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Climatic suitability of Portuguese grapevine varieties and climate change adaptation

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ABSTRACT: Grapevine varietal suitability is strongly linked to regional environmental conditions and growers tend to select varieties that are best suited to these conditions. A high agreement between current growing regions and optimal climatic zones is thus anticipated for a given variety. A changing climate is, however, expected to impose new challenges to this long-term varietal selection. The present research examines the spatial distribution of the main grapevine varieties in Portugal, establishing current and future optimal climatic zones for each variety. The spatial locations of 44 varieties are assessed, and their growing degree-day (GDD) requirements are computed using a high resolution climatic dataset (<1 km). A clustering methodology is applied to the spatial patterns of the optimal GDD of each variety, leading to three varietal groupings (early, intermediate and late). Future changes (2041–2060) in those patterns are then analysed using a 17 model-ensemble and two scenarios (RCP4.5 and 8.5). Results indicate that Portuguese varieties have high adaptability, because they are grown over a large range of thermal conditions. Although the three clusters provide a good agreement with the current growth conditions, a strong warming trend is projected in the future, resulting in projections of a northward shift and move to higher elevations for the cluster patterns. Hence, other European regions may experience improved growing conditions for the settlement of these Portuguese varieties. Nonetheless, future varietal selection will heavily depend on the interest of winemakers and global market policies for the production of specific wines. Adaptation measures may indeed be required for maintaining the current varietal distribution.

KEY WORDS grapevine varieties; optimal varietal zones; growing degree-day; Portugal; climate change; RCP

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1. Introduction

The wine industry is an important socioeconomic and cultural sector in many countries worldwide. Portugal is ranked as the 11th highest wine-producing country in the world (OIV, 2013), and the wine industry has a strong influence on economic stability and development in the country. Vineyards are grown throughout 12 broad viticultural regions in mainland Portugal (Figure 1), representing approximately 227×10^3 ha of vineyards (IVV, 2013). The highest density of vineyards is in the Douro/Porto and Lisbon wine regions (Figure 1) along with other renowned winemaking regions such as Alentejo and Minho. The wine identity and brand recognition of each region largely depend on the *terroir*, which not only comprises climate, soil, agricultural/enological practices but also the grapevine varieties grown (van Leeuwen *et al.*, 2004; Vaudour *et al.*, 2010; Fraga *et al.*, 2014a).

Climate largely controls the suitability of a given region to a specific variety (Tonietto and Carbonneau, 2004; Jones *et al.*, 2005b; Jones and Goodrich, 2008). Although grapevines show notable climate adaptability, specific climatic conditions are required for well-balanced ripening and high quality wine production (Jones *et al.*, 2004; Fraga *et al.*, 2013; Hannah *et al.*, 2013). As accumulated temperatures above 10 °C (base temperature) are required for grapevine growing onset (Winkler, 1974; Moriondo *et al.*, 2013; Bonada and Sadras, 2015), the growing degree-days (GDD) index shows not only good relationships with grapevine development and growth but also with yield and wine quality (Chuine *et al.*, 2003; Jones, 2003; Sadras and Moran, 2013; Neumann and Matzarakis, 2014). Throughout the years (or even centuries), growers have adapted varieties and viticultural management activities to keep harvests within preferred dates (van Leeuwen *et al.*, 2008). Therefore, not disregarding other factors, growers have been selecting the varieties that best suit the regional climatic conditions, leading to a reasonably high correspondence between their current growing regions and their optimal climatic zones (van Leeuwen *et al.*, 2008). Therefore, local varieties are, to some extent, an indirect manifestation of the regional climatic conditions. However, a multi-site study, covering a range of different climates, is needed to understand the actual cultivar thermal requirements (Parker *et al.*, 2013).

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Figure 1. The 12 viticultural regions in Portugal. The shaded areas represent the vineyard land cover according to the Corine land cover map (EEA, 2002).

Moreover, the concept of regional plasticity, i.e. the ability to adapt to different climates, also needs to be taken into account (Sadras *et al.*, 2009; Caffarra and Eccel, 2010). Despite specific varietal thermal requirements (Lopes *et al.*, 2008; de Cortazar-Atauri *et al.*, 2009; Kose, 2014), the same variety grown in different regions can show GDD differences up to 300 °C (degree-day) in Portugal (Lopes *et al.*, 2008; Alves *et al.*, 2013).

The Portuguese native varieties, which are much less widespread than some French varieties (Cabernet-Sauvignon, Pinot-Noir, etc.), have singular characteristics, greatly contributing to the distinctiveness of the Portuguese wines (Lopes *et al.*, 2008; Cristino *et al.*, 2013; Costa *et al.*, 2014). The main varieties grown are Aragonez and Touriga-Franca in Douro/Porto and Trás-os-Montes, Vinhão and Alvarinho in Minho, and Castelão in Alentejo (IVV, 2013). However, many other varieties are part of the Portuguese collection, with 341 regulated varieties (according to Decree 428/2000 and amendment 380/2012) that include more than 250 native varieties. As Portuguese grapevine varieties are generally more suitable to warmer and drier climates than other more widespread varieties (Lopes *et al.*, 2008), they have recently been introduced in other countries (e.g. Chile and Argentina). For instance, Touriga-Nacional, with high quality attributes (Mateus *et al.*, 2002), is a rapidly expanding variety worldwide (Anderson and Aryal, 2013), although most Portuguese varieties remain confined to the country (Anderson and Aryal, 2013).

Climate change is expected to bring new challenges to Portuguese viticulture, namely a reshaping of the optimal varietal zones. Future projections highlight a warming and drying of the growing season in Portugal (Jones and Alves, 2012), accompanied by increases in the frequency of climate extremes (Andrade *et al.*, 2014). Climate change may lengthen growing seasons and bring earlier phenological events (Moriondo and Bindi, 2007; Duchene *et al.*, 2010; Menzel *et al.*, 2011; Ruml *et al.*, 2012). Grapes are expected to ripen earlier in warmer climates (Chuine *et al.*, 2004; Jones *et al.*, 2005a; Bock *et al.*, 2011; Webb *et al.*, 2012), but unbalanced ripening may lead to lower wine quality (Webb *et al.*, 2011; Hannah *et al.*, 2013; Fraga *et al.*, 2014c). Therefore, the assessment of climate change impacts on optimal varietal zones may help adapting the sector to future climates. With these facts in mind, the objectives of this study are three-fold: (1) to analyse the current spatial distribution of the main grapevine varieties in Portugal, (2) to assess the optimal climatic zones for each variety and (3) to examine the impacts of climate change on this zoning. To our knowledge, no previous studies related the spatial distribution of a large number of grapevine varieties with climate and climate change projections.

2. Material and methods

2.1. Varietal distribution

In order to assess the varietal spatial distribution over mainland Portugal, the information from annual surveys, enforce collected by the Portuguese *Instituto do Vinho e da Vinha* (IVV) is used. The corresponding maps per variety were previously presented by Böhm (2010). The spatial distribution of 44 core varieties (24 white and 20 red; Table S1, Supporting Information) over the smallest Portuguese administrative divisions (median area of ca. 11 km^2) is provided. However, only vineyard areas within each division are taken into account in all subsequent computations. For that purpose, the CORINE land cover database (version 13; EEA-ETC/TE, 2002) is used on a 1:100.000 scale, which accurately represents the Portuguese vineyard cartography (Caetano *et al.*, 2006). The resulting dataset maps the location of 44 varieties from the Portuguese collection on a 100 m resolution (Figure S1). These high-resolution spatial patterns are defined using innovative GIS methodologies that combine varietal statistical surveys with vine land cover data. Figure S1 is a new digital atlas of the grapevine varieties growing in Portugal, which may also be a valuable reference for future studies. The outcomes are compared against several sources (Salvador, 2005; Magalhães, 2008; IVV, 2013), showing an overall good agreement.

2.2. Thermal requirements

For assessing the varietal thermal requirements, the GDD is calculated as follows (Equation (1); Winkler, 1974; McMaster and Wilhelm, 1997):

$$\mathrm{GDD} = \sum_{\mathrm{Apr}}^{\mathrm{Oct}} \left(\left[\frac{T_{\max} + T_{\min}}{2} \right] - T_{\mathrm{base}} \right) \quad (1)$$

where $T_{\max}$ and $T_{\min}$ are near-surface maximum and minimum temperatures, respectively, and T_{base} is the grapevine base temperature (10 °C). If $[T_{\max} + T_{\min}]/2$

$< T_{base}$, then $[T_{max} + T_{min}]/2 = T_{base}$ (McMaster and Wilhelm, 1997). GDD is then the degree-day sum over the growing season (April–October). Although the limits of the growing season can vary depending on the year, microclimate and variety [see e.g. a discussion for the Portuguese Douro Valley in Real *et al.* (2014)], a fixed growing season is required for the current spatial analysis, allowing a comparison between regions/varieties.

Gridded climatic normals of monthly mean T_{max} and T_{min}, on 30 seconds-arc resolution (~1 km), produced by the WorldClim project (www.worldclim.org; Hijmans *et al.*, 2005), are obtained. This dataset has previously been validated against other widely used observational datasets over Portugal (Fraga *et al.*, 2014b), showing high correlations throughout the country. The aforementioned variables are extracted for mainland Portugal (516 385 grid-cells) and are used to calculate the GDD for the recent-past (1950–2000). GDD values (area-minimum, -maximum and -mean) over each viticultural region in Portugal are also isolated for further analysis.

2.3. Varietal optimal zones

To obtain the full range of thermal conditions in which varieties are grown in Portugal, the GDD is combined with the spatial distribution of each variety. In this study, however, only the optimal climatic zone of each variety is considered, which is delimited by the 25th–75th percentile range of GDD. As stated above, this approach relies on the assumption that the varietal distribution over the country has been evolving throughout the centuries and growers have selected the most suitable location/climatic region for each variety. The optimal zone corresponds to the most common climate conditions for each variety, but excluding borderline climates, where varieties can be grown in either too cold or too warm conditions for well-balanced grape ripening.

2.4. Varietal clustering

Grapevine varieties can be classified according to maturation timing (Lopes *et al.*, 2011; Malheiro *et al.*, 2013; Parker *et al.*, 2013). However, for the scope of this study, the grapevine thermal requirements are assessed by their spatial distributions instead of their phenology. In fact, GDD is computed for the same growing season interval (April–October), regardless of the variety. Thus, varieties are classified according to the similarity between the spatial patterns of their optimal climatic zones. A K-means clustering (Hartigan and Wong, 1979) is applied to the spatial patterns of the 25th–75th percentile ranges of GDD for each variety (optimal zones). Despite the subjective choice of the number of clusters (Pham *et al.*, 2005), the 3-means clustering allows a categorization of grapevines into typical classes: early, intermediate and late varieties. Different numbers of clusters were also tested, but some of the resulting spatial patterns were not clearly distinguishable (not shown).

2.5. Climate change impacts

For climate change impact assessment, the GDD is calculated over the period 2041–2060 using a state-of-the-art 17-member ensemble of Global Climate Models (GCMs), following the latest Representative Concentration Pathways (RCP) 4.5 and 8.5 (IPCC, 2013). These datasets are supplied by the WorldClim project, after model calibration and bias correction using the observational WorldClim dataset, and statistically downscaled to ~1 km grid spacing (Table S2). Model ensembles are essential to provide comprehensive future climate projections, as the uncertainties in model parameterizations are taken into consideration (Deser *et al.*, 2012). The ensemble standard deviations (SD) under future climates are also assessed (model uncertainty).

The GDD calculated for the future period is then compared against the baseline period, over the 12 Portuguese winemaking regions, and changes on the optimum cluster distribution are assessed. Additionally, to determine the European regions with optimal conditions for the Portuguese varieties, under current and future climates (2041–2060), their continental-wide cluster patterns are defined. These assessments allow defining areas outside of the country where these varieties may currently grow, also providing their likely optimum zones in the future.

3. Results

3.1. Regional analysis

The 12 viticultural regions are now described regarding their GDD values and predominant varieties (Table 1 and Figure S1). The region with the lowest mean-GDD is Trás-os-Montes (1309 °C), closely followed by Terras-de-Cister and Minho (1346 and 1391 °C, respectively). Douro/Porto, Beira-Atlântico and Lisboa present very similar GDD (1657, 1672 and 1679 °C, respectively). Alentejo (flat inland region) presents the highest area-mean GDD (2116 °C). Regarding regional homogeneity, Península-de-Setúbal shows the lowest regional differences (SD = 75 °C), while Terras-da-Beira expresses the highest heterogeneity (SD = 351 °C). Concerning extreme GDD values, Terras-da-Beira depicts the lowest area-minimum (330 °C; due to the existing mountainous areas) and highest area-maximum (2393 °C), the latter with very similar values to Alentejo (2390 °C). The predominant nation-wide variety is Aragonez, due to its large presence in the Douro/Porto region (the region with the largest vineyard area). On a regional scale, the red varieties Castelão and Touriga-Franca and the white Síria and Fernão-Pires are grown in many regions (Table 1).

3.2. Varietal thermal demands

Figure 2 shows how the 44 grapevine varieties are distributed according to their GDD. As expected, white varieties exhibit the lowest GDD values (Gouveio, Avesso, Loureiro) of the 44 varieties and are mostly grown at higher elevations in cooler climates. Although white and

Table 1. GDD area-minimum, -maximum, -mean and -standard deviation for the 12 Portuguese mainland viticultural regions for the recent-past (1950–2000).

Viticultural region	Area-mean (°C)	Area-standard deviation (°C)	Area-minimum (°C)	Area-maximum (°C)	Predominant variety	
					Red	White
Trás-os-Montes	1309	257	452	1998	Touriga-Franca	Síria
Terras-de-Cister	1346	159	878	1838	Touriga-Franca	Gouveio
Minho	1391	246	459	1941	Vinhão	Loureiro
Terras-do-Dão	1501	295	360	1994	Touriga-Nacional	Encruzado
Douro/Porto	1657	198	608	2058	Aragonez	Síria
Beira-Atlântico	1672	168	759	2051	Baga	Fernão-Pires
Lisboa	1679	117	1182	2067	Castelão	Malvasia-Rei
Terras-da-Beira	1724	351	330	2393	Aragonez	Arinto
Algarve	1986	149	1139	2324	Castelão	Síria
Tejo	2002	117	1305	2294	Castelão	Fernão-Pires
Península-de-Setúbal	2084	75	1601	2226	Castelão	Fernão-Pires
Alentejo	2116	101	1392	2390	Trincadeira	Síria

The regions are ordered from lowest to highest mean-GDD.

red average GDD have no differences in mean/median, white varieties present 10% higher 25th–75th percentile ranges, particularly for Síria and Alvarinho, confirming their high climatic adaptability. Additionally, it is also a white variety that presents the highest mean GDD (Antão-Vaz), which is noteworthy taking into account that white varieties are traditionally considered better adapted to cooler climates. Yet, Antão-Vaz presents a relatively low GDD range, suggesting a narrow optimal zone.

The empirical statistical distributions in Figure 2 indicate that varieties with positive skewness (from Gouveio to Fernão-Pires) are largely predominant in northern cooler areas, but also spread over much warmer areas in the south. The opposite behaviour is found for negatively skewed distributions (from Moscatel-Graúdo to Antão-Vaz), which are preferably located in southern warmer climates, but can still be found in much cooler climates in the north. These asymmetries may reflect the existence of lower (upper) thermal thresholds in the positively (negatively) skewed distributions/varieties, but may also be partially explained by historical/cultural aspects, including the spreading of varieties within the country.

For the red varieties, Aragonez and Trincadeira feature high regional/climatic ranges. Borraçal and Vinhão exhibit the lowest mean GDD, whereas Castelão and Moreto reveal the highest values. However, the last four varieties show very low GDD ranges, suggesting either they are grown in suitable climates or have low adaptability. The grape variety presenting the lowest climatic/regional adaptability is Jaen (originating from northwestern Spain), reflecting its relatively recent introduction in the country and low genetic variability. Although this analysis presents GDD ranges for the full growing season, it is in clear agreement with inter-cultivar comparisons using GDD and phenology (Lopes *et al.*, 2008; Alves *et al.*, 2013; Malheiro *et al.*, 2013).

Taking into account the GDD values presented herein and the quality assessments in Amerine and Winkler (1944), it should be noted that many varieties of the Portuguese collection (from Tinta-Barroca to Alfrocheiro) are within the ranges for high quality wine production. This indicates the high potential of the Portuguese varieties to expand across other countries. In fact, comparing Portuguese varieties against other European varieties (Figure S2; Jones, 2006), it is clear that the full range of thermal requirements for the Portuguese varieties (shaded area in Figure S2) varies from cool (Sauvignon Blanc) to very warm (Nebbiolo) climates. However, the optimal zone (white area in Figure S2) depicts a much narrower range.

3.3. Varietal clustering

The 3 clusters of the 44 selected varieties are identified according to their optimal zone (25th–75th percentile range of the GDD; Figure 2). Cluster 1 (C1) corresponds to varieties with the lowest GDD values (1524–1765 °C) and are classified as early-varieties. Cluster 2 (C2) groups intermediate-varieties (1611–2083 °C), while Cluster 3 (C3) corresponds to late-varieties (2077–2178 °C). Thus, C1 incorporates 28 varieties (15 white, 13 red), ranging from Gouveio to Tinto-Cão, C2 integrates 13 varieties (8 white, 5 red), from Tália to Alfrocheiro, and C3 only comprises 3 varieties (1 white, 2 red), Castelão, Moreto and Antão-Vaz. Comparing the GDD ranges of the three clusters, C2 is the broadest cluster, with a range of 472 °C, C1 presents a range of 241 °C and C3, the narrowest, with a range of 101 °C.

Regarding the spatial patterns of each cluster, they present a good agreement with the spatial distribution of the corresponding grapevine varieties (Figure 3(a), (d) and (g)). Growth areas of each variety are mostly inside the respective cluster pattern. Areas where varieties are grown outside the cluster pattern indicate that they are grown out of their optimal climatic zone, defined by the 25th–75th percentile range of GDD. The existence of small vineyard areas outside the optimal ranges may be explained by historical reasons, by microclimatic effects or when targeting specific wine types. C1 extends mainly

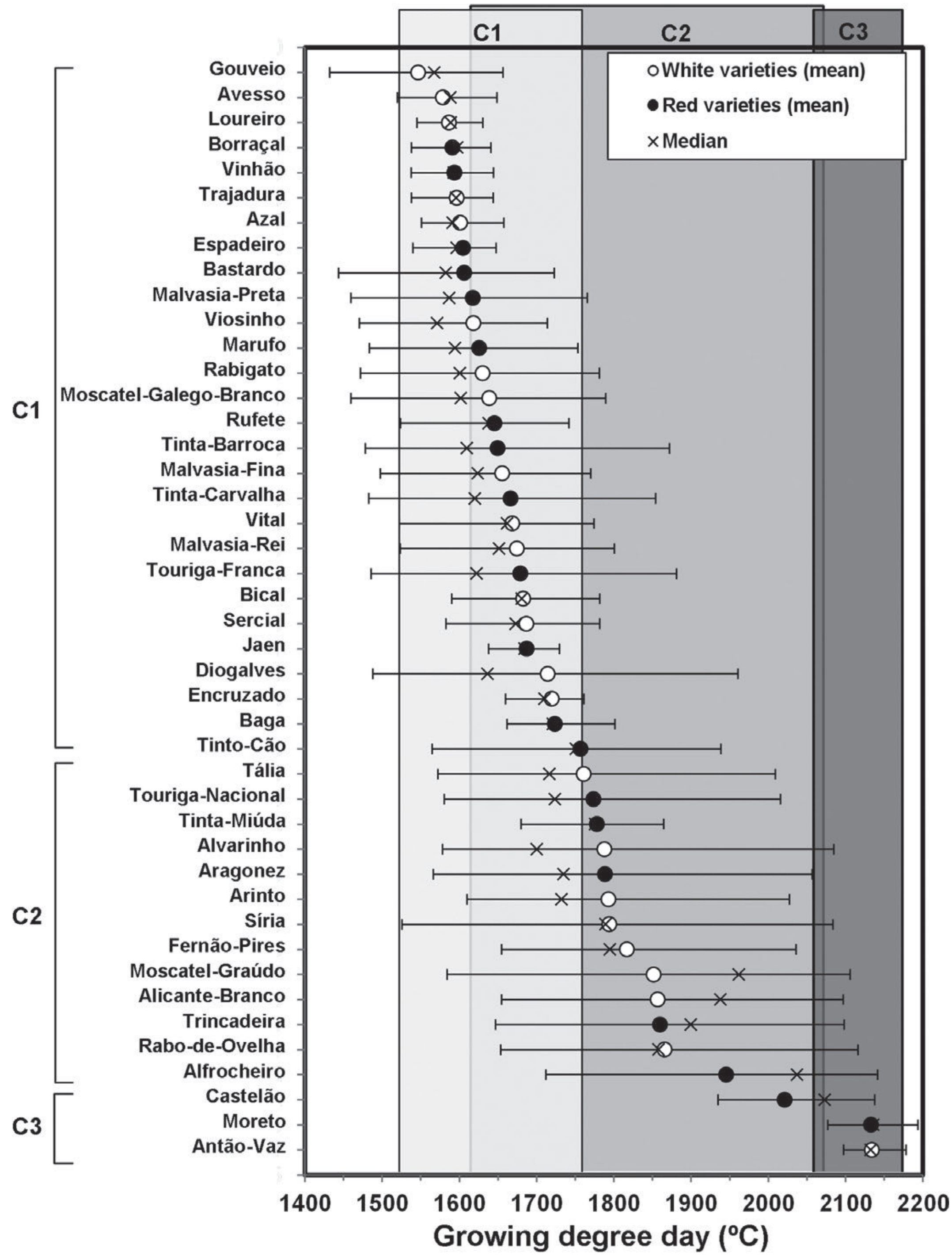

Figure 2. Growing degree-days (GDD) in which the selected 44 (red and white) grapevine varieties are grown in Portugal. The vertical bars indicate the 25th and 75th percentiles, the mean and median values are also represented. Grapevine varieties are grouped according to their respective K-means cluster (C1 – Cluster 1; C2 – Cluster 2; C3 – Cluster 3) and are ordered according to their mean GDD value.

to northern and western Portugal (Lisboa, Beira-Atlântico, Terras-da-Beira, Terras-do-Dão, Terras-de-Cister, Douro/Porto, Minho and Trás-os-Montes, Figure 3(a)). This cluster is also present in some southern winemaking regions (Alentejo and Algarve), but in very small areas (high-elevation cooler climates). Although C1 encompasses the largest number of varieties, its spatial pattern has the smallest extent (29 466 grid-cells; Table 2). C2 presents the largest extent of the three clusters (64 935 grid-cells; Table 2), and it is thus found in all of the Portuguese wine regions (Figure 3(d)), with the highest prevalence in central Portugal (Lisboa and Tejo wine regions). C2 is also present in the Douro/Porto, namely in the warmer innermost portions of the valley. C2 largely overlaps C1, but mostly over the Lisboa wine region. The C3 pattern (Figure 3(g)) is limited to the southern half of Portugal (Alentejo, Tejo, Algarve and southern Terras-da-Beira), showing a slightly greater extent than C1

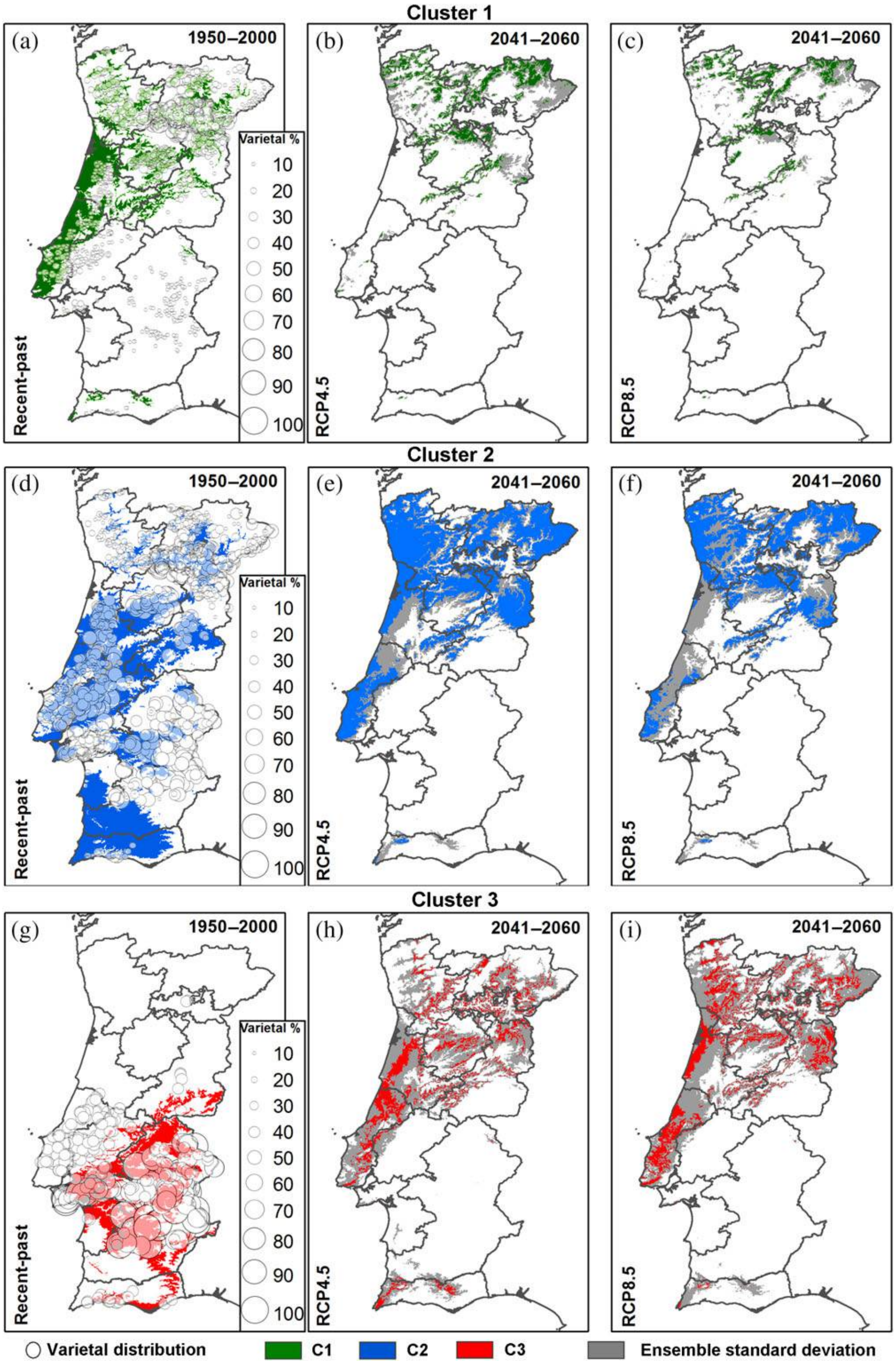

Figure 3. Spatial pattern of the grapevine optimal zone cluster 1 (C1) over Portugal, for the (a) recent-past (1950–2000) and for the (b, c) future (2041–2060), following the RCP4.5 and 8.5 scenarios, respectively. Cluster 2 (C2) is represented by panels (d–f) and Cluster 3 (C3) by (g–i). The geographical location and percentage of the grapevine varieties included in each cluster are also shown in panels (a, d, g). The ensemble standard deviation is also displayed.

(34834 grid-cells), despite being composed by only three varieties.

3.4. Climate change impacts on viticultural regions

Future projections for GDD in the 12 Portuguese winemaking regions give evidence for a strong warming trend (Table 3). Both scenarios point to increases in GDD, with the RCP8.5 the most severe scenario, surpassing RCP4.5 by an average of 120 °C in all regions. Increases in GDD: (1) area-mean values are of 401–547 °C in RCP4.5 and 503–686 °C in RCP8.5; (2) area-minimum values are of 337–554 °C in RCP4.5 and 441–695 °C in RCP8.5;

Table 2. Number of grid-cells in each cluster for the recent-past (1950–2000) and for the two future scenarios (2041–2060, RCP4.5 and RCP8.5).

Cluster	1950–2000 Recent-past	2041–2060 RCP4.5	2041–2060 RCP8.5
1	29 466	13 154 (−55%)	8795 (−70%)
2	64 935	53 562 (−18%)	37 901 (−42%)
3	34 834	12 075 (−65%)	17 840 (−49%)

Differences (in percentages) between the future and the recent-past are also shown.

and (3) area-maximum values are of 390–571 °C in RCP4.5 and 448–715 °C in RCP8.5 (Table 3). Concerning area-mean GDD, Terras-da-Beira is expected to experience the strongest warming (RCP4.5 – 547 °C; RCP8.5 – 686 °C). On the other hand, the lowest warming occurs in the Algarve (RCP4.5 – 401 °C; RCP8.5 – 503 °C). Regarding area-maxima, Terras-da-Beira is again projected to undergo the strongest warming (RCP4.5 – 571 °C; RCP8.5 – 716 °C), while Lisboa exhibits the lowest increases (RCP4.5 – 390 °C; RCP8.5 – 486 °C). The area-minimum GDD ranges from 554 °C/695 °C in Alentejo to 337 °C/441 °C (RCP4.5/RCP8.5) in Trás-os-Montes.

3.5. Climate change impacts on varietal suitability

The future optimal zones for each cluster (2041–2060), following RCP 4.5 (Figure 3(b), (e) and (h)) and 8.5 (Figure 3(c), (f) and (i)), are now discussed. Significant changes in the patterns of the optimal varietal zones are projected. For C1 (Figure 3(b) and (c)), both future RCP limit the cluster pattern to the northernmost mountainous areas (coolest climates). As a result, regions such as the Douro/Porto, which currently include most of these cluster varieties (over 60% in many cases, Figure 3(a)), may no longer present optimal thermal conditions for these varieties. For C2 (Figure 3(e) and (f)), its future pattern is mostly located over the northern half of the country and limited by elevation into 2041–2060. For C3 (Figure 3(h) and (i)), projections indicate it will nearly replace the current C1 pattern by being found more northward and towards the coast. As C3 is currently limited to southern Portugal, its displacement reveals a strong climate change signal.

After isolating the mean cluster changes (Figure 4), a northward displacement is clear (Figure 4(a)), mainly for C1, which in the future is northwards of 39°N. While no apparent longitudinal changes can be detected in the cluster patterns (Figure 4(b)), it is expected that optimal cluster zones also shift to higher elevations, particularly for C1 (Figure 4(c)). A decrease in the extent of these zones is also projected for all clusters (Table 2), with the areas of future optimal zones decreasing, particularly in C1 (from −55 to −70%) and C3 (from −49 to −65%). These outcomes are supported by both scenarios, with the strongest climate change signal in RCP 8.5, which represents the more severe scenario (IPCC, 2013). An exception is visible in C3 (Table 2), where the greatest decrease is in RCP4.5 rather than in RCP8.5, possible due the very specific thermal interval of this cluster. Model uncertainty, assessed through the ensemble SD, indicates a general good agreement amongst models. Uncertainty is generally low for all clusters, because the uncertainty zones show small departures from the mean zones. C3 shows higher uncertainty than other clusters, which may be attributed to its relatively narrow GDD ranges (Figure 1).

3.6. Changes in cluster regional distribution

Summarizing the impacts of future climate on regional cluster distribution, some viticultural regions are expected to have extensive changes (Table 4). Alentejo is expected to change from C2-C3 to exclusively C3. Similar considerations can be made for the Península-de-Setúbal winemaking region. For Tejo, these changes are even more evident. It is currently suitable for the three clusters, while it is

Table 3. GDD area-minimum, -maximum and -mean for the 12 Portuguese mainland viticultural regions for the two future scenarios (2041–2060, RCP4.5 and RCP8.5).

	Area-minimum (°C)		Area-maximum (°C)		Area-mean (°C)	
	RCP4.5 (Diff)	RCP8.5 (Diff)	RCP4.5 (Diff)	RCP8.5 (Diff)	RCP4.5 (Diff)	RCP8.5 (Diff)
Alentejo	1946 (**554**[a])	2087 (**695**[a])	2936 (546)	3080 (690)	2608 (492)	2733 (617)
Algarve	1510 (372)	1604 (466)	2787 (463)	2903 (580)	2387 (**401**[b])	2488 (**503**[b])
Beira-Atlântico	1220 (461)	1341 (582)	2539 (489)	2664 (614)	2131 (459)	2249 (577)
Douro/Porto	1021 (414)	1134 (527)	2618 (560)	2756 (698)	2192 (535)	2325 (668)
Lisboa	1583 (401)	1682 (500)	2457 (**390**[b])	2553 (**486**[b])	2084 (405)	2185 (506)
Minho	802 (343)	906 (447)	2443 (502)	2569 (628)	1837 (446)	1951 (560)
Península-de-Setúbal	1990 (389)	2086 (485)	2675 (449)	2788 (562)	2504 (420)	2608 (525)
Tejo	1750 (445)	1863 (558)	2815 (521)	2946 (653)	2459 (457)	2573 (571)
Terras-da-Beira	682 (352)	776 (446)	2964 (**571**[a])	3109 (**716**[a])	2272 (**547**[a])	2411 (**686**[a])
Terras-de-Cister	1349 (471)	1474 (597)	2357 (520)	2490 (652)	1872 (526)	2005 (659)
Terras-do-Dão	715 (355)	812 (452)	2495 (501)	2624 (631)	2006 (505)	2136 (634)
Trás-os-Montes	789 (**337**[b])	892 (**441**[b])	2546 (548)	2682 (684)	1831 (522)	1961 (652)
Average (Diff)	408	516	505	633	476	597

Differences (Diff) between the future and present periods are also shown. Bold values represent the highest (a) and lowest (b) differences amounts regions.

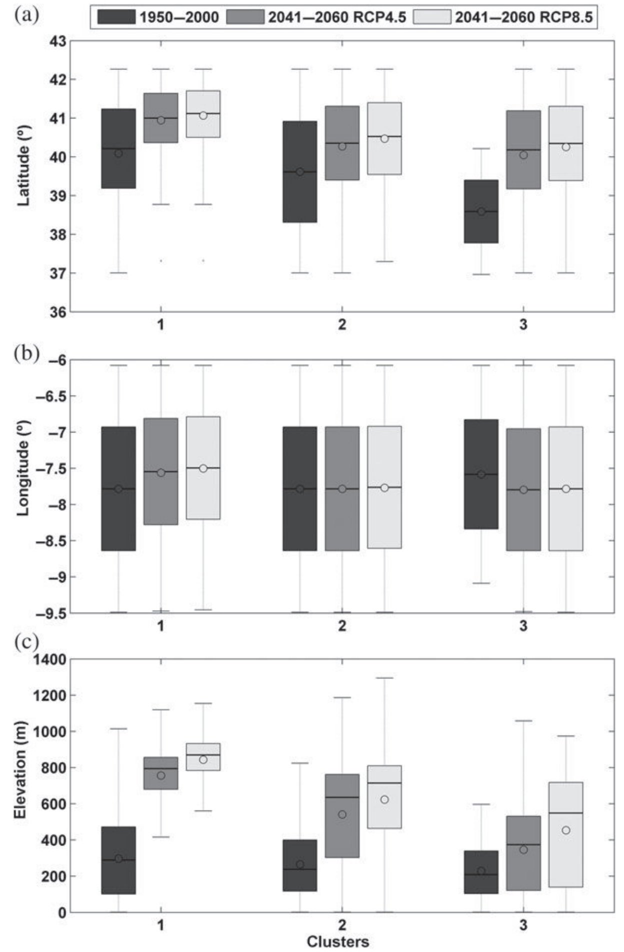

Figure 4. Boxplots representing the cluster changes in (a) latitude, (b) longitude and (c) elevation between the present (1950–2000) and the two future (2041–2060) scenarios (RCP 4.5 and 8.5).

projected to become suitable only to C3. Beira-Atlântico, Douro/Porto, Lisboa and Minho are expected to shift from C1-C2 optimal zones to C2-C3 optimal zones, while Terras-de-Cister shifts from C1 to C2-C3. Terras-da-Beira, Terras-do-Dão and Trás-os-Montes are the only regions maintaining all of the optimal cluster zones in the future and comes from each of the regions having more land at higher elevations (Table 4).

3.7. Future optimal zones for Portuguese varieties in Europe

Given the northward shift of the optimal climatic zones for each cultivar, it is expected that other winemaking regions in Europe may benefit from future warmer climates. The assessment of the cluster centroids over Europe (Figure 5(a)) suggests that the optimal zones are mostly limited to southern Europe. C1 and C2 show higher incidence in Southern Spain, Italy (coastal regions), southern France, Greece and some regions in Bulgaria, Romania and Turkey. C3 is largely limited to southern Iberia, some small regions in Italy, isolated areas on islands in the Mediterranean and Greece. This may also explain why Portuguese varieties are strongly confined to the country, because their required thermal conditions are not reached in many European regions under current climates.

Table 4. Cluster distribution in each of the 12 viticultural regions in mainland Portugal, in the present (1950–2000) and in the future periods (2041–2060, both RCP are considered jointly).

Viticultural region	Present-clusters	Future-clusters (both RCP)
Alentejo	2, 3	3
Algarve	2, 3	2, 3
Beira-Atlântico	1, 2	2, 3
Douro/Porto	1, 2	2, 3
Lisboa	1, 2	2, 3
Minho	1, 2	2, 3
Península-de-Setúbal	2, 3	3
Tejo	1, 2, 3	3
Terras-da-Beira	1, 2, 3	1, 2, 3
Terras-de-Cister	1	2, 3
Terras-do-Dão	1, 2	1, 2, 3
Trás-os-Montes	1, 2	1, 2, 3

In the future, however, both RCP scenarios project an extension of these optimal zones throughout Europe. In RCP4.5 (Figure 5(b)), C1 is projected to broaden through central Europe, reaching some renowned wine regions in France (Champagne, Loire Valley) and Germany (Mosel Valley). C2 is projected to extend to central-western France (Bordeaux), inner Spain and Italy, Hungary and Croatia. C3 is projected to be found in very small areas under the RCP4.5 scenario, but still present in many European countries, such as the south of France, the Piedmont and Chianti regions of Italy, Hungary, Serbia and southern Romania. For C1, considering RCP8.5 scenario, the extension of the clusters is greater than RCP4.5, projected to reach some areas in Poland and Ukraine. C2 is more confined, as some C3 areas now occupy C2 zones.

4. Discussion and conclusions

The goals of this study were to characterize the thermal conditions in which the main *Vitis vinifera* L. varieties are grown in Portugal. Differences in heat requirements of the 44 most important varieties are identified and the most suitable regions/climatic conditions for each variety are established. Adapting to future climates may comprise a selection of more resilient varieties to warming and drying. Portuguese varieties have a generally high adaptability, because they are grown across a large range of thermal conditions. Indeed, there are genetic, morphological and physiological differences between each variety that allow a better adaptation to different climates and result in the production of singular wines. However, the adaptation of some varieties to new climates may be insufficient, resulting in their abandonment to the detriment of others.

The results obtained in the climate analysis are in close agreement with the warming trends reported in several European countries (Duchene and Schneider, 2005; Orlandini *et al.*, 2009; Neumann and Matzarakis, 2011; Lorenzo *et al.*, 2012; Spinoni *et al.*, 2015). Given these future

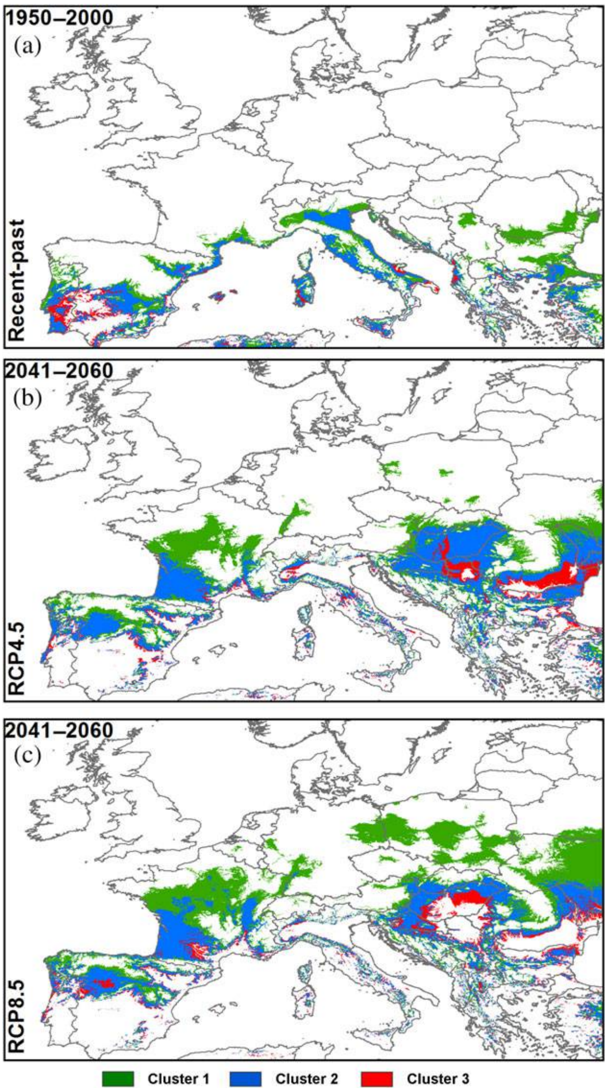

Figure 5. Spatial pattern of the three grapevine optimal zone clusters (1, 2 and 3) over Europe, for the (a) recent-past (1950–2000) and for the future (2041–2060), following the (b) RCP4.5 and (c) RCP8.5 emission scenarios.

projections, it is expected that varieties that have lower thermal demands, with lower mean GDD and ranges, may have higher difficulties in adapting to climate change. Varieties that fall into this category include Gouveio, Avesso, Loureiro and Trajadura (white), and Borraçal, Vinhão, Espadeiro and Jaen (red). These varieties may be used less in future warmer climates, as they can achieve rapid and unbalanced maturation, leading to low-quality wine production. Other varieties, such as Antão-Vaz (white) and Moreto and Tinta-Miúda (red), despite having relatively low GDD ranges that may indicate lower climatic adaptability, may be able to better adapt to temperature increases owing to its higher optimal GDD. Red varieties, such as Touriga-Franca, Touriga-Nacional and Aragonez, should remain as top varieties for wine production in Portugal, largely due to their most-valued enological characteristics and high GDD ranges. Similar considerations can be made for white varieties with high GDD ranges, such as Alvarinho and Síria.

Although the northward shift in each cluster over Portugal may indicate that some regions will no longer provide optimal climatic conditions for most current varieties (e.g. southern Portugal), this may also provide an opportunity to select other international varieties, with higher thermal demands. Several studies point to future varietal shifts as a measure to counteract the negative impacts of climate change (Orlandini *et al.*, 2005; White *et al.*, 2006; Sadras and Petrie, 2011; Hannah *et al.*, 2013; Moriondo *et al.*, 2013). Cultivars, such as Grenache and Sangiovese, which show high thermal resilience and are currently grown in warm Mediterranean regions (e.g. southern Spain and Italy), may be suitable for this purpose (Jones, 2006; Tomasi *et al.*, 2011; Koufos *et al.*, 2014). Furthermore, viticultural suitability to a given cultivar can be enhanced through the application of adaptation measures by growers (van Leeuwen *et al.*, 2013).

Growers can adopt several short and long-term measures to mitigate the negative impacts of climate change. As short-term measures, they can adjust pruning times and training systems (Duchene and Schneider, 2005), apply leaf sunscreens (e.g. Kaolin, Bordeaux mixture) or vine shadings (Greer *et al.*, 2011), implement controlled/deficit irrigation (Flexas *et al.*, 2010), cover cropping and tillage treatments (Monteiro and Lopes, 2007) and adjust enological practices (Orduna, 2010). Numerous approaches could be used for long-term adaptations including improvements in root-stock and clonal selection (Koundouras *et al.*, 2008), relocations to cooler areas (Fraga *et al.*, 2014b), increasing soil depths and water holding capacities (Pellegrino *et al.*, 2004), genetic breeding of new varieties (Duchene *et al.*, 2012) and, as this study suggests, the best cultivar selection according to their optimal climates.

Future varietal selections will depend heavily on the interest of winemakers to maintain the production of specific wines. It is known that the global wine market demand is typically focused on a very narrow range of grapevine varieties (e.g. Cabernet-Sauvignon, Chardonnay, Merlot, Pinot-Noir and Riesling) (Jones, 2006; Renouf *et al.*, 2010; Anderson and Aryal, 2013). Portuguese varieties offer a competitive alternative over many of these international varieties, as they are grown over a wide range of thermal conditions and are known to produce high quality wines. These advantages, combined with their high climatic adaptability, can enable the increased migration of Portuguese cultivars outside the country. Additionally, the increase in biodiversity by integrating these varieties in other European markets could potentially lead to an increased resistance to pests and diseases. However, the regulatory enforcements in each wine region concerning the varieties used for wine production and unknown future market trends may bring strong resistance to new varietal selections.

This study may be integrated into a wider framework, accounting for the potential socioeconomic impacts of climate change on the viticultural sector. The high-resolution maps provide clues on where growers can optimally plant new vineyards/varieties under future climates. This may bring not only important challenges to the current wine regions but can also imply a reshaping of these regions and of the winemaking sector. These results can be further integrated with other variety-dependent factors, such as yield, quality attributes, wine typicity and market values. The socioeconomic impacts can then be assessed on this basis, although this approach is out of the scope of this study and will be left for forthcoming analysis. Other more internationally renowned cultivars and larger target areas can also be considered. For a better adaptation to these new challenges, these outcomes can be used by stakeholders/winemakers for planning timely, suitable, sustainable and cost-effective adaptation measures.

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Supporting Information

The following supporting information is available as part of the online article:

Appendix S1. Supplementary material

Locations of the varieties (a) Alfrocheiro, (b) Alicante-Branco, (c) Alvarinho, (d) Antão-Vaz, (e) Aragonez, (f) Arinto, (g) Avesso, (h) Azal, (i) Baga, (j) Bastardo, (k) Bical, (l) Borraçal, (m) Castelão, (n) Diogalves, (o) Encruzado, (p) Espadeiro, (q) Fernão-Pires, (r) Gouveio, (s) Jaen, (t) Loureiro, (u) Malvasia-Fina, (v) Malvasia-Preta, (w) Malvasia-Rei, (x) Marufo, (y) Moreto, (z) Moscatel-Galego-Branco, (aa) Moscatel-Graúdo, (ab) Rabigato, (ac) Rabo-de-Ovelha, (ad) Rufete, (ae) Sercial, (af) Síria, (ag) Tália, (ah) Tinta-Barroca, (ai) Tinta-Carvalha, (aj) Tinta-Miúda, (ak) Tinto-Cão, (al) Touriga-Franca, (am) Touriga-Nacional, (an) Trajadura, (ao) Trincadeira, (ap) Vinhão, (aq) Viosinho and (ar) Vital.

Maturity groupings based on the growing season mean temperature, for a set of grapevine varieties. Adapted from Jones (2006) to include the Portuguese grapevine cultivars. For these varieties, the shaded bars indicate the full range of thermal conditions in Portugal, whereas the inner bar indicates the optimum zone (25th–75th percentile range).

List of varieties and corresponding nationwide synonyms used in this study.

List of the ensemble members (17 Global Climate Models – GCM) used in this study, along with their respective institutions and key references.

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