Supplementary material

Article

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

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Abstract: The climatic system is intertwined with land use and land cover. Therefore, climate extremes are stress factors contributing to land degradation and, eventually, to desertification. In this study, high-resolution observational gridded datasets are used to assess modifications in the Köppen-Geiger and the Worldwide Bioclimatic (WBCS) Classification Systems, between 1950–1979 and 1990–2019 in mainland Portugal. From the WBCS, a compound Bioclimatic-Shift Exposure Index (BSEI) is attained to identify the most exposed regions to changing climates. The temporal evolution of land use/cover for vineyards and olive groves between 1990 and 2018, as well as correlations with areas with bioclimatic shifts, are analyzed. The results show an increase (decrease) of the area of CSa Warm Mediterranean climate with hot summer (CSb, warm summer) of 18.1% (–17.8%) for 1990–2019 when compared to 1950–1979, with CSa extending northwards. The WBCS Temperate areas also shift northwards, with a decrease of –5.11%. The arid and semi-arid ombrotypes areas increased towards the north, to the detriment of the humid to sub-humid ombrotypes. Similar results were obtained for the thermotypic horizons. Overall, the BSEI showed significant changes in northwestern Portugal which are the most exposed to bioclimatic shifts. Vineyards have been displaced towards regions that are either the most cooler and humid, in the northwest (Vinho Verde wine region), or warmest and driest, in the south (Alentejo wine region). For oliviculture, the general trend for a shift towards cooler and more humid areas, suggest an attempt of the sector to adapt to the ongoing climate change, despite an areal growth in southernmost regions. As vineyards and olive groves in southern Portugal are commonly irrigated, instead of the rainfed conditions, thus, 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

Table S1. Criteria to calculate the Köppen-Geiger classification for the main climates and subsequent precipitation conditions for the first two letters. For the polar climates (E) no precipitation differentiations are given, only temperature conditions are defined, consequently, the polar climates (E) must be determined first, followed by the arid climates (B) and subsequent differentiation into the equatorial climates (A) and the warm temperate and snow climates (C) and (D), respectively [1].

Climate (Main group)	Description	Criterion
A – Tropical or Equatorial $T_{min} \geq +18$ °C	**Af** – Tropical rainforest, fully humid	$P_{min} \geq 60$ mm
	Am – Tropical monsoon	$P_a \geq 25(100-P_{min})$
	As – Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
	Aw – Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B – Dry or Arid $P_a < 10\ P^{th}$	**BW** – Desert	$P_a > 5\ P^{th}$
	BS – Semi-arid or steppe	$P_a \leq 5\ P^{th}$
C – Temperate or Warm temperate $-3°C<T_{min}<+18$ °C	**CS** – Warm temperate (or Mediterranean) with dry summer	$P_{smin}<P_{wmin}$, $P_{wmax}>3\ P_{smin}$ and $P_{smin}<40$ mm
	CW – Warm temperate (or Mediterranean) with dry winter	$P_{wmin}<P_{smin}$ and $P_{smax}>10\ P_{wmin}$
	Cf – Warm temperate (or Mediterranean) fully humid	neither CS nor CW
D – Continental or Cold $T_{min} \leq -3$ °C	**DS** – Continental with dry summer	$P_{smin}<P_{wmin}$, $P_{wmax}>3\ P_{smin}$ and $P_{smin}<40$ mm
	DW – Continental with dry winter	$P_{wmin}<P_{smin}$ and $P_{smax}>10\ P_{wmin}$
	Df – Continental, fully humid	neither DS nor DW
E – Polar $T_{max}<+10$ °C	**ET** – Tundra	$0\ °C \leq T_{max} < +10$ °C
	EF – Ice cap or frost	$T_{max} < 0$ °C

[1] In this Table, T_{max} is the monthly mean temperature of the warmest month (°C), T_{min} is the monthly mean temperature of the coldest month (°C), P_a is the accumulated annual precipitation (in mm), P_{min} is the precipitation of the driest month (in mm), P_{smin} and P_{smax} are the lowest and highest monthly precipitation values for the summer half-years (April to September) in mm, P_{wmin} and P_{wmax} are the lowest and highest monthly precipitation values for the winter half-year (October to March) in mm.

Table S2. Criteria for the third letter temperature classification (**h** and **k**) for dry climates (B) and (**a** to **d**) for the warm temperate (C) and continental (D) climates following the Köppen's climate classification [1].

Type description	Criterion
h – hot steppe or desert	$T_a \geq +18$ °C
k – Cold steppe or desert	$T_a < +18$ °C
a – Hot summer	$T_{max} \geq +22$ °C
b – Warm summer	Not **a** and at least $4T_{min} \geq +10$ °C
c – Cold summer and cold winter	Not **b** and $T_{min} > -38$ °C
d – Extremely continental	Like **c** but $T_{min} \leq -38$ °C

[2] In this Table, T_a is the annual mean temperature, T_{max} and T_{min} are the monthly mean temperatures of the warm and coldest months (°C), respectively. For **b** type warm summer, a threshold temperature value of +10 °C must occur for at least four months.

Table S3. Vineyard land cover evolution (in ha) over mainland Portugal, by Wine Region [2].

Wine Region	1989	01/09/2007	31/07/2010	31/07/2015	31/07/2018	31/07/2020
Minho	38 349	31 816	30 903	20 433	21 973	**24 240**
Trás-os-Montes / Douro e Porto	76 695	68 899	68 893	59 972	56 094	55 775
Trás-os-Montes	---	---	---	*17 788*	*13 539*	*11 613*
Douro e Porto	---	---	---	*42 184*	*42 556*	***44 162***
Beiras	56 637	57 321	56 242	53 100	46 401	42 821
Terras de Cister	---	---	---	---	*2 184*	***2 272***
Beira Atlântico	---	---	---	---	*14 630*	*13 314*
Terras da Beira	---	---	---	---	*15 110*	*13 914*
Terras do Dão	---	---	---	---	*14 476*	*13 321*
Tejo	28 124	19 518	18 082	13 589	11 944	12 751
Lisboa	46 046	25 198	24 527	20 359	17 989	19 639
Península de Setúbal	11 396	9 282	9 182	7 556	7 265	7 986
Alentejo	11 510	23 491	23 785	21 816	24 544	**25 057**
Algarve	2 750	2 063	1 985	1 858	1 352	1 400
Mainland Portugal totals (ha)	**271 507**	**237 588**	**233 597**	**198 683**	**187 562**	**189 668**

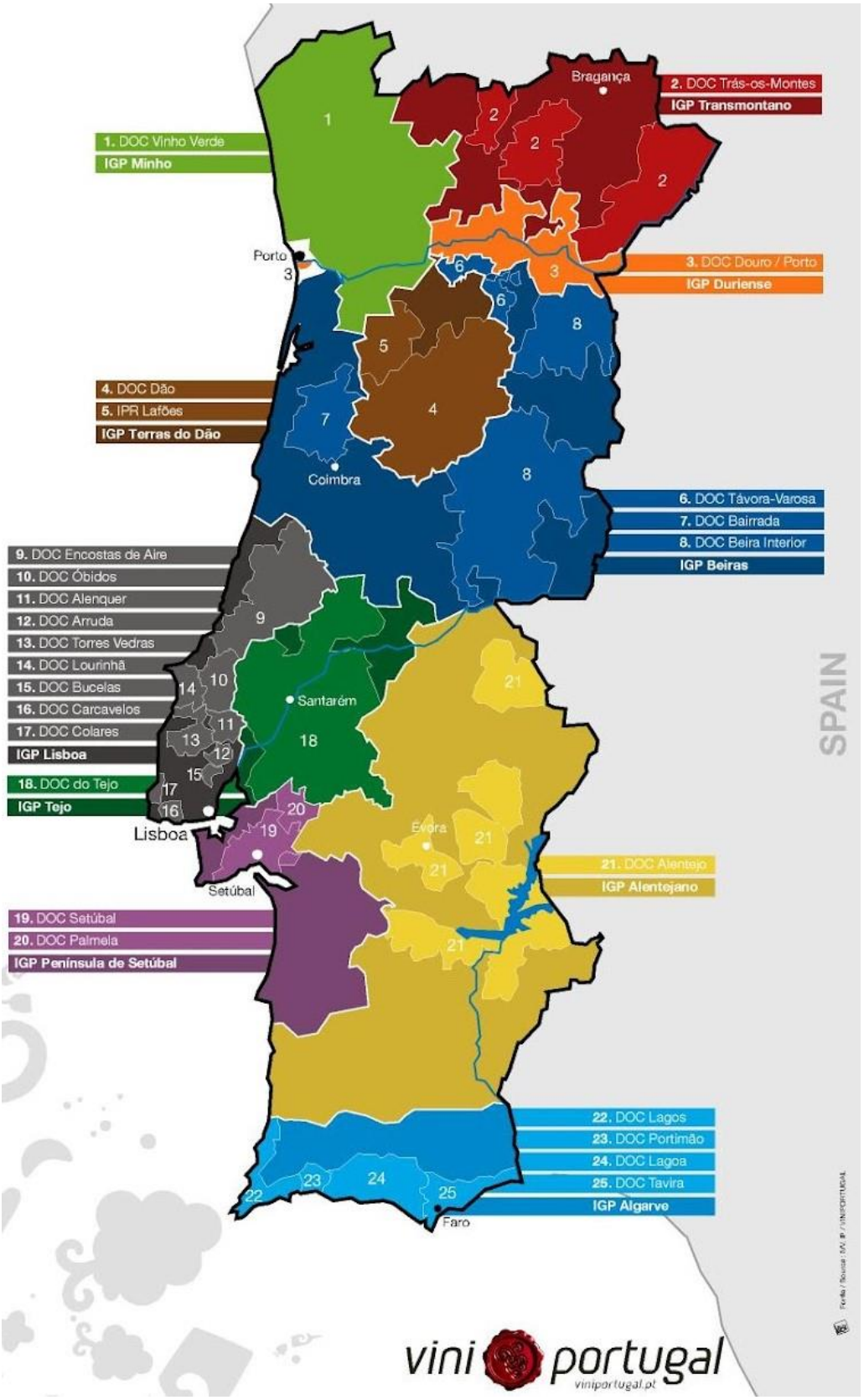
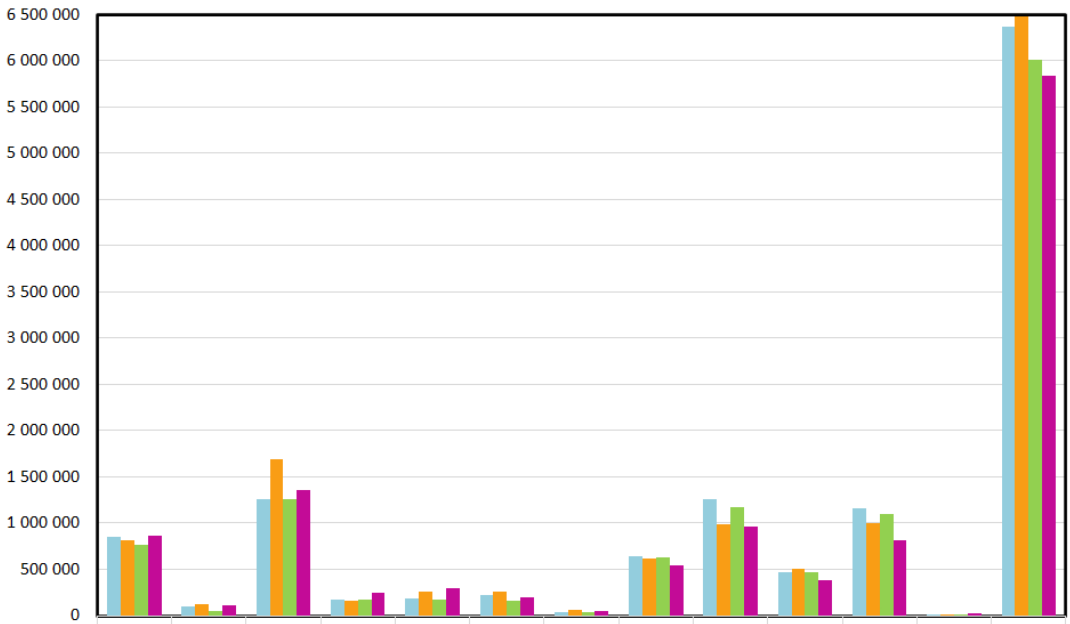


Figure S1. Viticulture regions (IGP or VR) in mainland Portugal with the associated Control origin denomination (DOC) (Map adapted from http://www.vinhoedelicias.com.br/2012/08/mapas-de-vinhos-portugal-geral-e-douro.html accessed on 09 July 2021, [3]).



	Minho	T. Montes	Douro	Beira Atlântico	Terras do Dão	Terras da Beira	Terras de Cister	Tejo	Lisboa	P. Setúbal	Alentejo	Algarve	Sub-total
2020/21	848 311	94 425	1 264 34	174 391	189 197	219 298	37 744	644 153	1 253 30	475 135	1 159 06	13 043	6 372 41
2019/20	816 396	118 014	1 692 18	159 063	257 481	255 658	59 417	615 736	987 009	503 579	996 290	13 926	6 474 75
2018/19	759 757	50 670	1 259 68	177 782	178 409	162 032	37 307	635 514	1 170 06	472 197	1 092 61	17 042	6 013 07
2009/10	866 985	110 614	1 351 94	246 705	297 483	192 084	47 872	544 935	962 323	379 371	810 338	23 650	5 834 31

Figure S2. Evolution of the total wine production (in hl) by viticulture region and subtotal for mainland Portugal for 2009, 2018/19, 2019/20, and 2020/21 (Data retrieved from [2]).

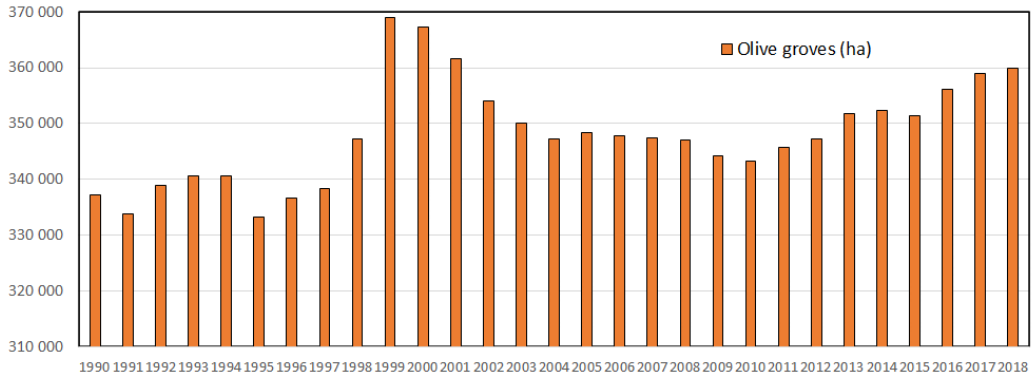


Figure S3. Evolution of the total olive grove areas (in ha) for mainland Portugal between 1990 and 2018 (Data retrieved from PORDATA - Ambiente de Consulta, accessed on [4]).

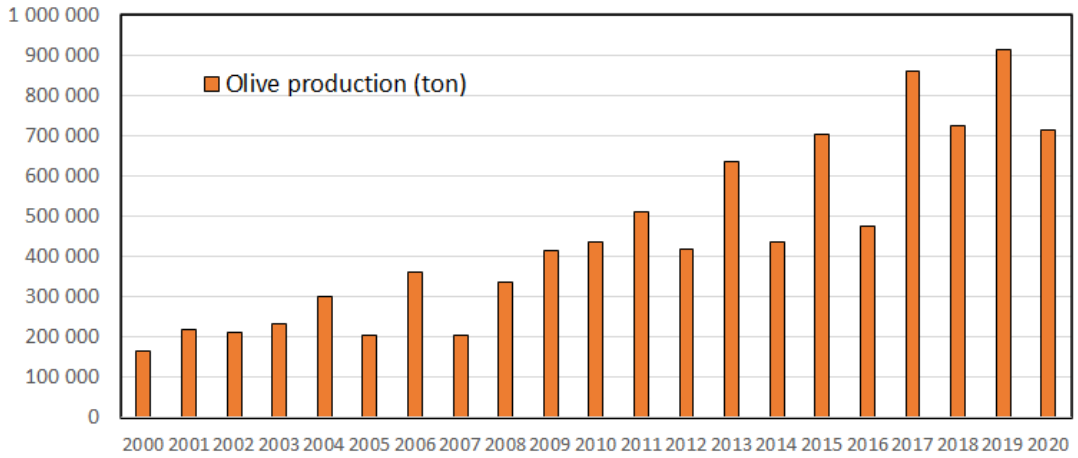


Figure S4. Evolution of the total olive production (in ton) for mainland Portugal between 2000 and 2020 (Data retrieved from PORDATA - Ambiente de Consulta, accessed on [4]).

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