# Bioclimatic shifts and land use options for Viticulture in Portugal

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## Abstract

Land use plays a relevant role in the climatic system. It endows means for agriculture practices thus contributing to the food supply. Since climate and land are closely intertwined through multiple interface processes, climate change may lead to significant impacts in land use. In this study, 1-km observational gridded datasets are used to assess changes in the Köppen–Geiger and Worldwide Bioclimatic (WBCS) Classification Systems in Portugal. Two past periods were analyzed: 1950–1979 and 1990–2019. A bioclimatic-shift exposure index (BSEI) is defined to identify the most exposed regions to recent climatic changes. The temporal evolution of land cover with vineyards between 1990 and 2018, and correlations with areas with bioclimatic shifts, are analyzed. Results show an increase/decrease of 18.1%/17.8% in the Warm Mediterranean with hot/warm summer (CSa/CSb) climate in Portugal. The WBCS Temperate areas reveal a decrease of 5.11%. Arid and semi-arid ombrotypes areas increased, whilst humid to sub-humid ombrotypes decreased. Thermotypic horizons depict a shift towards warmer classes. BSEI highlights the most significant shifts in northwestern Portugal. Results show that vineyards have been displaced towards regions that are either the coolest/humid, in the northwest, or the warmest/driest, in the south. As vineyards in southern Portugal are commonly irrigated, options for the intensification of these crops in this region may threaten the already scarce water resources and challenge the future sustainability of these sectors. As similar problems can be found in other regions with Mediterranean-type climates, the main outcomes from this study can be easily extrapolated to other countries worldwide.

## Introduction

Land supports the main basis not only for human livelihoods but also for well-being. It endows means for agriculture practices thus contributing to the food supply, supplying freshwater, and nurturing biodiversity in the several intricate ecosystems (IPCC, 2019). Land use also plays a relevant role in the climatic system, being closely intertwined (Tasser et al., 2017). As such, climate change, as well as climate and weather extremes, are important stress factors to land ecosystems and biodiversity, which are thus becoming increasingly vulnerable (Ellis, 2013; Martins et al., 2013). Changes in temperature and precipitation patterns are key factors triggering shifts in the climate of a region. These variables are fundamental to classify climates in different categories, such as in the Köppen-Geiger climate classifications system (Köppen et al., 1930) but also for the Worldwide Bioclimatic Classification System (WBCS) (Rivas-Martínez et al., 2011, 2017). Recent studies projected changes for the Iberian Peninsula (IP) not only for the Köppen-Geiger climatic classification (Andrade and Contente, 2020a) but also for the major divisions of the WBCS, mainly for the IP southernmost regions (Andrade and Contente, 2020b).
The Portuguese viticultural sector is of key socioeconomic significance, owing to the relatively high generated economic income and the important share of national exports (https://www.ivv.gov.pt/np4/499/), currently being Portugal the 10$^{th}$ wine exporter and the 11$^{th}$ wine producer (https://www.oiv.int/public/medias/7909/oiv-

state-of-the-world-vitivinicultural-sector-in-2020.pdf). Mainland Portugal has a total of 12 Wine Regions (WR), with a variation of vineyard land cover from 271,507 ha in 1989 to 189,668 ha on 31/07/2020 (https://www.ivv.gov.pt/np4/7179.html). With an opposite trend, wine production increased from about 5.8 Mhl in 2009/10 to about 6.5 Mhl in 2019/20 (https://www.ivv.gov.pt/np4/163.html). Different Denominations of Origin (DO) can also be found within each WR.

The main goal of this research aims to answer the question: 'Are land use options in viticulture and oliviticulture in agreement with ongoing bioclimatic shifts in Portugal?'. To answer this question, the Köppen-Geiger climatic classification and the WBCS were applied in a first step, as a comparison between two 30-year periods, namely 1950–1979 and 1990–2019, was carried out to link recent past climatic shifts with land-use changes. From the WBCS, which comprises the bioclimates, the thermotypes, and ombrotypes, a compound Bioclimatic-shift exposure index (BSEI) was computed to identify the most exposed regions in Portugal to bioclimatic shifts. In a second phase, the spatial patterns for the extension of vineyards for 1990, 2018, and between 1990–2018 are analysed. lastly, correlations between ombrotypes and thermotypes were assessed for 1990, 1995, 2007, 2010, 2015, and 2018.

## Materials and methods

In this study, four high-resolution gridded observational datasets were used between 1950–2019. The methodology for the development of this dataset is described by Fonseca and Santos (2018). The daily precipitation totals (P, in mm), maximum (TX, in °C), mean (TG, in °C), and minimum (TN, in °C) temperatures, are defined on a 0.01° regular grid. Two 30-year periods were analysed, i.e., 1950–1979 and 1990–2019, aiming at finding climatic shifts already in development in mainland Portugal.

The study area is within the geographical sector: 36.95° N – 42.16° N and 9.48° W– 6.17° W (Figure 1). Though, all figures presented herein will be clipped excluding the grid boxes over the Atlantic Ocean. Figure 1a shows a hypsometric chart, with a spatial resolution of 3 arc-second, and was compiled from mosaics retrieved from STRMGL3S Nasa Shuttle radar topography second sub-sampled V003 distributed by (MEaSUREs) SRTM (NASA, 2013). The study area includes 18 administrative regions in mainland Portugal (Figure 1b). All maps are projected onto the GCS ETRS 1989 Geographical Coordinate System.

The Land Use and Occupation maps were retrieved from https://snig.dgterritorio.gov.pt/, for the years 1990, 1995, 2007, 2010, 2015, and 2018. Only the spatial representation of vineyards was taken into consideration. The total area evolution for this culture and the related total amount of production was subsequently presented in tables and graphics between 1989 and 2020 (when available).

Köppen's climate classification is based on a subdivision of major climate types, which are represented by five capital letters, from A to E (considered the main group), followed by two others. In this study, C is used for temperate climates in the mid-latitudes. The second letter relates to the seasonal precipitation type: S for steppe, W desert, while f implies no dry season. The last letter specifies the level of heat, with a for hot summer, b for warm summer, c for cold summer, d for very cold winter, and h and k are associated with hot and cold climates, respectively. The whole calculation follows the methodology described by Kottek et al. (2006) whereas the nomenclature and color scheme follow Andrade and Contente (2020). In this study, the concept of high-altitude type (H climates) was not applied. Further details on this methodology can be found in Andrade and Contente (2020).

The WBCS includes four major divisions, according to Rivas-Martínez et al. (2011, 2017). The first division corresponds to the macrobioclimate, which is subsequently split into the other three: bioclimates, ombrotypes, and thermotypes. The major bioclimatic divisions comprise the computation of three additional indices: the Continentality Index (CI), the annual Ombrothermic Index (OI), and the Thermicity Index (TI). However, four additional ombrothermic indices are also computed: the ombrothermic index of the hottest month of the summer quarter ($Ios_1$), the ombrothermic index of the hottest two months of the summer quarter ($Ios_2$), the ombrothermic index of the summer quarter ($Ios_3$) and the ombrothermic index of the 4 months resulting from adding the summer quarter and the month immediately preceding it ($Ios_4$). Further details can be found in Rivas-Martínez et al. (2011, 2017), while a summary of the main equations can be found in Andrade and Contente (2020).

For the bioclimates, ombrotypes, and thermotypes, a comparison between a recent past period 1990–2019, and preceding past conditions 1950–1979 (reference period) was undertaken. Anomalies (% of change) were computed as the differences between the most recent period and the reference period. The statistically significant anomalies (S.S.) were assessed by the Mann-Whitney-Wilcoxon test (MWW), at a 5% significance level (Wilcoxon, 1945; Mann, 1945), using the 30-year mean values for each period and location of the study area.

This nonparametric test assumes equal medians under the null hypothesis ($H_o$), against the alternative hypothesis ($H_a$) of different medians. Locations with different medians will be identified by a black pattern in all associated figures.
The compound bioclimatic-shift exposure index (BSEI) was computed by adding the statistically significant differences between the bioclimates, ombrotypes, and thermotypes between 1990–2019, and 1950–1979, respectively. For each difference, two values are attributed, 0 when there is no change, 1 when a change in the climatic type occurs between the two 30-year periods. The three types are equally weighted in the final value of BSEI. This is performed for each grid point within the study area, separately. Hence, BSEI will vary from 0, representing regions not exposed to bioclimatic shifts, to 3, indicating regions highly exposed to bioclimatic shifts (changes in the three classifications simultaneously: bioclimatic, ombrotype, and thermotype) (Table 1). Despite its very simple definition, BSEI is a useful tool to assess the degree of change in bioclimatic conditions at a given region, i.e., their degree of exposure to climate change.

**Table 1.** Bioclimatic-shift expose index (BSEI) interpretation.

| BSEI | Degree of exposure |
|---|---|
| 0 | Not exposed |
| 1 | Weakly exposed |
| 2 | Moderately exposed |
| 3 | Highly exposed |

For each Land Use and Occupation map, the areas of Vineyards were extracted to assess their spatial-temporal development. Further, the data was compared with the bioclimates, ombrotypes, and thermotypes of the recent period to analyse the shift of land use.

## Results and discussion

The spatial depiction of the Köppen-Geiger climate classification in mainland Portugal for the period 1950–1979 shows three climate types (Figure 3a). Two within the CS 'Warm temperate/Mediterranean with dry summer' and one Cf 'Warm temperate/Mediterranean fully humid'. The main climate was CSa (Warm temperate/Mediterranean with hot summer) in 53.9% of the country, CSb (Warm temperate/Mediterranean with warm summer) in 45.8%, and only 0.03% for Cfb (Warm temperate/Mediterranean fully humid with hot summer). Besides a small area in the very southwest (Faro district, Figure 1b), the CSb type is mostly found in the northern half of Portugal, northwards of the Tagus River basin. On the other hand, the CSa type is prevalent in the southern half, and in a small region between the Vila Real and Bragança districts (Figures 1a, 1c). The small area of Cfb climate is located in a mountainous region in the northwest (Figures 1b, 1c). For 1990–2019, only two types are found (CSa and CSb), with an increase of +18.1% in CSa type (hot summer) and a resulting decrease of –17.8% in CSb (warm summer), a milder climate. This later climate type is now depicted along the north-central western coast and in mountainous areas in the northern half of the country.
For the WBCS classification only two macroclimates were found for the two time periods, the Mediterranean (M) and the Temperate (T), which decreased from 1950–1979 to 1990–2019. This can be concluded by observing Figures 2a and 2d, where the bioclimates are derived from the macroclimates. Results also show a transition from three bioclimates in 1950–1979 to four in 1990–2019, though Teho only underwent an increase of +0.03%. However, the most remarkable difference is related to the loss of temperate regions (–5.14%) of Teoc, with an increase of Mepo of +4.78%. These changes have occurred mainly in northwestern Portugal (Figures 2a and 2d). Climate change has also affected the ombrotypes. They changed from seven to eight types (Figures 2b and 2e), with the development of a new ombrotype, Sas, within the semi-arid ombrothermic horizons, and corresponding to 0.74% of the territory in 1990–2019. The most relevant changes have occurred for Sei, within the arid ombrothermic horizons with an increase of +24.07%, followed by an overall decrease in almost all humid horizons. The outcomes for the thermotypes, are consistent with the previous WBCS types. A loss of the area with temperate thermotypic horizons is verified, e.g., within the thermotemperate (Ttes, –0.91%), mesotemperate (Mtei and Mtes, –2.77 and –1.15%, respectively), and supratemperate (Stei –2.14% and Stes non-existent in 1990–2019). Nonetheless, within the Mediterranean thermotypic horizons, changes were

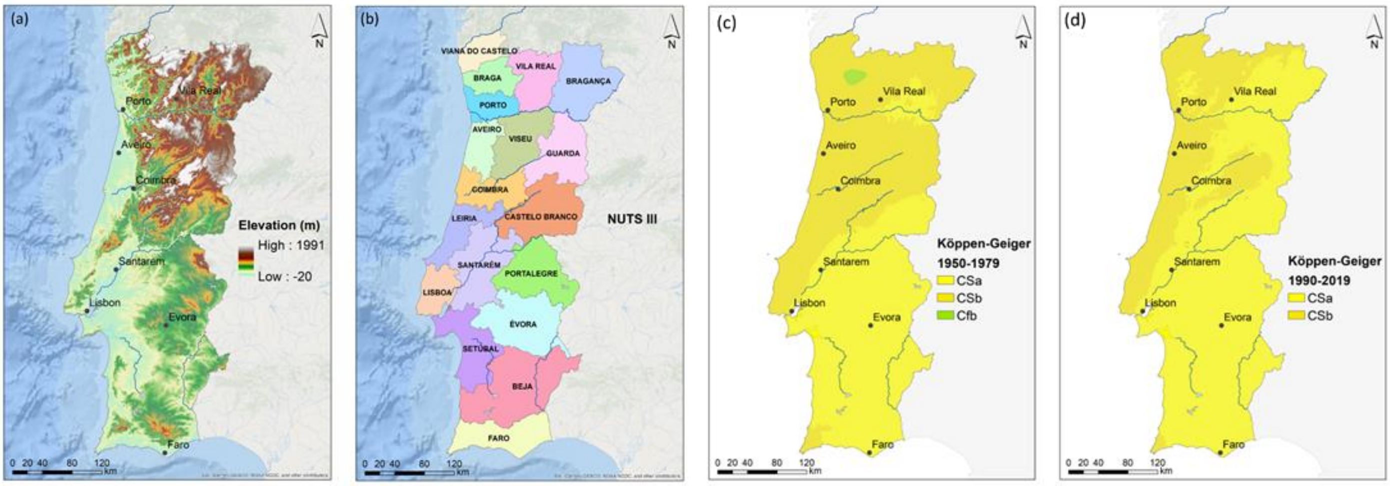


**Figure 1.** Mainland Portugal (a) elevation (in m) and (b) the related 18 administrative regions (districts). Köppen-Geiger climate classification for (c) 1950–1979 and (d) 1990–2019.
Adopted from Andrade et al. (2021).

also found. There was a major increase in the thermomediterranean horizons (Tmei and Tmes, +10.74 and +8.16%, respectively), followed by mixed results for the mesomediterranean horizons, with a decrease of –8.10% for Mmei and an increase of +4.74% for Mmes.
The BSEI captures the accumulated changes that have occurred between 1990–2019 and 1950–1979 between bioclimates, ombrotypes, and thermotypes. Figure 4a shows the highest exposures (BSEI=3, highly exposed) in Viana do Castelo, Braga, Porto, Aveiro, Viseu, and Guarda districts. These outcomes are consistent with both the loss of temperate regions and the increase of more arid/dry bioclimatic types in the former areas (Figure 3). Large areas with BSEI=2 (moderately exposed) can still be found in those districts, as well as in the northeast (Bragança). On the other hand, in the southern half of the country, BSEI=2 can be found in the Santarém, Portalegre, Évora, Beja, and Faro districts (Figure 2g). In these last regions, however, changes are mostly due to shifts in the ombrotypes and thermotypes (Figures 2b to 2f).
The vineyard cover area in Portugal has decreased from 1990 to 2018. The decrease is approximately of 6% (126 $km^2$) (Figure 2i), mainly in the Lisboa district. New vineyard cover areas are, however, observed in Alentejo (mostly Évora district) and in northwestern Portugal, which are in both cases areas with higher BSEI values.
The evolution of the growing bioclimatic conditions in the vineyard cover area from 1990 to 2018 (Figure 2j), shows a shift towards new regions that are both humid (Hui), in northwestern Portugal (Vinho Verde WR), and dry (Sei), in southern Portugal (Alentejo WR). Conversely, a decrease in the areas classified as subhumid (Sus and Sui) is also apparent. Hence, vineyards are gradually occupying more extremes conditions in terms of climate humidity. The change in thermotype conditions of vineyards areas is not statistically significant (Figure 2k).

## Conclusion

The current climatic characterization intended at identifying the regions in mainland Portugal that have undergone the most significant bioclimatic shifts from 1950–1979 to 1990–2019. Most of the areas or districts that experienced more accentuated shifts in the bioclimatic classes from one period to the other are located in northwestern Portugal. For the second period (1990–2019), satellite-based land cover data are available throughout the country on an annual timescale. Therefore, the evolution of vineyard was analysed to assess to what extent have these crops been expanded to more susceptible zones to bioclimatic shifts.
The spatial distribution of the Köppen-Geiger climate classification showed three climate types (Figure 1c) in 1950–1979. The prominent climate type was CSa, in 53.9% of the country, CSb in 45.8%, and a very small percentage of 0.03% for Cfb. The CSa type was prevalent in the southern half of Portugal and a narrow region in the south of the Vila Real and Bragança districts (Figures 1a and 1c). The CSb was dominant throughout most of the northern half of Portugal, mostly northwards of the Tagus River basin. However, a clear bioclimatic shift in 1990–2019 was detected, with an increase of +18.1% in CSa type, associated with hot summers, and a

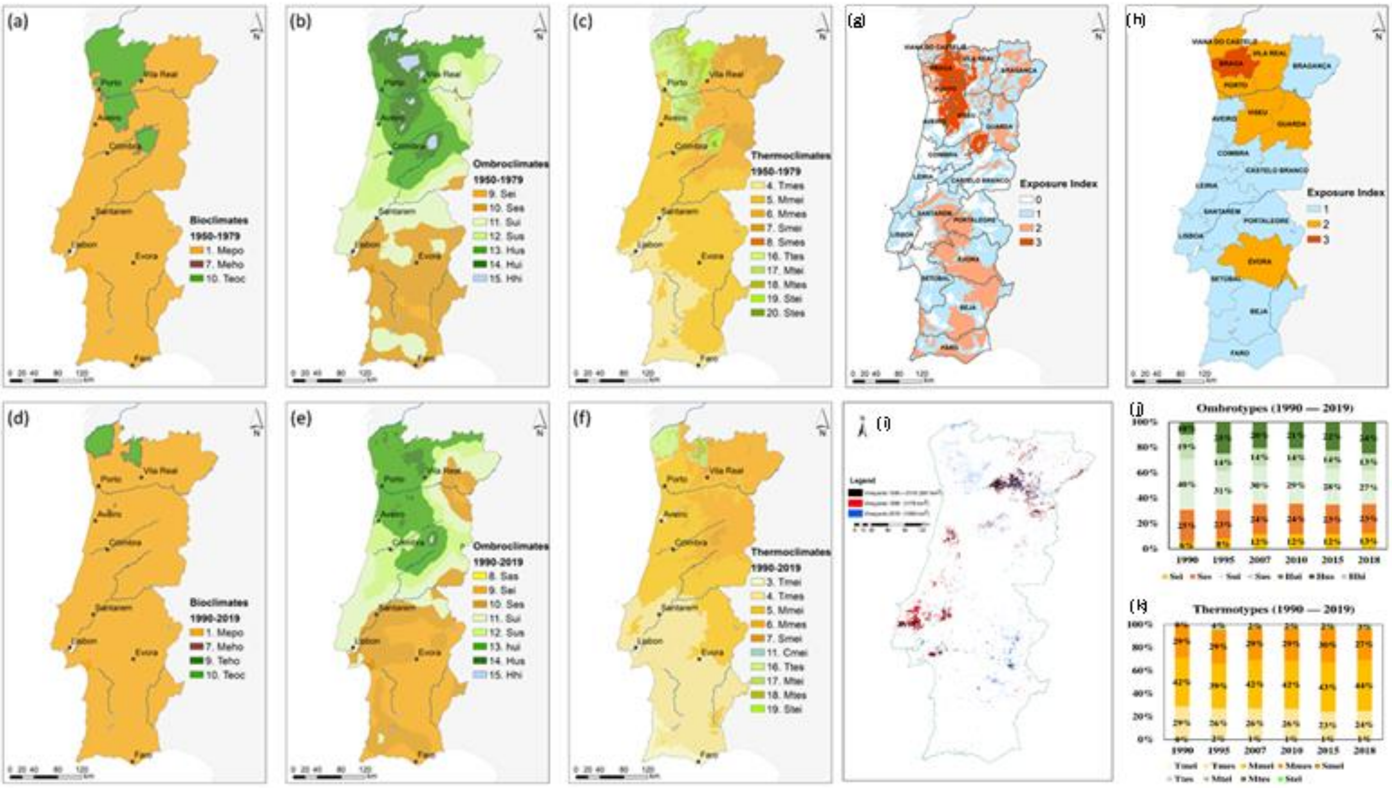


**Figure 2.** Classification for (a) bioclimates (b) ombrotypes and (c) thermotypes between 1950–1979 and (d, e, f) the same as for (a, b, c) but between 1990–2019. (g) Bioclimatic-shift exposure index (BSEI) for mainland Portugal and (h) related areal mean values for each district (Note: BSEI attained between 1990–2019 and 1950–1979). Spatial representation and related area (in km$^2$) of (i) vineyards and Percentage area regarding each Land Use and Occupation map for vineyards (j) and (k) ombrotype and (j, k) thermotype for the recent past period (1990–2019).
Adapted from Andrade et al. (2021).

corresponding decrease of –17.8% in CSb, associated with warm summers, and therefore a milder climate. These findings are in general agreement with Andrade and Contente (2020a).

The outcomes point out at shifts in the WBCS four major divisions from 1950–1979 to 1990–2019, related to a decrease of –5.11% in the temperate macroclimate in the northwest, followed by an increase in the Mediterranean macroclimate. This change affected the bioclimates since a transition from three bioclimates in 1950–1979 to four bioclimates in 1990–2019 was identified, with the decrease of –5.14% for Teoc, compensated by an increase of +4.78% for Mepo. As formerly, these changes have occurred mainly in the northwestern regions of Portugal (Figures 2a and 2d). The ombrotypes changed from seven to eight types (Figures 2b and 2e), with a new ombrotype, Sas, within the semi-arid ombrothermic horizons, corresponding to +0.74% of the territory in 1990–2019. The general decrease of –12.17% in the percentage of the territory of humid and hyper-humid regions (Sui, Hui, Hus and Hhi), in detriment of an increase of +24.81% of semi-arid and arid for 1990–2019, is particularly striking.
A loss of 7.12% in the percentage of the territory associated with all temperate thermotypic horizons was found along with changes within the mediterranean thermotypic horizons. There was a major increase in the thermomediterranean horizons of +18.9%. For the mesomediterranean horizons, a decrease of –8.10% for Mmei, an increase of +4.74% for Mmes, followed by a loss of –8.9% in supramediterranean thermotypic horizons were identified in 1990–2019. Overall, in the southern half of the country (Figures 4c and 4f), a gain of thermomediterranean horizons, associated with more arid/dry conditions, was observed. On the other hand, the loss of both Mediterranean and temperate thermotypic horizons, with milder conditions, was registered in the northwesternmost regions. Climate shifts were observed in the major divisions of the WBCS classification are in clear accordance with the study of Andrade and Contente (2020b) for the IP.

The outcomes showed changes in WBCS that have direct implications in the regional exposure to bioclimatic shifts, measured by BSEI. Braga district (in the northwest) was the most exposed (BSEI=3), followed by Viana do Castelo, Vila Real, Porto, also in the north, Viseu and Guarda in the center; and Évora in the south (BSEI=2). For grapevines, the results highlight the growth in their land cover areas in southern regions that are becoming dryer. Furthermore, the vineyard area is increasing in the northwest, in regions that present higher values of BSEI, hence more exposed to recent past bioclimatic shifts. This may significantly affect the regional terroirs, grape berry attributes, and wine typicity and style.
Overall, viticulture can be particularly challenged under future climate change scenarios, as suggested by Fraga et al. (2018) for viticulture in Portugal. As a result, better planning of the distribution of this key crop in Portugal should be envisioned, avoiding the increasing dependence on irrigation, which will eventually disrupt local and regional surface and underground water resources (Oliveira et al., 2019).

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