

## Article

# Are land use options in viticulture and oliviculture in agreement with bioclimatic shifts in Portugal?

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**Abstract:** Land and climate are strongly connected through multiple interface processes and climate change may lead to significant changes in land use. In this study, high-resolution observational gridded datasets are used to assess modifications in the Köppen-Geiger and Worldwide Bioclimatic (WBCS) Classification Systems, from 1950–1979 to 1990–2019 in Portugal. A compound Bioclimatic-Shift Exposure Index (BSEI) is also defined to identify the most exposed regions to recent climatic changes. The temporal evolution of land cover with vineyards and olive groves between 1990 and 2018, as well as correlations with areas with bioclimatic shifts, are analyzed. Results show an increase (decrease) of CSa Warm Mediterranean climate with hot summer (CSb, warm summer) of 18.1% (–17.8%). The WBCS Temperate areas also reveal a decrease of –5.11%. Arid and semi-arid ombrotypes areas increased, conversely to humid to sub-humid ombrotypes. Thermotypic horizons depict a shift towards warmer classes. BSEI highlights the most significant shifts in northwestern Portugal. Vineyards have been displaced towards regions that are either the coolest/humid, in the northwest, or the warmest/driest, in the south. For oliviculture, the general trend for a relative shift towards cool/humid areas suggests an attempt of the sector to adapt, despite the cover area growth in the south. As vineyards and olive groves 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.

**Keywords:** Köppen-Geiger climate classification; Worldwide Bioclimatic Classification System (WBCS); Bioclimates; Thermotypes; Ombrotypes; Vineyards; Olive groves; Portugal

## 1. Introduction

Land provides 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, also providing freshwater, and fostering biodiversity in the several intricate ecosystems [1]. Land use also plays a relevant role in the climatic system, being closely intertwined [2]. 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 [3,4]. Global population growth has implications for global food consumption, raw materials, and energy. An expansion of areas under agricultural and forestry systems [5,6] is, therefore, required to warrant food security. However, land-use intensification can decisively contribute to land/soil degradation and, henceforth, potentiates desertification [7,8].

Climate change has already deeply impacted biodiversity, ecosystems, and agroforestry systems [9–11]. Global warming and changes in the precipitation patterns are fostering an increase in arid/dry regions, and ultimately the expansion of desertic areas. Climate

change has increased the frequency, intensity, and duration of extreme events, such as droughts and heatwaves, namely in the Mediterranean region [12–15]. Changes in precipitation spatial patterns and temporal regimes not only affect the water content in reservoirs but also soil water availability [16,17]. These modifications in the regional climatic features are reflected on different time scales, from the annual-mean conditions to seasonality, daily cycle, and variability [18], which in turn affect crop-relevant bioclimatic conditions, such as growing season length, thermal forcing, chill accumulation or water availability for irrigation [19–21].

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 [22], but also for the Worldwide Bioclimatic Classification System (WBCS) [23,24]. Recent studies projected changes for the Iberian Peninsula (IP) not only for the Köppen-Geiger climatic classification [25] but also for the major divisions of the WBCS, mainly for the IP southernmost regions [11]. Since 1986, the IP has experienced an acceleration of land use for agriculture and forestry, promoted by the integration of these countries into the European Union [26]. The European Union's reform of the agriculture policies, under the Common Agricultural Policy, CAP, was a key factor for the observed changes, also observed in agricultural practices and cultivated species. Overall, these factors (climate and policies) jointly exacerbated land degradation, which is already particularly apparent in coastal areas, drylands, river deltas, riverine estuaries, permafrost, amongst others. Therefore, sustainable land management [27] is urgent to balance these projected changes, while maintaining crop yields, animal growth rates, water management, soil health, and land conditions [28].

The main goal of this research aims to answer the question: 'Are land use options in viticulture and oliviculture in agreement with ongoing bioclimatic shifts in Portugal?'.

The Portuguese viticultural sector is of major socioeconomic relevance, owing to the relatively high generated economic income and the important share of national exports [29], currently being Portugal the 10<sup>th</sup> wine exporter and the 11<sup>th</sup> wine producer [30]. Mainland Portugal has a total of 12 Wine Regions (WR), with a fluctuation of vineyard land cover from 271,507 ha in 1989 to 189,668 ha on 31/07/2020 [31] (Figure S1; Table S3). With an opposite trend, wine production increased from about 5.8 Mhl in 2009/10 to about 6.5 Mhl in 2019/20 [32] (Figure S2). Different Denominations of Origin (DO) can also be found within each WR (Figure S1).

On the other hand, the production of olive oil is also highly relevant to the Portuguese economy. Although Spain is the world's leading producer, Portugal, with a production of about 100,000 tons, currently holds the 7<sup>th</sup> position in the world production ranking, along with Turkey (183,000 tons), Tunisia (120,000 tons), and Morocco (200,000 tons) [33]. These rankings in both viticulture and oliviculture are particularly noteworthy taking into account the relatively small size of the country and are thereby key factors for its socioeconomic development.

To answer the aforementioned question, the Köppen-Geiger climatic classification and the WBCS were applied in the first step, while a comparison between two 30-year periods, namely 1950–1979 and 1990–2019, was carried out to relate recent past climatic shifts with land-use changes. From the WBCS, which encompasses 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 and olive groves for 1990, 2018, and between 1990–2018 are presented. Subsequently, correlations between ombrotypes and thermotypes were calculated for 1990, 1995, 2007, 2010, 2015, and 2018.

## 2. Materials and Methods

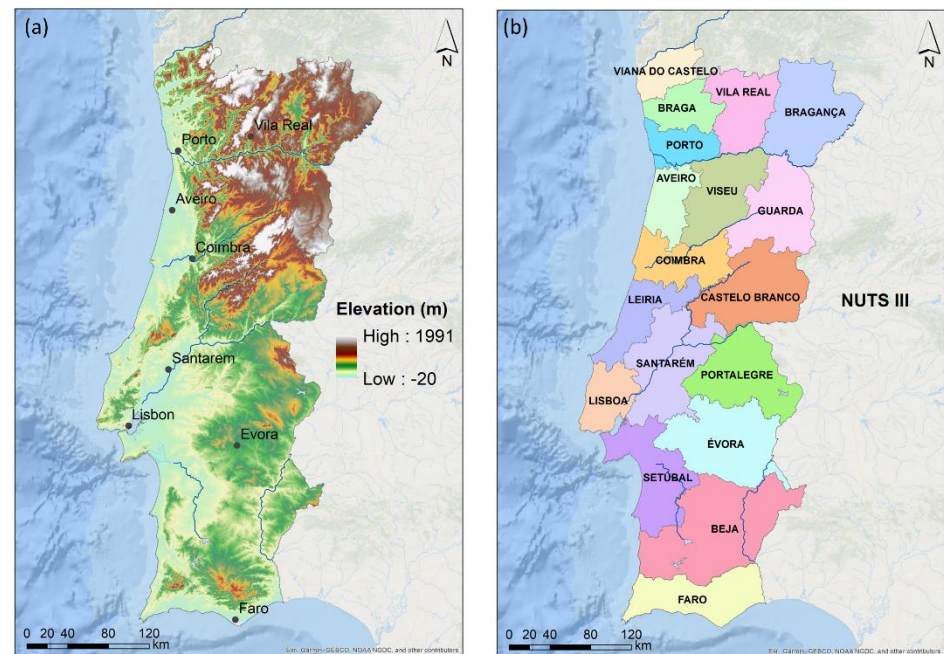
### 2.1 Data and study area

In this study, four high-resolution gridded observational datasets were used between 1950 and 2019. The methodology for the development of this dataset is described by

Fonseca and Santos [34]. The daily precipitation totals ( $P$ , in mm), maximum ( $TX$ , in  $^{\circ}C$ ), mean ( $TG$ , in  $^{\circ}C$ ), and minimum ( $TN$ , in  $^{\circ}C$ ) temperatures, are defined on a  $0.01^{\circ}$  regular grid. Two 30-year periods were analyzed, i.e., 1950–1979 and 1990–2019, aiming at finding climatic shifts already in progress in mainland Portugal.

The study area is within the geographical sector:  $36.95^{\circ} N - 42.16^{\circ} N$  and  $9.48^{\circ} W - 6.17^{\circ} W$  (Figure 1). However, 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 [35]. The area of interest also includes 18 districts 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/> accessed on 30 June 2021 [36], for the years 1990, 1995, 2007, 2010, 2015, and 2018. For this study, only the spatial representation of monocultures was taken into consideration (vineyards or olive groves separately). The level that presents both vineyards and olive groves land use was disregarded to avoid misleading conclusions. However, the total area evolution for both cultures and the related total amount of production are subsequently presented in tables and graphics between 1989 and 2020 (when available).



**Figure 1.** Mainland Portugal (a) elevation (in m) and (b) the related 18 districts.

## 2.2. Köppen's climate classification

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 our study, C is used for temperate climates in the mid-latitudes. The second letter identifies the seasonal precipitation type: S for steppe, W desert, while f indicates 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. [37] in Tables S1 and S2, whereas the nomenclature (Table S1) and color scheme follow Andrade and Contente [25]. 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 [25].

### 2.3. Worldwide bioclimatic classification system (WBCS)

The WBCS includes four major divisions, according to Rivas-Martínez et al. [23,24]. The first division corresponds to the macrobioclimate, which is subsequently split into the other three: bioclimates (Table 1), ombrotypes (Table 2), and thermotypes (Table 3). 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. [23,24], while a summary of the main equations can be found in Andrade and Contente [11].

**Table 1.** Bioclimatic classification for Mediterranean and Temperate macrobioclimates, according to Rivas-Martínez et al. [23].

Bioclimates	Abbr.	CI	OI
1. Mediterranean pluviseasonal oceanic	<b>Mepo</b>	$\leq 21$	$> 2.0$
2. Mediterranean pluviseasonal continental	<b>Mepc</b>	$> 21$	$> 2.0$
3. Mediterranean xeric oceanic	<b>Mexo</b>	$\leq 21$	$1.0-2.0$
4. Mediterranean xeric continental	<b>Mexc</b>	$> 21$	$1.0-2.0$
5. Mediterranean desertic oceanic	<b>Medo</b>	$\leq 21$	$0.2-1.0$
6. Mediterranean desertic continental	<b>Medc</b>	$> 21$	$0.2-1.0$
7. Mediterranean hyperdesertic oceanic	<b>Meho</b>	$\leq 21$	$< 0.2$
8. Mediterranean hyperdesertic continental	<b>Mehc</b>	$> 21$	$< 0.2$
9. Temperate hyperoceanic	<b>Teho</b>	$\leq 11$	$> 3.6$
10. Temperate oceanic	<b>Teoc</b>	$11-21$	$> 3.6$
11. Temperate continental	<b>Teco</b>	$> 21$	$> 3.6$
12. Temperate xeric	<b>Texe</b>	$\geq 4$	$\leq 3.6$

<sup>1</sup> In this Table, CI is the continentality index and OI is the ombrothermic index.

**Table 2.** Ombrothermic horizons, according to Rivas-Martínez et al. [23].

Ombrothermic horizons	Abbr.	OI
1. Lower ultrahyperarid	<b>Uhai</b>	$0.0-0.1$
2. Upper ultrahyperarid	<b>Uhas</b>	$0.1-0.2$
3. Lower hyperarid	<b>Hai</b>	$0.2-0.3$
4. Upper hyperarid	<b>Has</b>	$0.3-0.4$
5. Lower arid	<b>Ari</b>	$0.4-0.7$
6. Upper arid	<b>Ars</b>	$0.7-1.0$
7. Lower semiarid	<b>Sai</b>	$1.0-1.5$
8. Upper semiarid	<b>Sas</b>	$1.5-2.0$
9. Lower dry	<b>Sei</b>	$2.0-2.8$
10. Upper dry	<b>Ses</b>	$2.8-3.6$
11. Lower subhumid	<b>Sui</b>	$3.6-4.8$

12. Upper subhumid	<b>Sus</b>	4.8–6.0
13. Lower humid	<b>Hui</b>	6.0–9.0
14. Upper humid	<b>Hus</b>	9.0–12.0
15. Lower hyperhumid	<b>Hhi</b>	12.0–18.0
16. Upper hyperhumid	<b>Hhs</b>	18.0–24.0
17. Ultrahyperhumid	<b>Uhu</b>	>24.0

<sup>2</sup> In this Table, OI is the ombrothermic index.

**Table 3.** Thermotypic horizons, to Mediterranean and Temperate macrobioclimates. Tp is only used if CI ≥21, or TI, TIc<120, according to Rivas-Martínez et al. [23].

Thermotypic horizons	Abbr.	TI, TIc	Tp
1. Lower inframediterranean	<b>Imei</b>	515–580	>2600
2. Upper inframediterranean	<b>Imes</b>	450–515	2400–2600
3. Lower thermomediterranean	<b>Tmei</b>	400–450	2250–2400
4. Upper thermomediterranean	<b>Tmes</b>	350–400	2100–2250
5. Lower mesomediterranean	<b>Mmei</b>	285–350	1800–2100
6. Upper mesomediterranean	<b>Mmes</b>	220–285	1500–1800
7. Lower supramediterranean	<b>Smei</b>	150–220	1200–1500
8. Upper supramediterranean	<b>Smes</b>	120–150	900–1200
9. Lower oromediterranean	<b>Omei</b>	–	675–900
10. Upper oromediterranean	<b>Omes</b>	–	450–675
11. Lower crioromediterranean	<b>Cmei</b>	–	100–450
12. Upper crioromediterranean	<b>Cmes</b>	–	1–100
13. Pergelid	<b>Gme</b>	–	0
14. Infratemperate	<b>Ite</b>	>410	>2351
15. Lower thermotemperate	<b>Ttei</b>	350–410	2176–2350
16. Upper thermotemperate	<b>Ttes</b>	290–350	2000–2175
17. Lower mesotemperate	<b>Mtei</b>	240–290	1700–2000
18. Upper mesotemperate	<b>Mtes</b>	190–240	1400–1700
19. Lower supratemperate	<b>Stei</b>	120–190	1100–1400
20. Upper supratemperate	<b>Stes</b>	–	800–1100
21. Lower orotemperate	<b>Otei</b>	–	590–800
22. Upper orotemperate	<b>Otes</b>	–	380–590
23. Lower criorotemperate	<b>Ctei</b>	–	100–380
24. Upper criorotemperate	<b>Ctes</b>	–	1–100
25. Pergelid	<b>Gme</b>	–	0

<sup>3</sup> In this Table, CI is the continentality index, TI is the thermicity index and TIc is the compensated thermicity index, Tp is the annual positive temperature (tenths of °C), when the mean monthly temperature is higher than 0°C.

#### 2.5. The bioclimatic-shift exposure index (BSEI)

The compound bioclimatic-shift exposure index (BSEI) is 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. Therefore, BSEI will vary from 0, indicating regions not exposed to bioclimatic shifts, to 3, signaling regions highly exposed to bioclimatic shifts (changes in the three classifications simultaneously: bioclimatic, ombrotype, and thermotype) (Table 4). Despite its very simple definition, BSEI is a useful tool to assess the degree of change in climatic conditions at a given location/region, i.e., the degree of exposure to climate change.

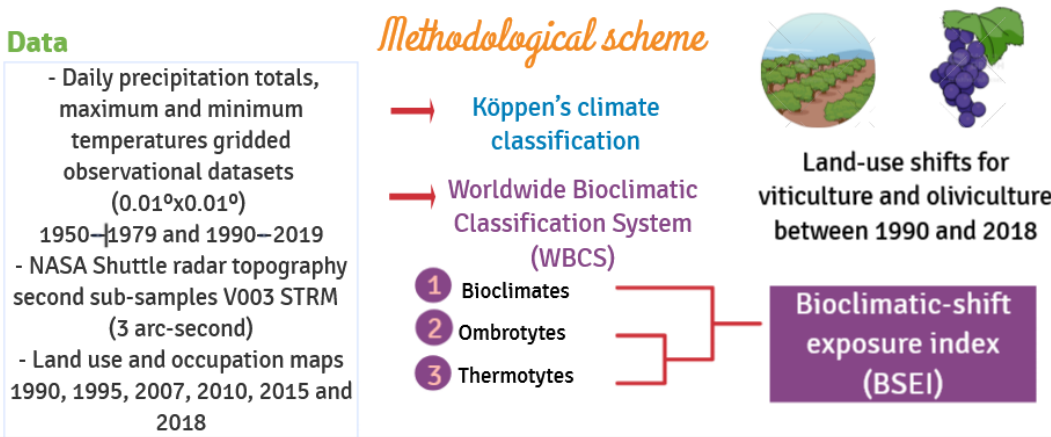
**Table 4.** Bioclimatic-shift expose index (BSEI) interpretation.

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

2.4. Statistical analysis

For the bioclimates, ombrotypes, and thermotypes, a comparison between a recent past period 1990–2019, and preceding past conditions 1950–1979 (baseline climate) was undertaken. Anomalies (% of change) were computed as the differences between the most recent period and the baseline climate. The statistically significant anomalies (S.S.) were assessed by the Mann-Whitney-Wilcoxon test (MWW), at a 5% significance level [38,39], using the 30-year mean values for each period and location of the study area. This non-parametric test assumes equal medians under the null hypothesis ( $H_0$ ), against the alternative hypothesis ( $H_a$ ) of different medians. Locations with different medians will be identified by a black pattern in all related figures.

For each Land Use and Occupation map, the areas of Vineyards and Olives groves were extracted to assess their spatial-temporal development. Further, the data was compared with the bioclimates, ombrotypes, and thermotypes of the recent period to analyze the shift of land use in both cultivars. The overall methodological schematics of this study can be depicted in Figure 2.



**Figure 2.** Methodological schematics of this study.

3. Results

3.1. Köppen's-Geiger climate classification and WBCS

The spatial representation of the Köppen-Geiger climate classification in mainland Portugal for the period 1950–1979 reveals three climate types (Figure 3a). Two within the CS 'Warm temperate/Mediterranean with dry summer' and one Cf 'Warm

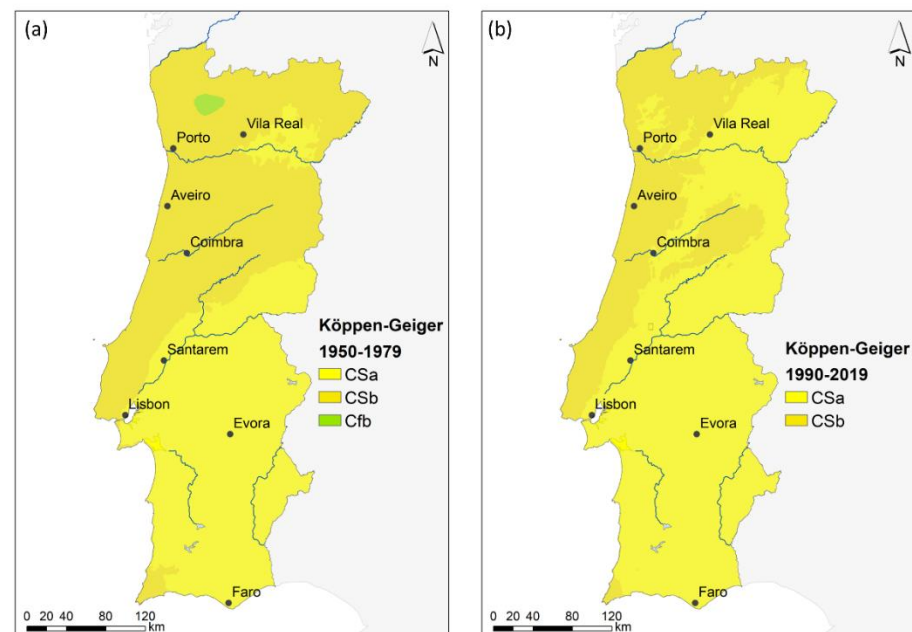
temperate/Mediterranean fully humid' (Table S1). The prominent climate was CSa (Warm temperate/Mediterranean with hot summer) in 53.9% of the territory, CSb (Warm temperate/Mediterranean with warm summer) in 45.8%, and only 0.03% for Cfb (Warm temperate/Mediterranean fully humid with hot summer) (Tables 5, S1 and S2). Besides a small area in the very southwest (Faro district, Figure 1b), the CSb type is mostly found in the northern half of the country, northwards of the Tagus River basin. Conversely, the CSa type is predominant in the southern half, and a small region between the Vila Real and Bragança districts (Figures 1a and 3a). The small area of Cfb climate is located in a mountainous region in the northwest (Figures 1b and 3a).

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 (Table 5). This later climate type is now depicted along the north-central western coast and in mountainous areas in the northern half of the country.

The changes depicted in the Köppen-Geiger climatic system are also translated for the WBCS classification in which only two macroclimates were found for the two time periods, the Mediterranean and the Temperate, which decreased from 1950–1979 to 1990–2019. This can be inferred by observing Figures 4a and 4d, where the bioclimates are derived from the macroclimates identified by the prefix M for the Mediterranean and T for the Temperate.

**Table 5.** Percentage of the territory (in %) for each Köppen-Geiger climate classification for mainland Portugal for 1950–1979 and 1990–2019.

Köppen-Geiger climate classification	1950–1979	1990–2019	% Change
CSa	53.90	72.00	↑ 18.10
CSb	45.80	28.00	↓ 17.80
Cfb	0.03	0.00	↓ 0.03

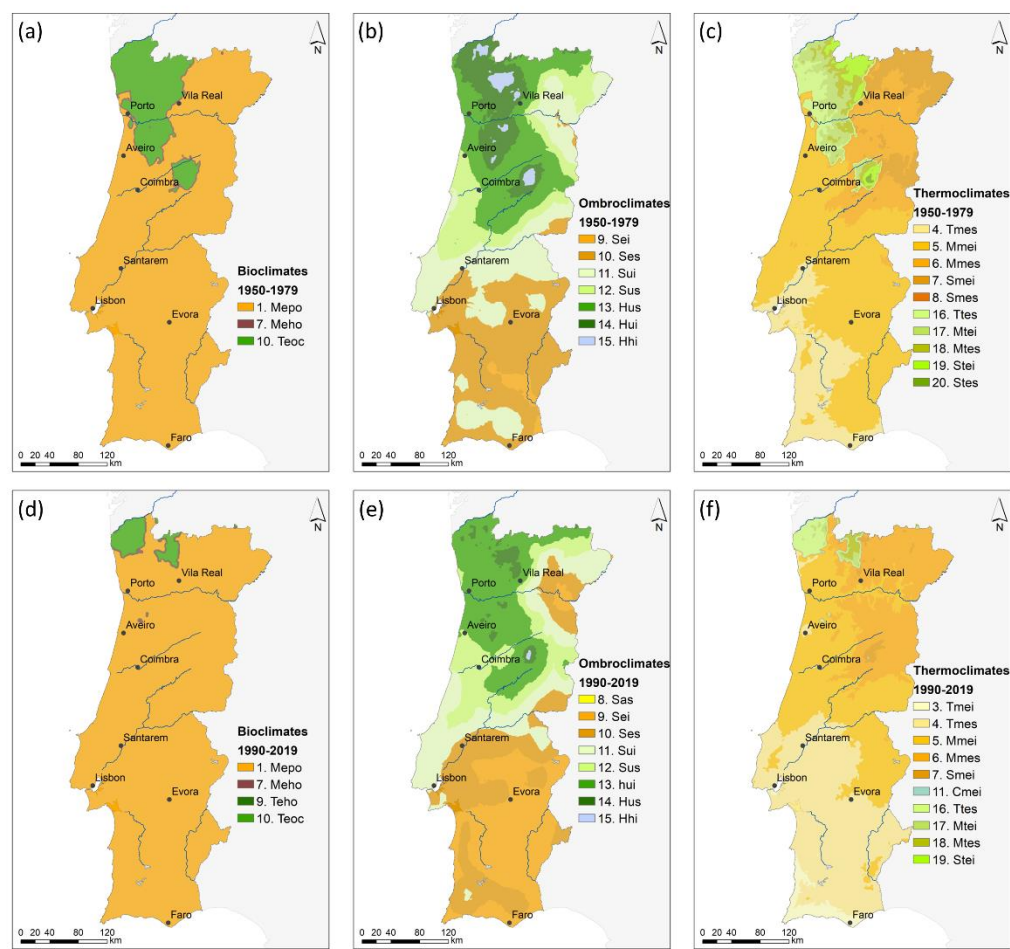


**Figure 3.** Köppen-Geiger climate classification for (a) 1950–1979 and (b) 1990–2019.

The 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% (Table 6). Nevertheless, the most striking 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 4a and 4d).

Climate change has also affected the ombrotypes. They changed from seven to eight types (Figure 4b and 4e), with the emergence of a new ombrotype, Sas, within the semi-arid ombrothermic horizons, and corresponding to 0.74% of the territory in 1990–2019 (Table 6). 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 exception was for Sus (upper subhumid), though with a marginal increase of only 1.02% in 1990–2019. Although the Ses (upper dry) ombroclimate area has decreased –13.66%, it is still worth noting the decrease in the percentage of the territory of humid and hyper-humid regions (Sui, Hui, Hus, and Hhi), with an overall total decrease of –12.17% in 1990–2019. These changes have occurred mainly in central (in the vicinity of Serra da Estrela mountainous region) and northwestern Portugal (Figures 4b and 4e).



**Figure 4.** Classification for (a) bioclimate (b) ombrotypes and (c) thermotypes between 1950–1979 and (d, e, f) the same as for (a, b, c) but between 1990–2019.

**Table 6.** Percentage of the territory (in %) for each bioclimate, ombrotype, and thermotype classification for mainland Portugal, for the periods 1950–1979 and 1990–2019.

Classification		1950–1979	1990–2019	% Change
Bioclimates	1. Mepo	91.40	96.18	↑ 4.78
	7. Meho	0.80	1.13	↑ 0.33



<b>Ombrotypes</b>	9. Teho	0.00	0.03	↑ 0.03
	10. Teoc	7.80	2.66	↓ 5.14
	8. Sas	0.00	0.74	↑ 0.74
	9. Sei	3.63	27.70	↑ 24.07
	10. Ses	38.13	24.47	↓ 13.66
	11. Sui	23.98	18.54	↓ 5.44
	12. Sus	10.96	11.98	↑ 1.02
	13. Hui	15.23	15.16	↓ 0.07
	14. Hus	7.07	1.37	↓ 5.70
	15. Hhi	1.00	0.04	↓ 0.96
	3. Tmei	0.00	10.74	↑ 10.74
	4. Tmes	20.73	28.89	↑ 8.16
	5. Mmei	45.35	37.25	↓ 8.10
	6. Mmes	14.32	19.06	↑ 4.74
	7. Smei	9.53	0.91	↓ 8.62
	8. Smes	0.28	0.00	↓ 0.28
	11. Cmei	0.00	0.48	↑ 0.48
	16. Ttes	2.21	1.30	↓ 0.91
	17. Mtei	3.17	0.40	↓ 2.77
	18. Mtes	1.95	0.80	↓ 1.15
	19. Stei	2.31	0.17	↓ 2.14
	20. Stes	0.15	0.00	↓ 0.15

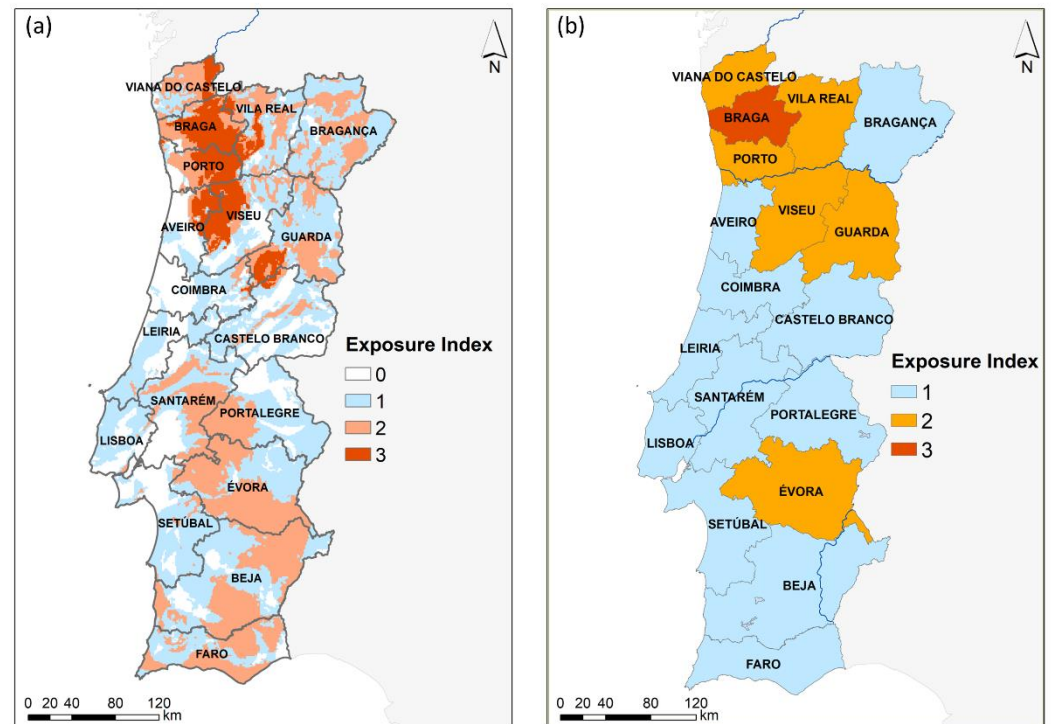
Regarding the thermotypes, the findings are consistent with the previous WBCS types. A loss of the territory with temperate thermotypic horizons is verified, e.g., within the thermotemperate (Ttes,  $-0.91\%$ ), mesotemperate (Mtei and Mtes,  $-2.77$  and  $-1.15\%$ , respectively), and supratemperate (Stei  $-2.14\%$  and Stes non-existent in 1990–2019) (Table 6). Nonetheless, within the Mediterranean thermotypic horizons, changes were 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. Lastly, a decrease in the supramediterranean thermotypic horizons are found (Smei and Smes,  $-8.62$  and  $-0.28\%$ , respectively), as well as the arising of a small region of Cmei ( $+0.48\%$ ) in 1990–2019. The gain of Tmei and Tmes areas (associated with more arid/dry conditions) have occurred mainly in the southern half of the country (Figures 4c and 4f), whilst the loss of temperate thermotypic horizons was registered in the northwesternmost regions.

### 3.2. The bioclimatic-shift expose index (BSEI)

The BSEI captures the accumulated changes that have occurred between 1990–2019 and 1950–1979 between bioclimates, ombrotypes, and thermotypes. Thus, it captures the most exposed regions to the bioclimatic shifts analyzed in the previous sub-section. Regions with no changes have a zero score, while regions with changes in the three WBCS indicators have a score of three. Figure 5a depicts 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 regions (Figure 4). Large areas with BSEI=2 (moderately exposed) can still be found in the aforementioned districts, as well as in the north-east (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 5a). In these

latter regions, however, changes are mostly due to shifts in the ombrotypes and thermotypes (Figures 4b, 4c, 4e, and 4f).

For a better understanding of the extent of exposure to the bioclimatic shifts, the areal mean values for each district were computed. The Braga district is the most exposed (BSEI=3), followed by Viana do Castelo, Vila Real, Porto, Viseu, Guarda, and Évora districts, all of them with BSEI=2 (Figure 5b). All the remaining districts have BSEI=1 (weakly exposed).



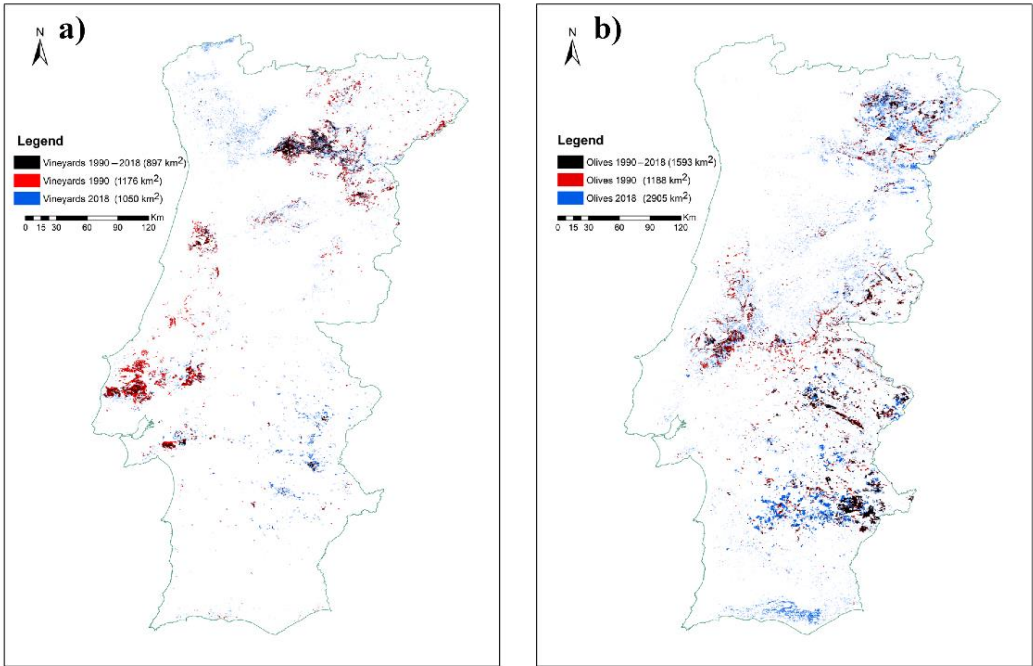
**Figure 5.** (a) Bioclimatic-shift exposure index (BSEI) for mainland Portugal and (b) related areal mean values for each district (Note: BSEI attained between 1990–2019 and 1950–1979).

### 3.3. Land-use changes for viticulture and oliviculture from 1990 to 2018

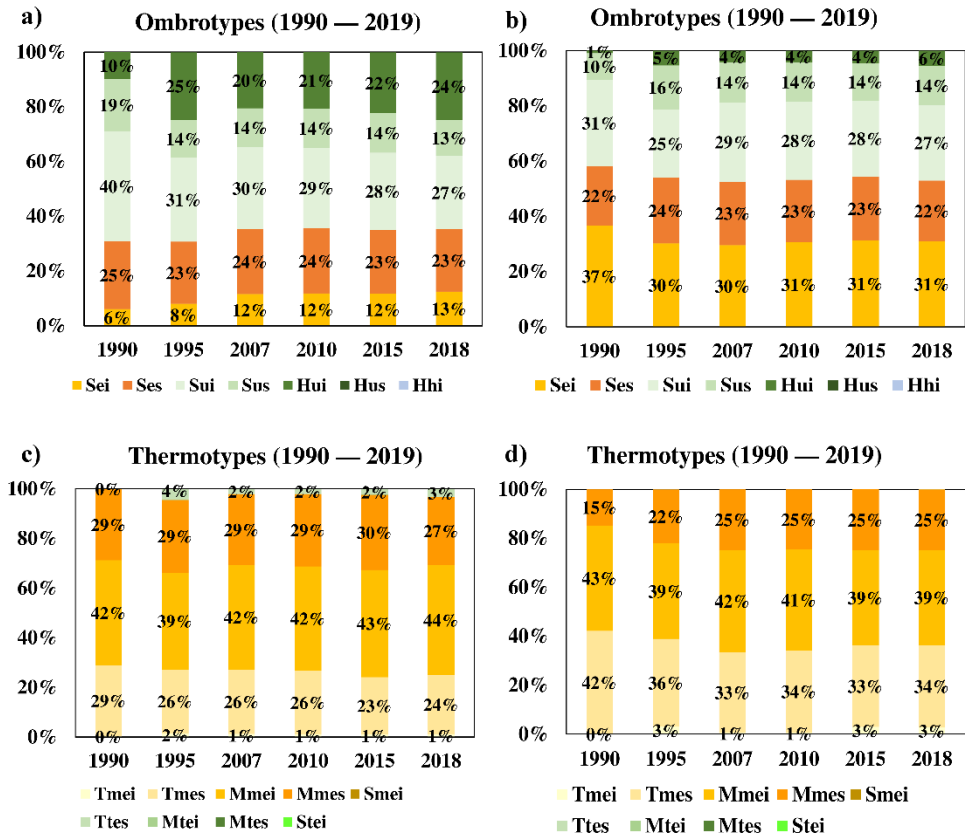
The vineyard cover area in Portugal has decreased from 1990 to 2018 (only land use levels for monocultures were considered). The decrease is approximately 6% (126 km<sup>2</sup>) (Figure 6a), mainly in the Lisboa district. New vineyard cover areas are, however, observed in Alentejo (mostly Évora district) and in northwestern Portugal, which are in both cases areas with higher BSEI values. For the olive groves, the area has significantly increased by approximately 62% (1717 km<sup>2</sup>) (Figure 6b), mainly in Faro, Beja, Vila Real, and Bragança districts, among which only Vila Real shows a higher BSEI (2, moderate exposure).

Concerning the evolution of the growing bioclimatic conditions in the vineyard cover area from 1990 to 2018 (Figure 7a), there is a shift towards new regions that are both humid (Hui), in northwestern Portugal (Vinho Verde WR), and dry (Sei), in southern Portugal (Alentejo WR) (Figure S1). 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 7c).

For the temporal evolution in land use for olive groves, there is a general trend for a shift towards more humid (an increase of cover area in classes Hui and Hus) and cooler areas (increase in Mmes and decreases in the warmer classes of Mmei and Tmes).



**Figure 6.** Spatial representation and related area (in km<sup>2</sup>) of (a) vineyards and (b) olive groves in Portugal for the period between 1990 and 2018. Areas maintained throughout the period in black (persistent areas), only for 1990 in red (discontinued areas), and 2018 in blue (emerging areas).



**Figure 7.** Percentage area regarding each Land Use and Occupation map for vineyards (a) and (c) and olive groves (b) and (d) according to each specific climatic classification: (a, b) ombrotype and (c, d) thermotype for the recent past period (1990–2019).

#### 4. Discussion

The present climatic characterization aimed at identifying the regions in mainland Portugal that have endured the most significant bioclimatic shifts from 1950–1979 to 1990–2019. Most of the areas or districts that experienced more accentuated alterations 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 and olive grove areas was analyzed to assess to what extent have these crops been expanded to more susceptible zones to bioclimatic shifts.

The evolution in the vineyard cover area from 1990 to 2018 (Figure 7a) shows a bidirectional displacement, towards the regions with more extreme bioclimates in the territory. The vineyard area has been increasing in the relatively cool and humid regions of northwestern Portugal (Vinho Verde WR), as well as in the warm and dry regions of southern Portugal (Alentejo WR) (Figure S1). In effect, from 2018 to 2020, vineyard areas have increased in the north, e.g., in Minho 2267 ha, in Douro/Porto 3212 ha, but also southern Portugal, in Alentejo VR 513 ha (Table S3). These regions are, nevertheless, located in areas for which the BSEI indicates stronger bioclimatic shifts during the last decades (Minho WR, Douro/Porto WR, and Alentejo WR). Even though the increase in the vineyard area in regions with cooler and more humid climates can be considered a climate-smart adaptation strategy, thus enhancing the climate resilience of the sector, the pronounced bioclimatic shifts observed in these regions may considerably affect the regional terroirs and, as a result, the wine typicity and style [40]. In addition, the emergence of vast areas with irrigated vineyards under the typically warm and dry conditions of southern Portugal will threaten the already limited water resources [41], thereby requiring more efficient water management and water-saving agricultural practices. The lack of water availability may indeed challenge the future sustainability of the sector in this region. This will be particularly relevant under the projected future warmer and drier climates, which will exacerbate the current warm and dry conditions, becoming irrigation even more vital [42].

As for viticulture, the olive grove land cover in Portugal has been changing between 1990 and 2018 (Figure S3). These fluctuations have also impacted olive yield, which was approximately 700 000 t in 2019 (Figure S4). The recent area expansion occurred mainly in the Faro, Beja, Vila Real, and Bragança districts, the last two showing relatively high BSEI (Figure 6b). Regions in the north are indeed gradually experiencing climatic conditions that were more typical of southern Portugal a few decades ago and are, thereby, becoming more suitable for oliviculture. Although the area of olive groves has undergone a significant increase in southern Portugal, most of them irrigated, the progressively higher relative coverage in cooler climates, still predominantly rainfed orchards, may already suggest higher awareness and a more or less conscious attempt of the sector to adapt to the ongoing climate change.

#### 5. Conclusions

The present study assessed the climate change trends that have already influenced the Köppen-Geiger climate classification and the WBCS between 1950 and 2019 in mainland Portugal. For this purpose, a comparison between two 30-year periods, i.e., 1950–1979 and 1990–2019, was undertaken for these two climate classifications. It is worth mentioning that these calculations were carried out using high-resolution gridded datasets, with approximately 1 km grid resolution, thus providing accurate and detailed information throughout the country. To our knowledge, this is the first study analyzing these climate classifications in Portugal at such a high resolution.

The spatial representation of the Köppen-Geiger climate classification revealed three climate types (Figure 3a) in 1950–1979. The leading climate type was Csa, in 53.9% of the territory, CSb in 45.8%, and a very small percentage of 0.03% for Cfb. The Csa type was predominant in the southern half of Portugal and a narrow region in the south of the Vila Real and Bragança districts (Figures 1a and 3a). 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 corresponding decrease of –17.8% in CSb, associated with warm summers, and therefore a milder climate (Table 5). These findings are in general agreement with Andrade and Contente [25].

The results also hint 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 impacted 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, counterbalanced by an increase of +4.78% for Mepo. As previously, these changes have occurred mainly in the northwestern regions of Portugal (Figures 4a and 4d). The ombrotypes changed from seven to eight types (Figures 4b and 4e), with a new ombrotype, Sas, within the semi-arid ombrothermic horizons, corresponding to +0.74% of the territory in 1990–2019 (Table 6). The overall 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 noteworthy.

For the thermotypes, a loss of 7.12% in the percentage of the territory associated with all temperate thermotypic horizons was found (Table 6). Within the Mediterranean thermotypic horizons, changes were also found. 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 supra-mediterranean 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 [11] for the IP. The changes in WBCS have direct implications in the regional exposure to bioclimatic shifts, measured by BSEI. At the district level, the Braga district (in the northwest) is 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 both grapevines and olive trees, which are major crops in Portugal, 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. Conversely, the relative share of southern Portugal to the total olive grove area has been decreasing, which may already suggest an adaptation strategy of the sector, by progressively relocating olive orchards in northern regions that are currently experiencing similar conditions to those found in southern regions a few decades ago.

Both viticulture and oliviculture may be particularly challenged under future climate change scenarios, as suggested by Fraga et al. [42] for viticulture in Portugal, or by Fraga et al. [43] and Fraga et al. [44] for olive yields in Portugal and the Mediterranean region, respectively. As a result, better planning of the distribution of these key crops in Portugal should be envisioned, avoiding the increasing dependence on irrigation, which will eventually disrupt local and regional surface and underground water resources [45]. New agricultural practices and options are urging to enhance the water use efficiency of crops [46]. New water-saving and go-green policies and strategies will be particularly relevant under the projected future warmer and drier climates in Portugal [47,40]. On the other hand, warranting the future environmental and socio-economic sustainability of these sectors is of foremost relevance for the national economy and food security, thereby deserving further research. As similar problems can be found in many other regions with Mediterranean-type climates, the main outcomes from this study can be easily extrapolated to other countries worldwide.



**Author Contributions:** For this research, the author's contributions were: Conceptualization, Andrade C and Santos JA; methodology, Andrade C and Santos JA; software, Andrade C and Fonseca A; validation, Andrade C and Santos JA; formal analysis, Andrade C, Fonseca A, Santos JA; investigation, Andrade C, Fonseca A, Santos JA; resources, Andrade C and Fonseca A; data curation, Andrade C and Fonseca A; writing—Andrade C; writing—Andrade C and Santos JA; visualization, Andrade C and Fonseca A; supervision, Andrade C and Santos JA; project administration, Santos JA; funding acquisition, Santos JA. All authors have read and agreed to the published version of the manuscript."

**Funding:** This research was funded by National Funds by FCT – Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020. This study was funded by the European Commission-funded project "Climate change impact mitigation for European viticulture: knowledge transfer for an integrated approach – Clim4Vitis" [grant 810176].

**Institutional Review Board Statement:** not applicable.

**Informed Consent Statement:** not applicable.

**Data Availability Statement:** not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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