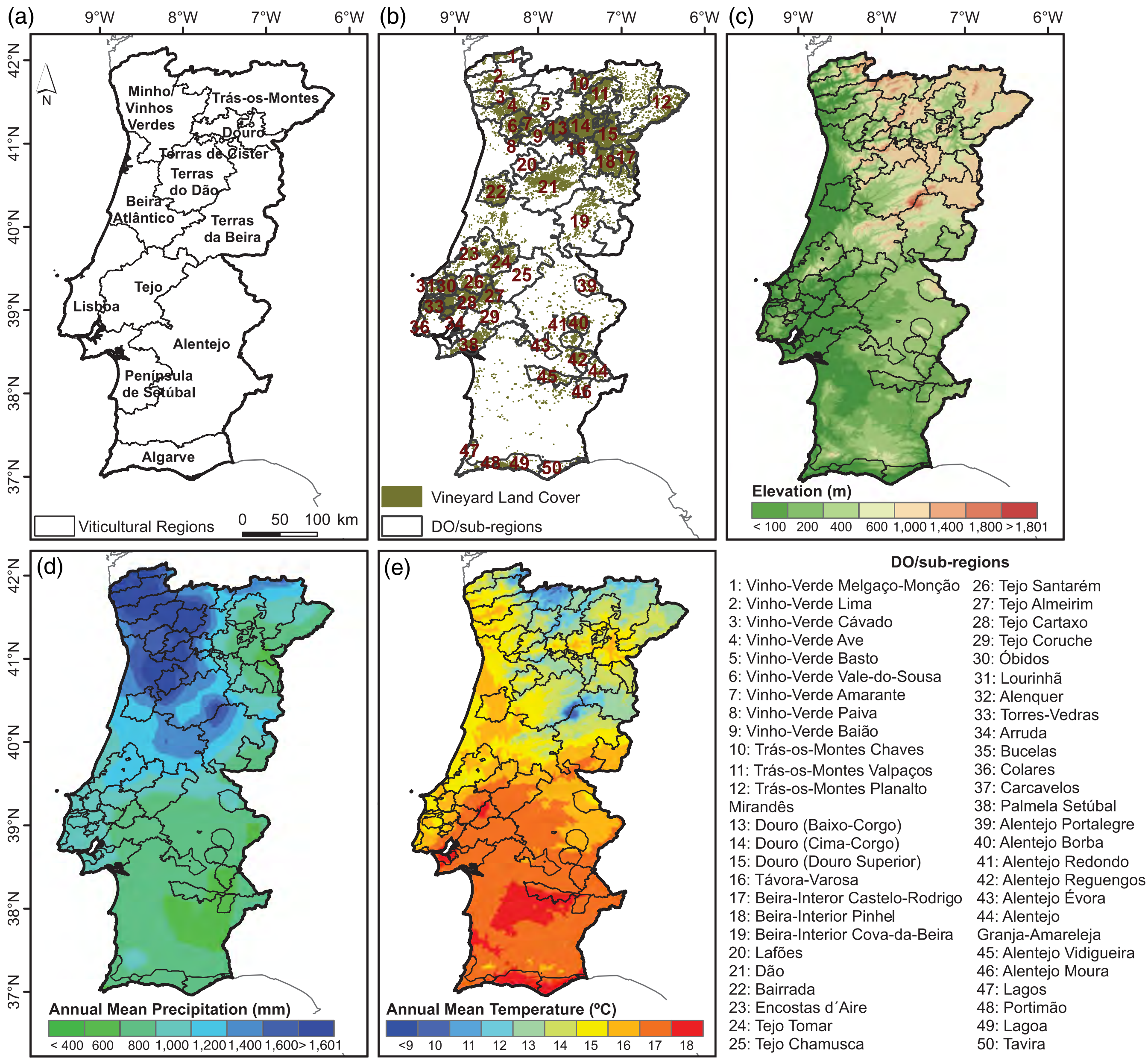

FIGURE 1 (a) Winemaking regions in mainland Portugal. (b) Geographical location of the protected denominations of origin (DOs) and sub-regions (see the list for their designations) and vineyard land cover over mainland Portugal using land use and occupation map (COS2007). (c) Elevation of mainland Portugal. (d) Annual mean precipitation for mainland Portugal and for the 1981–2015 period. (e) Annual mean of daily mean air temperature for mainland Portugal and for the 1950–2015 period [Colour figure can be viewed at wileyonlinelibrary.com]

climates. Therefore, the objectives of this study are threefold: (a) to improve the bioclimatic information available, by using recently developed high-resolution climate data (Fonseca and Santos, 2017) that covers a longer time period (1981–2015); (b) to categorize the different DO/sub-regions under present conditions using an optimized combined index; and (c) to explore possible shifts in their bioclimatic classification, thus anticipating possible future changes in viticultural suitability.

2 | DATA AND METHODS

2.1 | Study area

In mainland Portugal, the highest elevation above mean sea level is roughly 2,000 m, and there is an evident contrast between the north of the country, which is much more mountainous, and the south, which predominantly flat or rolling, hilly landscapes (Figure 1). The mean annual precipitation varies from over 2,000 mm in the north-western mountain peaks to roughly 400 mm over the south-eastern part of the country, thus revealing a close connection with the relief and the latitude (Santos *et al*., 2017) (Figure 1). However, strong zonal (east–west) precipitation gradients are also observed in northern Portugal, the result of the orographic condensation barrier effect on the westerly flow of moist air masses off the Atlantic. The annual mean temperature, ranges from 9°C in the highest mountains, to 18°C along the southern coast (Figure 1), for the period of 1950–2015 (Fonseca and Santos, 2017).

The current climatic conditions in Portugal are generally favourable to viticulture and to the production of high-quality wines, but also reveal a wide range of typicity (Tonietto, 1999) and terroirs (Van Leeuwen and Seguin, 2006). For example, the Alentejo region in southern Portugal, is a mostly lowland landscape with a relatively homogenous warm and dry climate, while the Minho (in north-western Portugal) is characterized by relatively high annual precipitation and relatively mild summers (Fraga *et al*., 2014). A variation on this north–south climate framework can be found in northern Portugal in the Douro region (famous for its Port wine production), which is characterized by the steep slopes of the Douro Valley, relatively low precipitation and high summertime temperatures, though strong temperature and precipitation gradients can be found in this region (Fraga *et al*., 2014). These highly diverse climates and suitable viticulture conditions explain the existence of 50 DOs or sub-regions in such a small territory (Figure 1). The corresponding average area in vineyards for each DO/sub-region, as well as the range in elevations are listed in Table S1. The average vineyard area in the DO/sub-regions range from less than 1 km^2, in Colares and Carcavelos, to 268 km^2, in Douro-Cima Corgo (Table S1). Some DO/sub-regions, mainly in the south of the country, have very low mean elevations (<100 m), while others in the interior regions or in northern Portugal have mean elevations >600 m (e.g., Beira-Interior Pinhel, Távora-Varosa, Beira-Interior Castelo-Rodrigo, Trás-os-Montes Planalto Mirandês) (Table S1).

2.2 | Data

Several bioclimatic indices have been developed to assess the viticultural suitability of different regions (Bonnefoy *et al*., 2013). These indices use variables such as temperature, precipitation, insolation or frost frequency and timing. From among the most commonly used bioclimatic indices, the following were selected for the present study due to their applicability in the country: (a) the dryness index (DI) and (b) the Huglin Index (HI), using the mathematical definitions found in Table 1. The DI (Tonietto and Carbonneau, 2004) is based on the potential water availability in the soil estimated from the Riou index (Riou *et al*., 1994). DI was related to grapevine growth (Hardie and Martin, 2000) and wine quality (Hardie and Martin, 2000; Tonietto and Carbonneau, 2004; Fraga *et al*., 2014) and encompasses four classes, varying from very dry ($DI \leq 100$ mm) to humid ($DI > 150$ mm). The input data for the DI are an estimate of soil water reserve at the end of the first month (W_0), precipitation (P), potential vineyard transpiration (T_v) and direct evaporation from soil (E_s). T_v and E_s were assessed by the Thornthwaite method (Thornthwaite, 1948). This method tends to overestimate the actual dryness and to excessively depend on temperature. The FAO Penman–Monteith method is commonly considered as a better approach for this estimation (Allen *et al*., 1998). It is based on fundamental physical principles, which ensure the universal validity of the method (Chen *et al*., 2005). However, this latter estimation needs several meteorological variables that are not available for Portugal on the selected spatial resolution (1 km grid spacing). Therefore, the calculation of the DI was carried out herein following the Thornthwaite method.

The HI (Huglin, 1978) is calculated for the period from 1 April to 30 September, in the Northern Hemisphere, and has a correction coefficient that accounts for the latitudinal variations in the day length during the grapevine growing season (Fraga *et al*., 2012; Lorenzo *et al*., 2013). This index assesses the temperatures required for adequate grapevine development and grape berry ripening (Huglin, 1978). The HI contains six classes, varying from unsuitably cool ($HI \leq 900$ units) to unsuitably hot ($HI > 3,000$ units).

To assess climate change impacts, three-time periods were considered in this research. For the baseline period, representing recent past conditions (1981–2015, 35 years),

TABLE 1 Bioclimatic indices, their corresponding mathematical definitions, units and classes

ID	Index	Mathematical definition	Units	Classes
DI	Dryness index	$\sum_{\text{April}}^{\text{Sept}}(W_0+P-T_v-E_s)$ W_0—initial available soil water reserve (mm) on the first month; P—Precipitation (mm); T_v—Potential vineyard transpiration (mm); E_s—Direct evaporation from the soil (mm) T_v; E_s assessed by the Thornthwaite method	mm	Excessively dry: <−100 Moderately dry: −100–50 Sub-humid: 50–150 Humid: >150
HI	Huglin index	$\sum_{\text{April}}^{\text{Sept}}\frac{(T-10)+(T_{max}-10)}{2}d$ T—mean air temperature (°C); T_{max}—maximum air temperature (°C); d—length of day coefficient, from 1.02 to 1.06	units	Unsuitably cool: <900 Too cool: 900–1,200 Very cool: 1,200–1,500 Cool: 1,500–1,800 Temperate: 1,800–2,100 Warm/temperate: 2,100–2,400 Warm: 2,400–2,700 Very warm: 2,700–3,000 Too hot: >3,000

the two indices were calculated using high-resolution gridded datasets (~1 km grid) of daily precipitation, minimum and maximum air temperatures over mainland Portugal. For the two future periods (medium-term: 2041–2070, and long-term: 2071–2100), the two indices were calculated using daily gridded temperature and precipitation from a five-member ensemble of global climate model (GCM)—regional climate model (RCM) chain simulations (Table S2), generated by the EURO-CORDEX project (Giorgi *et al.*, 2004; Jacob *et al.*, 2014). Simulated data were originally available at a spatial resolution of 0.125° latitude × 0.125° longitude (~14 km × 11 km) and under RCP4.5 and RCP8.5 scenarios. Furthermore, the CORDEX simulations were bias-corrected, following a distribution-based scaling methodology (SMHI-DBS45) (Landelius *et al.*, 2016). The selection of the models envisioned the incorporation of several GCMs and RCMs. In the present study, three GCMs (CNRM-CERFACS-CNRM-CM5, MPI-M-MPI-ESM-LR, ICHEC-EC-EARTH) and three RCMs (CLMcom-CCLM4-8-17, SMHI-RCA4, DMI-HIRHAM5) are considered in order to take into account model uncertainties in the climate change projections. Although all models were bias-corrected following the same approach and baseline, their climate change signals are different and thus provide more robust information than a single-model experiment. In fact, ensemble means are commonly considered the best approach to capture climate change projections than single-model simulations (Semenov and Stratonovitch, 2010).

The two bioclimatic indices were first calculated for each year of the three target periods and for each ensemble member, separately. Mean patterns were then produced for each index and for each period (baseline means and ensemble means for the future periods). The Mann-Kendall (Mann, 1945; Kendall, 1976) test was applied to determine the significance of the trends of the HI and DI indices (confidence level > 99.9%), and the Sen's slope estimator (Sen, 1968) was used to estimate the magnitude of the detected trends.

In order to classify each DO or sub-region according to their main climatic features, a single composite index, which optimally combines the spatial variability of HI and DI over Portugal, was subsequently identified. For this purpose, a principal component analysis (PCA) (Jolliffe, 2002), was applied to the time mean spatial patterns of the two selected bioclimatic indices (DI and HI) for the baseline period (1981–2015) and only over the vineyard land cover areas. A preliminary sensitive analysis using other bioclimatic indices, such as those referred by Malheiro *et al.* (2010), revealed strong correlations with HI or DI, thus not rendering significant differences in the final outcomes after performing PCA. The PCA was based on the correlation coefficient matrix, using non-parametric Spearman correlations, of the spatial distribution of the two bioclimatic indices and for the baseline period (1981–2015). The future periods data (2041–2070 and 2071–2100 ensemble means) were considered as additional independent individuals projected on the PCA established by the baseline data (1981–2015). To assess vineyard land cover area in this analysis, the Land Use and Occupation Map (COS2007, Level 5) is used on a 1:25000 scale. Non-vineyard land cover areas were discarded, as they do not contribute to the diversity of grapevine growing conditions in Portugal. The crossing of the spatial patterns of bioclimatic indices, with the vineyard land cover areas were defined using zonal statistics in geographic information system environment. The climatic characteristics of the different DO/sub-regions were determined by the scores of the leading principal component (PC1).

The DO/sub-regions were then classified into equally sized intervals of PC1, using a geographical information approach, and considering a total of 11 classes for all periods. The number of classes chosen is a parsimonious solution between a low number of classes, which does not allow a clear differentiation between regions, and a high number of classes that may make further analysis difficult and may artificially key similar regions to different classes. Although this was an empirical choice, the selection of slightly different number of classes does not rendered significantly different results (not shown).

Furthermore, the main grapevine varieties of Portugal were compared with PC1, through a spatially implicit join between PC1 scores and the grapevine spatial distribution. This spatial overlap thus allowed for the retrieval of variety-dependent information on the current grapevine growing climatic conditions from an optimized DI–HI combined index. To identify the location of the 44 main varieties, information was primarily gathered from annual surveys collected by the Portuguese "Instituto do Vinho e da Vinha". This dataset contains the mean spatial location of these varieties over the Portuguese administrative Civil Parishes (smallest subdivision). For more details about this dataset please see Fraga *et al*. (2016b). Overall, there are 44 core varieties identified in the IVV data, of which 24 are white and 20 are red (Table S3 and Figure S3). The present study only aims at providing a brief insight into the relationships between the spatial location of the different cultivars and the projected climatic changes, not exploring in detail the potential impacts of climate change on each variety. A more detailed analysis of the cultivar-climate relationships and of the underlying cultivar potential plasticity is out of the scope of the present study and will be specifically analysed in a forthcoming study.

3 | RESULTS

3.1 | Present/past conditions

The baseline (1981–2015) mean patterns of DI and HI are shown in Figure 2. The DI exhibits moderately dry conditions in the south of the country and humid conditions in the northwest. The DO/sub-regions in the southern half of Portugal show dry conditions, with DI less than 50 mm. The HI, for the baseline period, shows that only very limited high-elevation areas in the northern half of the country are classified as unsuitably cool (HI: <900 units) and no areas are considered unsuitably hot (HI: >3,000 units), thus hinting at the favourable climatic conditions in Portugal for viticulture. HI depicts relatively high values in the upper Douro Valley and in the southern DO/sub-regions of Portugal (2400–2,700 units) while, most of the DO/sub-regions of the Vinho Verde show conditions with HI < 1,700 units (very cool). It should also be noted that low (high) HI values do not necessarily mean lower suitability, but may rather represent conditions that might be optimal for some early (late) ripening grapevine cultivars (Fraga *et al*., 2013).

Figure 2c presents the temporal variability of DI and HI within the baseline period (1981–2015), averaged over all DO/sub-regions in Portugal. The time series clearly highlights the strong inter-annual variability in both indices (the standard deviation is 50 mm for the DI and 187 units for the HI), with the DI variability being a major concern for the winemaking sector. The wettest years were 1987 (DI: 165 mm), 1996 (DI: 180 mm) and 2014 (DI: 104 mm). The driest years on average, were: 2005 (DI: −27 mm), 2010 (DI: −10 mm) and 2003 (DI: −9 mm). According to the HI, the hottest years were: 2011 (HI: 2454 units), 2010 (HI: 2364 units) and 2005 (HI: 2306 units). The coolest years, on average, were: 1993 (HI: 1644 units), 1983 (HI: 1763 units) and 1984 (HI: 1770 units) (Figure 2). According to the Mann-Kendall test, there is a statistically significant upward trend in the HI index, of 11 units per year. The downward trend in DI is not statistically significant. Overall, these long-term trends are in clear agreement with the warming and drying trends at climate stations in Portugal and provide insight regarding the evolution of these two indices under future climates.

The PCA enabled the classification of the 50 DO/sub-regions in climatic classes according to an optimized combined index of DI and HI (Figure S4). The leading principal component represents 96.6% of the total variability of the initial data, thus highlighting its strong representativeness of the diversity of climatic conditions within the Portuguese winegrowing regions. This very high fraction of explained variance is a manifestation of the strong correlation between HI and DI under current climatic conditions. Although in the future this relationship may undergo non-linear modifications that cannot be easily anticipated, these changes are not expected to significantly alter the present study results. Further research will be needed regarding the interplay between HI and DI both at the present and in the future. The leading principal component (PC1) was then categorized into the pre-defined 11 equally sized classes (Figure S5). As the class increases from 1 to 11, DI gradually decreases (drier conditions) while HI increases (warmer conditions) (Figure 3). For Class 1, DI is classified as sub-humid and HI as cool. For Class 11, DI is classified as excessively dry and HI as too hot. In present conditions (Figure 4a), the DO/sub-regions vary from Class 1 to 6, also revealing a clear gradient from the northwest (Class 1) to the southeast (Class 6) of mainland Portugal.

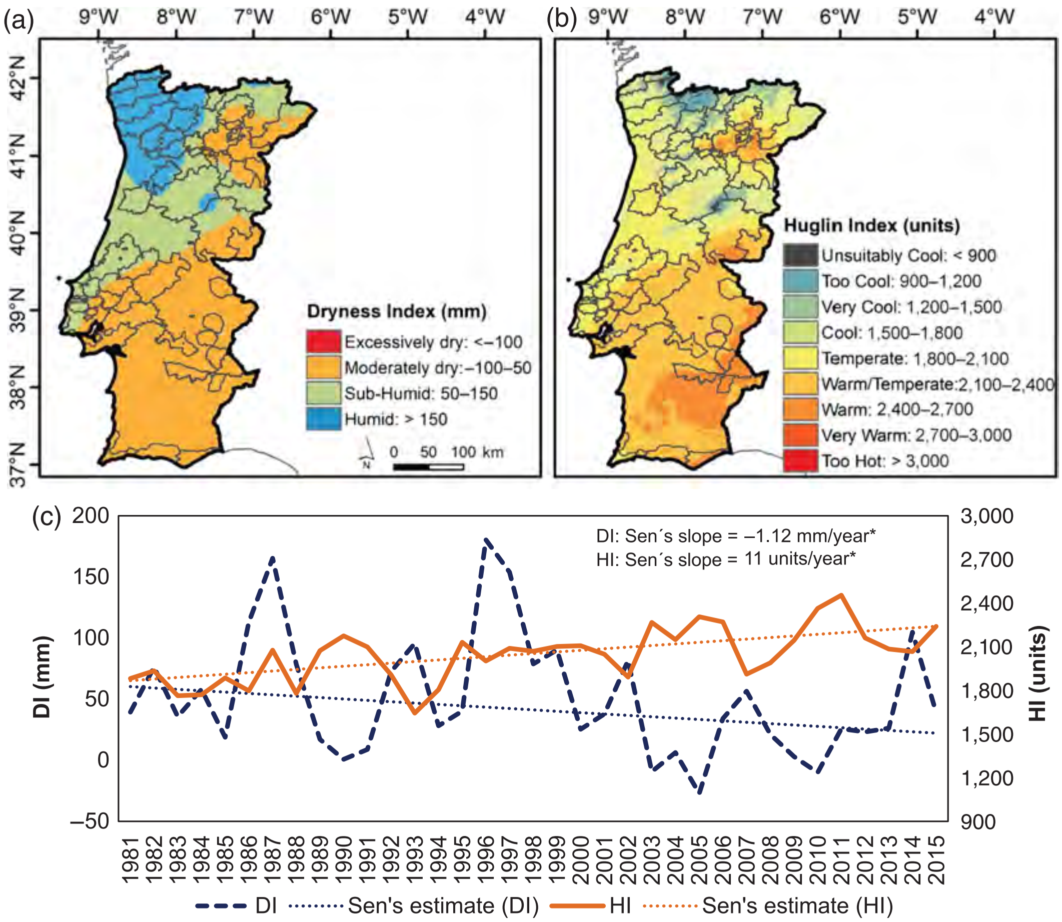

FIGURE 2 (a) Dryness index (DI; mm) and (b) Huglin index (HI; in units) for mainland Portugal and for the period 1981–2015; (c) time series of the area-mean DI (mm) and HI (units) for the baseline period of 1981–2015 and only over the vineyard land cover areas defined in Figure 1b (source: COS2007), along with their corresponding Sen's slope estimate (see legend for details). * indicates that the trend is statistically significant, with the confidence level >99.9% [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Future conditions

Figures S1 and S2 outline the spatial variability of DI and HI by DO/sub-region in current and future conditions, for the two future periods (2041–2070 and 2071–2100) and under both scenarios (RCP4.5 and RCP8.5). For present conditions, the north-western DO/sub-regions typically reveal sub-humid and cool climates, while much warmer

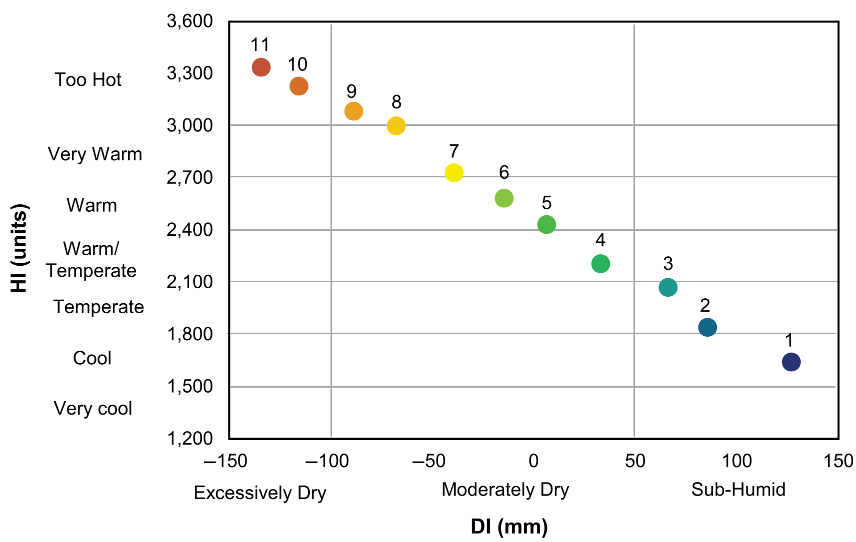

FIGURE 3 Scatterplot of the area-means of DI and HI for the different DI–HI combined bioclimatic classes (from 1 to 11) for baseline (1981–2015) and future periods (2041–2070 and 2071–2100), under RCP4.5 and RCP8.5. Area-means are computed only over the vineyard land cover areas defined in Figure 1b (source: COS2007). DI, dryness index; HI, Huglin index [Colour figure can be viewed at wileyonlinelibrary.com]

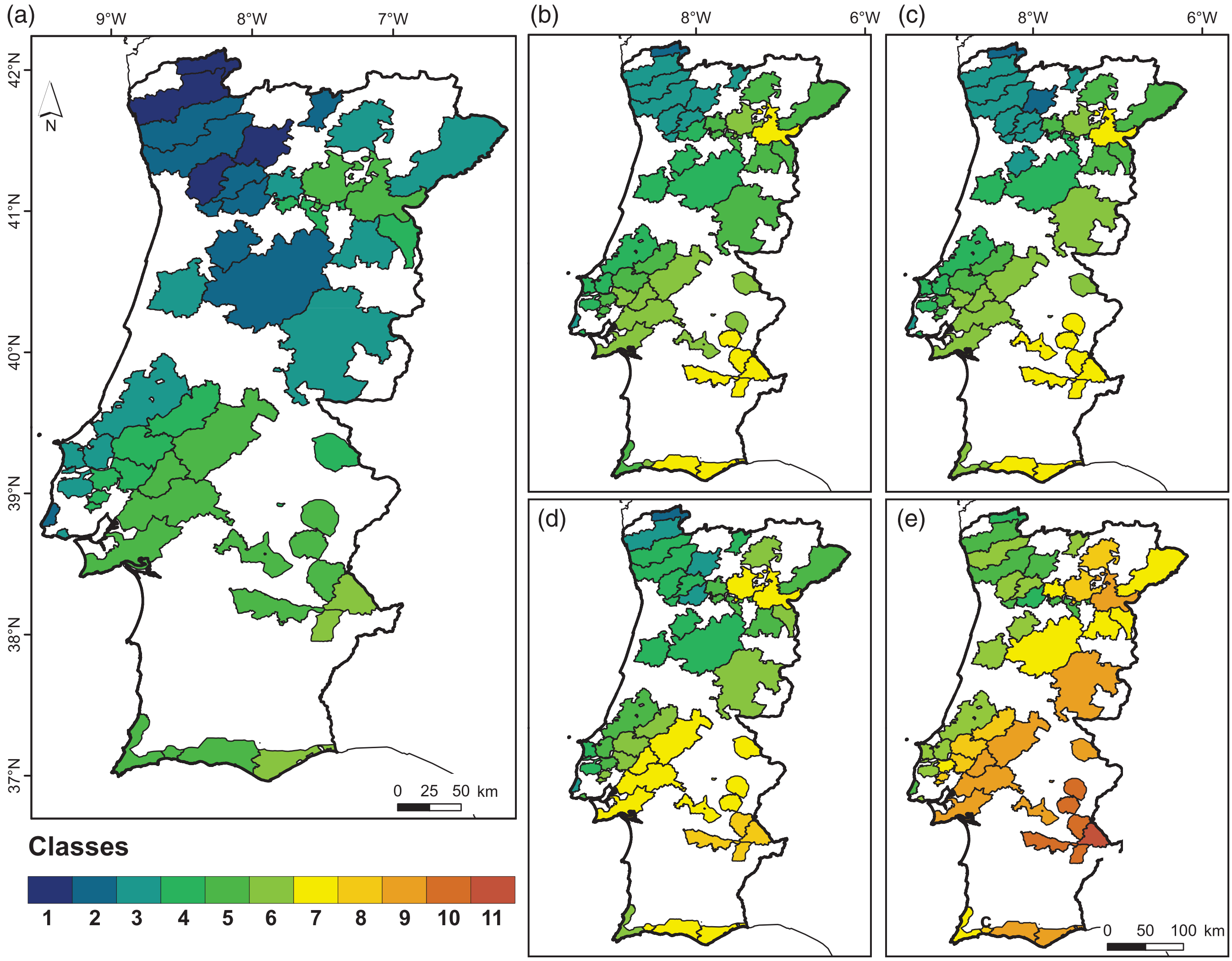

FIGURE 4 Maps of the different DI–HI combined bioclimatic classes (from 1 to 11 according to the shading colour scale) of the DOs and sub-regions over mainland Portugal for (a) the baseline period (1981–2015), and future periods of (b) 2041–2070 and (c) 2071–2100, under RCP4.5; (d) 2041–2070 and (e) 2071–2100, under RCP8.5 (cf. Figure 1 for designations of mapped DO/sub-regions). DI, dryness index; DOs, denominations of origin; HI, Huglin index [Colour figure can be viewed at wileyonlinelibrary.com]

and drier climates can be found in the southern DOs. In the most severe scenario (RCP8.5, 2071–2100) and for some DOs, such as Douro Superior, Alentejo Borba, Alentejo Redondo, Alentejo Reguengos, Alentejo Granja-Amareleja, Alentejo Vidigueira, Alentejo Moura or Tavira, DI will be less than −100 mm and, therefore, conditions are expected to become unsuitable for rainfed viticulture. Furthermore, in the future, a decrease in spatial variability of DI is projected for most of the DO/sub-regions, apart from the DOs of Trás-os-Montes (Valpaços and Planalto Mirandês), Douro (Baixo-Corgo, Cima-Corgo and Douro Superior), Távora-Varosa and Beira-Interior (Castelo-Rodrigo, Pinhel, Cova da Beira), each of which are located in northern-central inland Portugal, which are characterized by increased bioclimatic spatial heterogeneity (Figures S1 and S2). Therefore, with the exception of north-central inland Portugal, the other DO/sub-regions are likely to be less resilient to climate change due to decreases in internal climate diversity, thus limiting meso-microclimatic selection in the location of new vineyards as an adaptation measure.

The DI patterns for the future period under RCP4.5 project increasing dryness, mainly in the DO/sub-regions of Douro Baixo-Corgo, Douro Cima-Corgo, Vinho-Verde Baião, Vinho-Verde Paiva and Távora-Varosa (DI, with changes of <-60 mm in the period of 2041–2070 with respect to baseline; Figure S6). The DO/sub-regions classified as humid (DI: >150 mm) in the baseline period are projected to change to sub-humid (DI: 50–150 mm) in the northwest of the country. For RCP8.5, the changes are projected to be more intense, with severe dryness (DI < -100 mm) in the upper Douro Valley (Douro Superior) and Alentejo (DO/sub-regions: Portalegre, Borba, Redondo, Reguengos, Évora, Granja-Amareleja, Vidigueira and Moura) for the period of 2071–2100 (Figure S7). The remaining DO/sub-regions are also expected to become drier, with DI between −100 and –50 mm.

For the HI in the future period there is a significant increase in temperatures, mainly in the interior DO/sub-regions of the country (Figures S8 and S9). Some DO/sub-regions, such as Trás-os-Montes and Beiras-Interior, show potential increases above 400 units in the moderate scenario (RCP4.5). The Douro Demarcated Region (Baixo-Corgo, Cima-Corgo and Douro Superior) and Alentejo also are projected to undergo significant changes in the HI, from warm (2,400–2,700 units) to very warm (2,700–3,000 units). For RCP8.5, the changes are much higher. For 2071–2100, the south of the country and the Douro region are projected to be classified as too hot (HI > 3,000 units). The DO/sub-regions that are currently classified as too cold (HI: <900 units) are projected to become more suitable, due to more favourable temperatures. The box plots in Figure S10 indicate the range of values of DI and HI for all DO/sub-regions. As expected, there is a greater variability under RCP8.5, the most severe scenario. However, these plots also corroborate the warmer and drier conditions expected across the country in the future (Figure S10).

Figure 4 and Table S4 show the classifications of the DO/sub-regions into the 11 classes for the baseline period (1981–2015) and the future time periods (2041–2070 and 2071–2100), under two different scenarios. The Vinhos Verdes DO/sub-regions (Amarante; Ave; Baião; Basto; Cávado; Lima; Melgaço-Monção; Paiva and Vale-do-Sousa) are projected to undergo changes that are from Class 1 or 2 to 2 or 3 under RCP4.5. These DO/sub-regions are currently the most humid in the country. However, these DO/sub-regions are projected to reach Classes 4 and 5 in 2071–2100 under RCP8.5 (Figure 4). In the Trás-os-Montes DO/sub-regions (Chaves, Planalto Mirandês e Valpaços) warmer and drier climates are also expected, with shifts from Class 2 or 3 up to 8 in the case of Valpaços. The Douro DO/sub-regions (Baixo-Corgo, Cima-Corgo and Douro Superior) are characterized by a very complex topography and Mediterranean climate (Blanco-Ward *et al*., 2017), with intense water stress during summer, mainly in the Cima-Corgo and Douro Superior sub-regions (Jones and Alves, 2012a). In the Douro Baixo-Corgo, the Class 3 area is projected to change to Class 5 (RCP4.5) or 7 (RCP8.5), while the Douro Cima-Corgo, currently in Class 5 is projected to change to Class 8 (RCP8.5). However, the warmest and driest conditions are projected in the Douro-Superior region. Currently, this region is in Class 5, but in the future, it is projected to change to Class 7 (RCP4.5) or 9 (RCP8.5) (Figure 4).

In central Portugal, the DO/sub-regions closest to the North Atlantic (Bairrada and Lafões) are in Classes 2 and 4, while in the future they are projected to shift to Classes 4 (RCP4.5) and 6 (RCP8.5). Regarding Távora-Varosa, changes mainly occur from Class 4 to 5. The Beiras DO/sub-regions (Castelo-Rodrigo, Pinhel and Cova-da-Beira) undergo changes from Classes 3 and 4 to 5 and 6 (RCP4.5) or 7 and 8 (RCP8.5), with the Cova da Beira sub-region projected to be the warmest and driest in the future. The Dão sub-region is currently in Class 2, though it is projected to be in Class 7 in the most severe scenario (RCP8.5) (Figure 4).

In the Lisboa region, Óbidos, Encostas D´Aire, Lourinhã, Carcavelos and Torres Vedras DO/sub-regions are currently in Class 3, but in the future, they will potentially reach Class 6 (RCP8.5). Located in the municipality of Sintra, between the Sintra mountain and the Atlantic Ocean, Colares is projected to change from a Class 2 to 3 (RCP4.5) or 5 (RCP8.5), similar to other regions in the Vinho Verde. Arruda, Bucelas and Alenquer, also in the Lisbon region, shows potential changes to warmer and drier classes, from 4 to 5 (RCP4.5) or 7 and 8 (RCP8.5) (Figure 4).

For the Tejo DO/sub-regions (Almeirim, Cartaxo, Chamusca, Coruche, Santarém, Tomar), changes are projected to be mostly from Classes 4 and 5 to 8 and 9 (RCP8.5). For the Palmela-Setúbal region, projected changes are expected to be comparable to the Tejo region, with Class 5 changing to 9 (RCP8.5) (Figure 4). The Alentejo DO/sub-regions is projected to shift from Classes 5 or 6 to 7 and 8 (RCP4.5) or 9, 10 and 11 (RCP8.5), that is, very dry and very warm future climates, where viticulture may be significantly constrained due to extreme dryness. In the future, the Alentejo DO/sub-regions of Granja-Amareleja and Reguengos will likely have the warmest and driest climates in the country (Figure 4). For Tavira and Lagoa (eastern Algarve), the projections are identical to those in the Alentejo, that is, shifts from Classes 5 and 6 to Class 7 (RCP4.5) or Class 9 (RCP8.5). Finally, Lagos and Portimão (western Algarve) are projected to change from Class 5 to 6 (RCP4.5) or Classes 7 and 8 (RCP8.5), respectively (Figure 4).

Figure 5 shows the location of the main grapevine varieties in the different classes for the baseline (1981–2015) and for the future periods (2041–2070 and 2071–2100). Varieties are ranked according to the first the leading principal component (PC1), that is, from cooler and wetter climates to warmer and drier climates. In both scenarios (RCP4.5 and RCP8.5), the Espadeiro, Borraçal and Vinhão varieties, characteristic of the Vinhos Verdes region, will likely remain in the coolest and most humid areas of Portugal, though at conditions that will likely be much warmer and drier than today. Conversely, Moreto, Antão Vaz and Castelão varieties will likely remain in the warmest and driest regions of the country. The Moreto and Antão Vaz varieties, characteristic of the Alentejo and therefore more adapted to very warm climates, will likely be found only in the hottest and driest

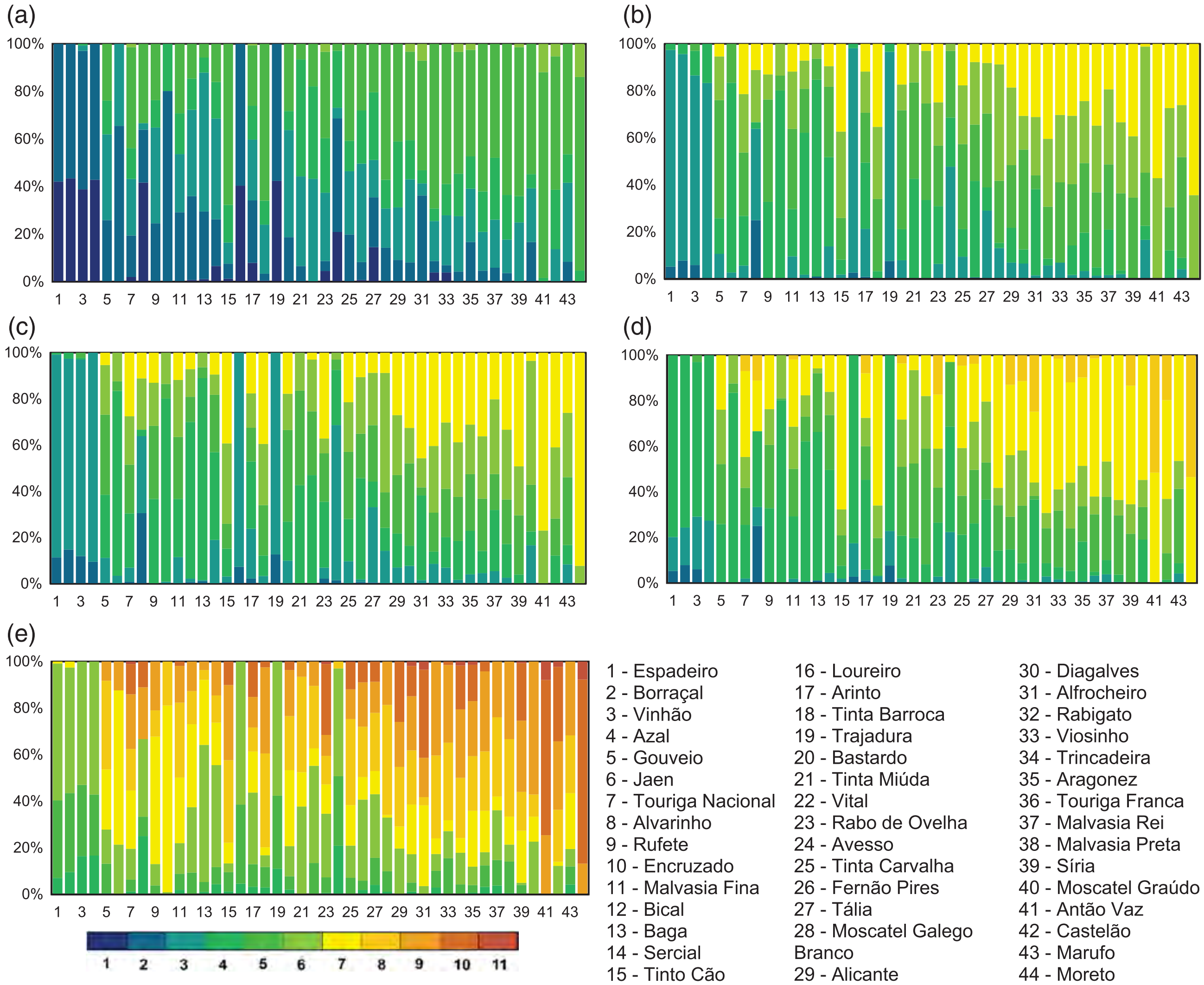

FIGURE 5 Stacked relative bar charts (in %) for each grape variety and for 11 classes, from a principal component analysis based on DI–HI pairs, for (a) baseline (1981–2015), and for (b) 2041–2070 and (c) 2071–2100, under RCP4.5, and for (d) 2041–2070 and (e) 2071–2100, under RCP8.5. Varieties are ranked according to the first factor of the PCA, that is, from cooler and wetter climates to warmer and drier climates. DI, dryness index; HI, Huglin index [Colour figure can be viewed at wileyonlinelibrary.com]

areas of the country in the future. The Alfrocheiro grape variety, native to the Dão region, but also being found more in Alentejo, Tejo and Palmela DO/sub-regions, will also be predominantly in the Classes 10 and 11 (very hot and dry climates). The same happens to Castelão, characteristic of the Tejo, Lisboa, Península de Setúbal and Alentejo DO/sub-regions (Figures 5 and S11).

4 | DISCUSSION AND CONCLUSIONS

In this study, a high-resolution bioclimatic zoning over DO/sub-regions in mainland Portugal is performed based on DI and HI and on an optimized DI-HI combined index, which corresponds to the leading principal component (PC1) of the spatial variability of DI and HI in vineyard land cover areas in Portugal. The analysis is based on a very high-resolution dataset for a baseline period (1981–2015). Climate change projections are also carried out for two scenarios (RCP4.5 and RCP8.5) and using a five-member ensemble over the future periods of 2041–2070 and 2071–2100. The DI clearly shows the contrast between the more Atlantic and the more typically Mediterranean climates. It should be noted that the DI is calculated using the Thornthwaite method, which does not take into account other variables, such as radiation, wind speed and water vapour pressure deficit, which may alter the evaporative demand under future climates. The southern region of the country and the upper Douro Valley are classified as experiencing moderate dryness, while the northwest is classified as mostly humid. The remaining areas of mainland

Portugal are classified as sub-humid. HI identifies the thermal regions with south-eastern Alentejo and the Douro Valley (Baixo-Corgo, Cima-Corgo and Douro Superior) exhibiting the highest values, while the north and central mountains show the lowest values. Viticultural zoning in mainland Portugal indeed reflects this large bioclimatic diversity. The PCA reveals that the leading component accounts for nearly 97% of the spatial climatic variability (DI and HI). In the future, warmer and drier conditions are expected across the country where areas classified as humid will be substantially reduced or even disappear in the most severe scenario (RCP8.5). Conditions of extreme dryness are projected for south-eastern Portugal and for the Douro Superior sub-region. Furthermore, temperatures are projected to increase across the entire country.

The expected warming and drying results in shifts of the DO/sub-regions to higher classes. These results are in agreement with the warming and dryness reported in other southern European countries (e.g., Duchêne and Schneider, 2005; Neumann and Matzarakis, 2011; Lorenzo *et al*., 2013; Dunn *et al*., 2017; Koufos *et al*., 2018).

Warmer and drier climates represent important challenges for the wine sector, affecting wine typicity and quality. As is widely accepted, moderately dry conditions are commonly favourable for the maturation of grapes (Tonietto and Carbonneau, 2004). Conversely, in very humid conditions, a better maturation of grapes tends to occur in less humid years (Tonietto and Carbonneau, 2004). In fact, changes in the grapevine phenological cycle would be expected based upon observed changes to date (Jones *et al*., 2005a; Dalla Marta *et al*., 2010; Lereboullet *et al*., 2014). Higher temperatures may lead to an accelerated phenological cycle, shorter growth intervals, shorter growing seasons and biophysical reductions in yield (Lereboullet *et al*., 2014). Extreme hot and dry conditions may cause changes in the composition of organic compounds, leading to unbalanced ratios of sugar and acid concentrations, and negatively affect the amount and composition of phenolic compounds (Koch and Oehl, 2018). Furthermore, the combined effect of increasing temperature and decreasing precipitation will likely lead to greater evapotranspiration and, consequently, higher water demands (Lereboullet *et al*., 2013). The potential increase in the frequency of extreme weather events in Portugal, such as heavy precipitation, hail or frost (Costa *et al*., 2012; Santos *et al*., 2017; Santos and Belo-Pereira, 2018) may also bring negative impacts. In addition, Parente *et al*. (2018) shows that heat waves will likely increase in number, duration and amplitude, more significantly for RCP 8.5 and by the end of the 21st century. Temperatures above critical values, combined with high levels of solar radiation, will bring detrimental impacts on grapevines, such as leaf or berry sunburn, and will likely hinder normal plant physiological development (e.g., through stomata closure, photosynthesis inhibition and altered biosynthesis of berry compounds), with negative implications in berry quality attributes. In the Alentejo DO/sub-regions and Douro Superior, severe dryness is projected, and irrigation will likely be essential to maintain production and quality near current levels. If irrigation is not feasible, it may lead to inadequate conditions for viticulture (Fraga *et al*., 2014). On the other hand, the north-western DO/sub-regions (Vinhos Verdes), as well as Lisboa and Beira-Atlântico, located in the lower classes, may partially benefit from warmer and drier climates. Despite the expected increase in temperature and dryness, changes in these DO/sub-regions will likely enable shifts to later maturing varieties, different wine styles and potentially better quality (Fraga *et al*., 2014). Higher temperatures and lower humidity will likely reduce the risk of pests and pathogens, such as mildew (Caffarra *et al*., 2012; Launay *et al*., 2014). Schultze *et al*. (2016) showed that the warming trend in the climate of the state of Michigan (United States), may bring positive effects to that wine region. Thus, climate change can bring risks to the quality/characteristics of wine, but also opportunities for cooler regions (Neethling *et al*., 2017) The dependence of grapevine varieties on specific climatic conditions and the perennial nature of grapevines limits the adaptation of the current DO/sub-regions to climate change (Webb *et al*., 2010; Metzger and Rounsevell, 2011; Dunn *et al*., 2017). In areas with the most negative impacts, potential adaptations include (a) modifications in vine training and canopy architecture, (b) adjustment of vine practices, for example, irrigation and soil management, (c) moving vine cultivation to new areas at higher elevations and/or to north-facing slopes, (d) varying wine style preferences (e.g., red or sweet wines as an alternative to white wines) (Koufos *et al*., 2018) or (e) the growth of new grapevine varieties in DOs that have greater adaptability with future warmer and drier climates.

Earlier work by Fraga *et al*. (2014) created a viticultural bioclimatic zoning for Portuguese wine regions, using an aggregated index that combines aspects of heat accumulation, dryness and ripening conditions, for a period between 1950 and 2000 and for future conditions (2041–2070), following an earlier emission scenario (A1B). The results suggest lower bioclimatic diversity in the future, with much warmer and drier climates in most of Portuguese wine regions. The results of this research are in overall agreement with those reported by Fraga *et al*. (2014). However, this research applies an updated database of vineyard land cover areas and a new set of very high-resolution climatic data over Portugal (1981–2015), with important corrections compared to previously used datasets (Fonseca and Santos, 2017), along with the application of the most recent generation of anthropogenic forcing scenarios (RCP4.5 and

RCP8.5) and for two different future periods (2041–2070, 2071–2100). In addition, the DI and HI were calculated using daily temperatures and precipitation from a state-of-the-art set of five GCM–RCM chains. Furthermore, the present study is focused on the DOs and sub-regions, rather than on aggregated larger wine regions, thus providing more detailed information and allowing a categorization of DOs and sub-regions and their corresponding exposure to climate change. When compared to the previous study, some important differences were found, for both the recent past and future periods, which can be attributed to the improved quality of the datasets. As an illustration, it can be mentioned that the climatic changes projected for the whole wine regions are not the same as for their individual DOs/sub-regions, since some are projected to undergo greater changes in the future than others.

This research has highlighted the differences between DO/sub-regions, allowing for a better understanding of the nature of climate change across diverse regions of the country and further indicates the types adaptation strategies that the Portuguese wine sector will need to develop in the future. Additional work will include other geographical variables, such as land cover, soil, aspect, slopes and elevation to help develop a comprehensive suitability model for Portuguese viticulture.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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