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RESEARCH

Applications of bioclimatology to assess effects of climate change on viticultural suitability in the DO León (Spain)

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Abstract

Spain accounts for 13.1% of the world's vineyard area, and viticulture is crucial for the socioeconomic and cultural sectors. Vineyards are among the perennial crops that can suffer most negative impacts under climate change which can pose challenges to the sustainability of viticulture. Local and regional studies are needed to assess these impacts to help implement effective strategies in response to climate change. To this end, our approach involves integrating both conventional agroclimatic indices and those new bioclimatic indices that have proven to be essential for the characterization and demarcation of vineyards into species distribution models to assess areas suitable for viticulture under climate change projections. The proposed methodology was tested in a viticultural region located in northwestern Spain (DO León). An ensemble platform was used to build consensus models encompassing three general circulation models, two emission scenario pathways and two time horizons. Only the predictors that effectively characterize each grape variety were included in the models. The results revealed increases in the continentality index, compensated thermicity index, hydrothermic index of Branas, and temperature range during ripening in all the future scenarios analyzed in comparison to current conditions. Conversely, the values for the annual ombrothermic index and growing season precipitation may decrease in the future. The pattern of changes for 2070 will be more pronounced than for 2050. A significant loss of future habitat suitability was detected within the limits of the study area for the grape varieties analyzed. This negative impact could be counteracted to some degree with new and favorable areas for the cultivation of vineyards in territories located at the north of the DO limits. We suggest that our results could help policymakers to develop practices and strategies to conserve existing grape varieties and to implement efficient adaptation measures for mitigating or anticipating the effects of climate change on viticulture.

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1 Introduction

According to the State of the Vitiviniculture World Market report (OIV 2020), vineyards are present in more than 40 countries and cover an area of approximately 7.331 million ha worldwide. The international wine trade in 2020 was mainly dominated in terms of volume by the three European countries: Spain, Italy, and France, who together exported 54.6 mhl, accounting for 52% of the world market (OIV 2020). This indicates the importance of the vitivinicultural sector for the environment, society, and the economy (Cardell et al. 2019a).

Spain is home to 13.1% of the world's vineyards. Most viticultural areas are coordinated by denominations of origin (DO). The notion of DO is synonymous with singularity and quality and denotes a product originating in a specific location, region, or country, that is essentially or exclusively the result of a particular geographic environment, and whose production stages take place exclusively within the designated geographical area (Spanish Conference of Councils regulators viticultural, CECRV). The DO sets the requirements for the preparation and production of its wines, blending natural elements such as climate and soil with expertise to ensure that they achieve the utmost quality linked to their origin. Spain is home to 97 designations of origin (DO). The prevailing European legislation governing wine products (EU 1308/2013) establishes a common framework for agricultural market organization and outlines the regulations for wine products safeguarded by a quality mark.

Undoubtedly, climate is a key factor contributing to the success of agricultural systems (Jones et al. 2012). The climate is crucial not only for the selection of appropriate zones for viticulture but also for the quality and quantity of the wine produced (Ruml et al. 2016; Irimia et al. 2018; Sánchez et al. 2019; del Río et al. 2021a; Comte et al. 2022; Torres et al. 2022). In this regard, Honorio et al. (2018) emphasized the significance of integrating several climatic indices to determine the suitability of a territory for viticulture. In agreement with it, del Río et al. (2021a) confirmed that several parameters and bioclimatic indices from the "Worldwide Bioclimatic Classification System" (WBC) (Rivas-Martínez et al. 2011, 2017) are useful for delimitating and characterizing vineyards due to its high predictive value. This classification system establishes relationships between the worldwide vegetation types and several bioclimatic indices.

The climate system is unquestionably warming and has undergone unprecedented changes in the decades since the 1950s (IPCC 2014). The last 40 years have been warmer than any previous period since 1850. During the first two decades of the 21st century (2001–2020), the global surface temperature exhibited an increase of 0.99 [0.84 to 1.10] °C compared to the period between 1850 and 1900. The mean temperature has been consistently increasing in Europe, with the highest rates observed in the northern latitudes of the continent (IPCC 2021).

According to the IPCC (IPCC 2014), increases in rainfall since 1901 have been documented across regions situated at mid-latitudes in the Northern Hemisphere, whereas mean precipitation has decreased in southern Europe. It implies that the Mediterranean Basin will suffer a reduction in precipitation (Vitale et al. 2012; López-Tirado et al. 2018).

Vineyards are among the perennial crops potentially suffering the most negative impacts due to climate change, not only related to temperature changes but also to available water.

Wine grape varieties have specific climate requirements for optimal growth and high-quality yields, making them more susceptible to climate changes than other agricultural crops (Wang et al. 2010; Hewer and Gough 2021) and probably endangering the future viability of *Vitis vinifera* (Droulia and Charalampopoulos 2021).

Several studies have been carried out around the world during the last decade to evaluate the climate change effects on viticulture. Some of the most direct impacts concern variations in the phenological development stages of grapes and the growing season length (Fraga et al. 2016; Ruml et al. 2016; Cola et al. 2017; Alikadic et al. 2019; Dinu et al. 2021; Rodrigues et al. 2021); grape quality and production (Holland and Smit 2014; Blanco-Ward et al. 2017, 2019; Bonfante et al. 2017; Biasi et al. 2019; Cardell et al. 2019a; Meggio et al. 2020; Venios et al. 2020; Hewer and Gough 2021) and the distribution of insect pests and pathogens (Caffarra et al. 2012; Reineke and Thiéry 2016; Bois et al. 2017; Rigamonti et al. 2018; Lessio and Alma 2021). Climate change can also cause variations in the geographic distribution of vineyards (Malheiro et al. 2010, 2012; Gaál et al. 2012; Fraga et al. 2013, 2014; Hannah et al. 2013; Moriondo et al. 2013; Tóth and Végvári 2016; Omazić et al. 2020; Sgubin et al. 2023; Vlăduț et al. 2023).

In Spain, some studies on the effects of climate change on viticulture have been conducted for particular regions or for the country as a whole (de las Nieves et al. 2012; Malheiro et al. 2012; Ramos et al. 2015, 2018, 2021; Ramos and Jones 2018; Sánchez et al. 2019; Santillán et al. 2019; Diago et al. 2020; Piña-Rey et al. 2020; Ramos and de Toda 2020; Bergmeier et al. 2021; Chacón-Vozmediano et al. 2021; Moral et al. 2022; Gaitán and Pino-Otín 2023; Ramos and Yuste 2023).

In agreement with Nicholas et al. (2011), a thorough understanding of the spatial distribution of a wine region is crucial for assessing the long-term viability and sustainability of wine production. A potent and useful tool used to generate spatial predictions of habitat suitability for species are species distribution models (SDMs) (Guisan and Thuiller

2005). These models are applied in studies about conservation biology, climate change, and species management. Maximum entropy (MaxEnt) is widely employed in SDMs, using presence data to predict environmental tolerances and species distributions. It has been proved that MaxEnt consistently exhibits competitive predictive performance and outperforms other methods (Elith et al. 2011).

In spite of their effectiveness, SDMs unavoidably introduce a certain level of uncertainty associated with the inherent unpredictability found in natural systems (Bardon et al. 2021). Ensemble forecasting provides an effective and useful solution for mitigating this variability by integrating outcomes from multiple sources of uncertainty (Araújo and New 2007). Consequently, this approach enables more robust decision-making in the presence of uncertainty and proves highly valuable for designing conservation strategies (Willcock et al. 2020). Data on emission scenario pathways and general circulation models (GCMs) can also be integrated in the models to calculate the uncertainties related to climate change predictions (Goberville et al. 2015).

It is broadly argued that it is also necessary to carry out more locally and regionally specific analyses to define appropriate vineyard management practices in response to climate change scenarios due to the variability between the different viticultural areas and the responses of the grapevine varieties (Pons et al. 2017; Ramos et al. 2018; Santillán et al. 2019; Comte et al. 2022).

Nevertheless, and to the best of our knowledge, few studies (Hannah et al. 2013; Tóth and Végvári 2016)—although none in NW Spain—have used MaxEnt to evaluate the potential effects of climate change on the potential distribution of vineyards. In addition, the climatic variables are frequently processed independently in such studies (Gaál et al. 2012; Fraga et al. 2013; Moriondo et al. 2013; Lazoglou et al. 2018; Cardell et al. 2019a; Omazić et al. 2020; Piña-Rey et al. 2020; Alba et al. 2021), without taking into consideration the combination and integration of all the bioclimatic indices simultaneously.

In light of the foregoing, and as a continuation of previous research (del Río et al. 2021a), the main aim of this research was to test and prove the usefulness of the methodology proposed for evaluating the potential impacts of climate change on the suitability for the vineyard cultivation. The study constitutes a novelty in this work field, as it combines traditional agricultural indices used in viticulture with other new bioclimatic indices and also with soil factors as predictor variables. These variables are integrated into species distribution models to build suitability maps under different climate change scenarios at a fine-scale spatial resolution.

It should be noted that this methodology can be applied to any wine-growing region in the world and could help policymakers to develop practices and strategies to conserve existing grape varieties and to implement efficient adaptation measures for mitigating or anticipating the effects of climate change on viticulture.

2 Data and methods

2.1 Study area

The area under study is the León Denomination of Origin (hereafter DO León) situated in the south of the province of León (Castilla y León region, NW Spain) (Fig. 1). The DO also comprises part of the province of Valladolid and limits with Palencia and Zamora. The registered area in the Viticola Registry is 1369 ha. with a production zone of about 3317 km^2.

The climate in this area is Mediterranean (Rivas-Martínez et al. 2011), due to the existence of a drought in at least two consecutive summer months. Summers are hot and dry with monthly average temperature above 20 °C. Autumn is characterized by mild temperatures and ample rainfall, while the winter period is long, severe, and marked by persistent fog and frost conditions. Spring is an irregular period, alternating mild temperatures with spring frosts. The annual precipitation is about 500 mm (on average) and is mostly concentrated in winter. The continentality is strong and there is about 2700 h of annual sunshine. The soils of the DO León are highly suited to viticulture because they are situated on alluvial terraces and below 900 m of altitude.

Viticulture has been an identifying feature of these territories since the Middle Ages. The first documents dating back to the 10th century highlight the value of this activity as an economic resource for the region, alongside cereal crops. The monasteries in the area were largely responsible for the development of viticulture, as the monastic communities bought land for the cultivation of vines and the southern part of León became a supplier of wine to practically the whole of the northern part of Spain.

This ancient origin can also be seen in the landscape in the form of large numbers of wine cellars or caves in its popular architecture and dug out of small hills of clay soils that are typical of the territory. Their interior offers an ideal microclimate for wine production.

In 1985, a group of Cooperatives and Wineries belonging to the Valdevimbre-Los Oteros-Cea area took the first steps to constitute what would become a Professional Association of winegrowers, winemakers, and bottlers, whose main objective was to obtain the denomination of origin for their wines. This was granted on 27 July 2007 under the name DO Tierra de León and changed its name on 02 April 2019 (European Commission Implementing Regulation (EU) 2019/550) to the current DO León (DO León Regulatory Council).

The autochthonous Prieto Picudo grape variety, which is used for the production of red and rosé wines, is the claim to originality of this DO, and which distinguishes it from other

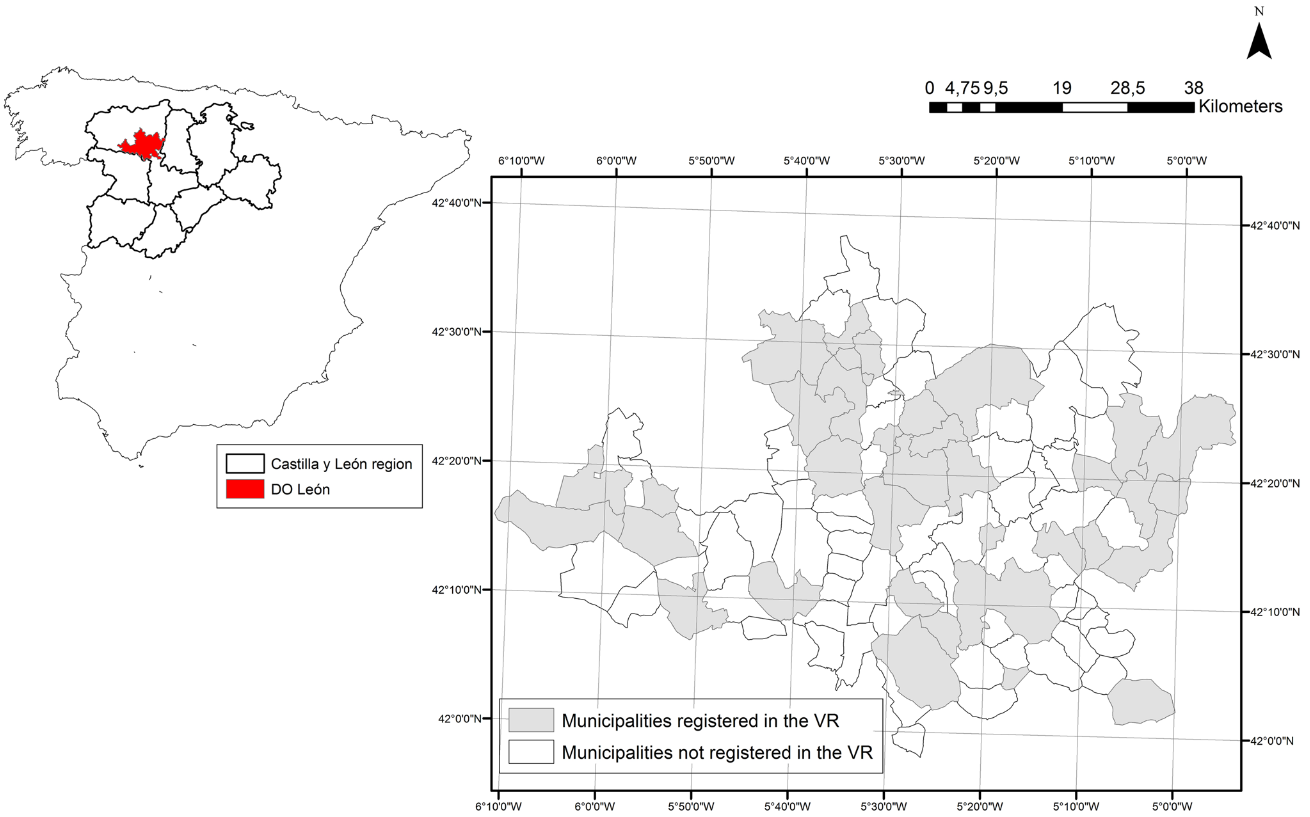

Fig. 1 Location of the study area (source: del Río et al. 2021a)

wine-producing regions worldwide. It occupies around 70% of the cultivated vineyard area and accounts for 69% of the total number of vines, with an extension of around 3000 hectares. Mencía, Albarín, Verdejo, Godello, Garnacha, Tempranillo, Palomino, and Malvasía are other grape varieties authorized in the DO. Among them, it is worth noting the white grape variety Albarín, which is native to the northern Iberian Peninsula and whose vineyards cover an area of less than 100 hectares throughout the world, most of which are in the southern region of the León province (DO León) and in southern Asturias (DO Cangas).

2.2 Predictor variables

The predictor variables considered in this research to assess appropriate areas for vineyard plantation under future climate conditions were those identified by del Río et al. (2021a) as key for the discrimination and characterization of each of the grape varieties analyzed in the DO León. They comprised six bioclimatic indices and seven soil variables (Table 1). The predictors that effectively characterize the grape varieties analyzed are displayed in Table 2.

Several statistical analyses including a factorial analysis with principal components extraction method as well as the variance inflation factor (VIF) analysis were used to reduce dimensionality and multicollinearity and to select the predictor variables. More detailed information about it is reported in del Río et al. (2021a).

2.3 Future projections of bioclimatic predictors

The downscaled CMIP5 climatologies for 2050 and 2070 (averages for 2041–2060 and 2061–2080, respectively) accessible from the CHELSA climate dataset were used to obtain the future climate variables. CHELSA is a very high-resolution (30 arc sec, ~ 1 km) global downscaled climate data set for the Earth's land areas (Karger et al. 2019). CMIP5, which stands for the Coupled Model Intercomparison Project Phase 5, is a research initiative led by the World Climate Research Program (WCRP) aimed at generating time-projected environmental variables for the Intergovernmental Panel on Climate Change (IPCC).

CCSM4, MPI-ESM-LR, and HadGEM2-ES were the Global Circulation Models (GCMs) selected to reduce the resulting uncertainty in the use of single GCMs. Buras and Menzel (2019) have demonstrated the satisfactory performance of these calibrated models for the Northern Hemisphere, particularly for Europe. Several authors have incorporated these Global Climate Models (GCMs) into climate change investigations conducted in Spain (López-Tirado et al. 2018; Chacón-Vozmediano et al. 2021; del Río et al. 2021b).

Table 1 Description of selected variables. Modified from del Río et al. (2021a)

Bioclimatic variables	Definition/formula
Annual ombrothermic index (IO)	IO = (Pp/Tp) 10 Pp is the positive precipitation, and Tp is the positive temperature
Continentality index (IC)	IC = Tmax − Tmin Tmax is the average temperature of the warmest month, and Tmin is the average temperature of the coldest month
Growing season precipitation (GSP)	GSP = $\sum P$ from April to September P is the precipitation
Hydrothermic index of Branas (BI)	BI = $\sum T \times P$ from April to September T is the mean temperature, and P is the precipitation
Temperature range during ripening (DTR)	Tmax − Tmin August and September
Thermicity compensated index (ITC)	ITC = $(\text{Ty} + M + m)$*10 Ty is the yearly average temperature, M is the average maximum temperature of the coldest month of the year, and m is the average minimum temperature coldest month of the year
Soil variables	Definition/formula
Clay content (CC)	Percentage by weight of fine soil in the sample. Particles with a diameter less than 0.002 mm
Permeability (PE)	Permeability defines the speed with which a saturated soil transmits water through it under the influence of gravity. A soil is saturated when all of its pores are filled with water, and therefore, the permeability value is at its maximum. It is expressed as mm per day
pH	Soil acidity expressed as pH
Sand content (SC)	Percentage by weight of fine soil in the sample. Particles with a diameter between 0.05 and 2 mm
Silt content (SLC)	Percentage by weight of fine soil in the sample. Particles with a diameter between 0.002 and 0.05 mm
Soil retention capacity (SRC)	Maximum amount of water available to plants that can store a given soil. It is the difference between the water content at field capacity and wilting point. It is expressed as volumetric humidity in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample
Soil saturation humidity (SSH)	Moisture content in the soil matrix when all of its pores are filled with water. It depends solely on the soil texture and is not affected by salinity or gravel content. It is expressed as volumetric humidity in percentage, that is, the volume of the liquid fraction with respect to the volume of the soil sample

Table 2 Variables that characterize better each variety (X)

	ALB	GAR	MEN	PIC	TEM	VER
Bioclimatic variables						
Annual ombrothermic index (IO)	X			X		
Continentality index (IC)	X	X	X	X	X	X
Growing season precipitation (GSP)			X		X	X
Hydrothermic index of Branas (BI)		X				
Temperature range during ripening (DTR)		X				
Thermicity Compensated Index (ITC)	X	X	X	X	X	X
Edaphic variables						
Clay content (CC)	X	X	X	X	X	X
Permeability (PE)	X		X	X	X	X
pH	X	X	X	X	X	X
Sand content (SC)	X	X		X		
Silt content (SLC)		X	X			
Soil retention capacity (SRC)	X	X	X	X	X	X
Soil saturation humidity (SSH)	X	X	X	X	X	X

ALB, Albarín; *GAR*, Garnacha; *MEN*, Mencía; *PIC*; Prieto Picudo; *TEM*, Tempranillo; *VER*, Verdejo. del Río et al. (2021a)

Two representative concentration pathways (RCPs) approved by the Intergovernmental Panel on Climate Change (AR5 Synthesis Report) (IPCC 2014) were applied for each GCM selected. The emission pathways provide scenarios of pollutants and greenhouse gas concentrations resulting from human activity. RCP 4.5 is described by the IPCC as an intermediate scenario where emissions peak around 2040 and then decline. For the pessimistic scenario (RCP 8.5), the emissions continue to rise throughout the 21st century (IPCC 2014).

The delta change method has been applied to integrate the current data collected from the Agroclimatic Atlas of Castilla y León (ITACYL-AEMET 2013) and the CHELSA information for scenario modeling. This approach has previously been used by several authors (Wang et al. 2006; Fraga et al. 2014; Poggio et al. 2018; Piña-Rey et al. 2020). The methodology provides future climate scenarios at a finer resolution integrating locally available data (Poggio et al. 2018).

After this process, rasters for all six bioclimatic predictor variables (IO, IC, GSP, BI, DTR, and ITC; see Table 1) were built for each GCM, RCP, and the time periods projected for future using** Map Algebra with ArcGis 10.8 (ESRI 2019) at spatial resolution of 500 m.

2.4 Distribution modeling

MaxEnt (maximum entropy modeling) algorithm implemented in the Ensemble Platform for Species Distribution Modeling (Biomod2) was used to assess the suitability of each grape variety under climate change projections. Biomod2 is a R package which includes functions for species distribution modeling, calibration and evaluation, ensemble of models, ensemble forecasting, and visualization (Thuiller 2003; Thuiller et al. 2009). Models were generated with RStudio (R Core Team 2020).

At this step, and to build suitability maps for wine-growing in the future, a total of 720 single models were computed (3 GCMs × 2 RCPs × 2 time horizons × 10 runs × 6 grape varieties) using the recommended default parameters for MaxEnt and Biomod (Thuiller et al. 2009).

The ensemble models were then derived by calculating a consensus projection of single-model predictions (Thuiller et al. 2009). The ensemble models were exclusively generated by selecting single models with a minimum area under the curve (AUC) value of ≥ 0.95 and a true skill statistic (TSS) value of ≥ 0.85. The median probability of occurrence was calculated for each grid cell based on the selected models. The threshold that optimizes both specificity and sensitivity was selected to convert the results of probability into binary maps and to distinguish between suitable and non-suitable areas for the studied grape varieties. This has been demonstrated to be a good technique to determine the threshold (Allouche et al. 2006; Jiménez-Valverde and Lobo 2007). The suitability maps were implemented into ArcGis 10.8. (ESRI 2019).

Twelve future suitability maps were constructed for each grape variety (six for the 2050 time horizon and six

Table 3 Minimum (Min) and mean and maximum (Max) values for the bioclimatic indices analyzed under current conditions and climate change scenarios studied in the DO León

Bioclimatic index	Statistics	Current	2050 RCP 4.5	2050 RCP 8.5	2070 RCP 4.5	2070 RCP 8.5
IC	Min	15.74	16.29	16.97	16.23	17.43
	Mean	17.43	18.02	18.66	17.97	19.28
	Max	19.11	19.67	20.44	19.74	20.86
IO	Min	2.70	2.42	2.23	2.33	1.57
	Mean	3.29	2.96	2.74	2.87	1.92
	Max	6.07	5.30	4.98	5.24	3.43
ITC	Min	155.87	169.93	184.40	176.79	207.59
	Mean	191.58	211.45	234.10	223.36	261.55
	Max	220.11	237.03	262.28	250.66	288.75
IB	Min	1699.01	1871.96	1813.19	2007.13	1844.35
	Mean	1957.40	2150.91	2076.55	2278.24	2109.94
	Max	2447.38	2739.30	2602.51	2920.90	2681.35
DTR	Min	16.58	17.14	17.26	17.30	17.71
	Mean	18.59	19.11	19.34	19.22	19.62
	Max	20.79	21.24	21.79	21.36	21.70
GSP	Min	169.68	144.10	140.49	143.20	122.11
	Mean	196.93	166.96	165.92	165.05	143.86
	Max	258.46	216.22	215.81	214.86	188.38

IC, continentality index; *ITC*, compensated thermicity index; *IO*, annual ombrothermic index; *IB*, hydrothermic index of Branas; *DTR*, temperature range during ripening; *GSP*, growing season precipitation for 2070) at the conclusion of the process. The last step consisted of combining the maps into four final suitability maps for each variety (two for the 2050 horizon and two for 2070). A buffer of 30 km around the DO has been considered to determine whether the areas currently defined for cultivation will remain suitable in the future, or if new areas could be adequate for plantation outside the limits of the DO.

The presence of statistically significant variations in habitat suitability between the current conditions and climate change scenarios was verified at a 95% confidence interval with the Wilcoxon signed-rank test.

2.5 Changes in future suitable areas for vineyards

The reduction (loss), expansion (gain), or maintenance of habitat suitability in comparison with current conditions were analyzed for each grape variety. Habitat loss was considered as being when the total area suitable for the plantation of vineyards (including the buffer of 30 km) is lower than under current conditions. Expansion or gain occurs if the area suitable for vineyards in the future is higher than under current conditions. If no changes between the current and future areas are observed, the habitat suitability is maintained.

The analysis is complemented with the calculation of the percentage of projected future range change (C) proposed by Hu and Jiang (2011), which is estimated with the formula:

$$C = 100^{*}(\mathrm{RG} - \mathrm{RL})/\mathrm{PR}$$

where RG (range gain) is the number of grid cells that were projected as unsuitable under current conditions but deemed suitable in future scenarios.

RL (range loss) is the number of grid cells projected as unsuitable in future scenarios but considered suitable under current conditions.

PR (present range) is the number of grid cells projected as suitable under present conditions. A negative C value indicates a loss in overall range size and a positive value means an increase.

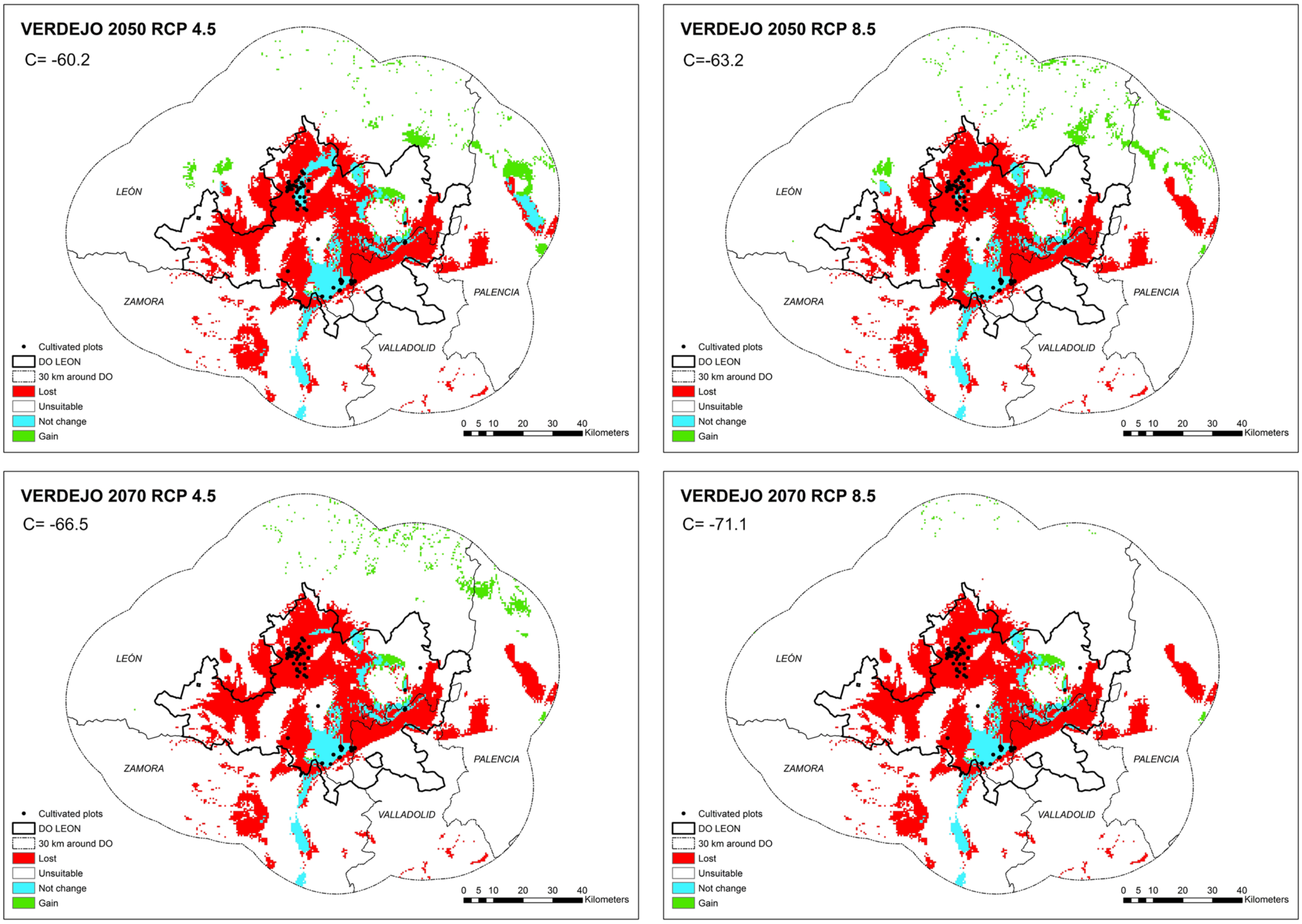

Fig. 2 Predicted changes in suitable areas and value of range change (C) for Verdejo variety under climate change scenarios

3 Results and discussion

3.1 Future projections of bioclimatic predictors

Our results revealed generalized increases in temperature and decreases in rainfall for the future scenarios analyzed, which will be more pronounced under the pessimistic projection (2070, RCP 8.5). These findings are in accord with those shown by several authors in recent years in Spain (del Rio et al. 2011a, b, 2012; González-Hidalgo et al. 2011, 2020; Ríos et al. 2012, 2013; Mukadi and González-García, 2021; Sandonis et al. 2021). Climate projections for Europe also highlight a continuous rise in temperatures until the end of the 21st century. The most significant warming is expected in southern areas. Furthermore, the models suggest a decline in precipitation across the southern of the continent (Christensen and Christensen 2007; IPCC 2014; Cardell et al. 2019b).

Table 3 shows the main descriptive statistics for the six bioclimatic indices used in this study under the climate scenarios analyzed.

According to our results, increases in the continentality index (IC), compensated thermicity index (ITC), hydrothermic index of Branas (IB), and temperature range during ripening (DTR) have been observed in all the future scenarios analyzed in comparison to current conditions (Table 3). Conversely, the annual ombrothermic index (IO) and the growing season precipitation (GSP) values tend to decrease in future (Table 3). The highest variations are expected for the 2070-time horizon and under the RCP 8.5 emission pathway.

Regarding Rivas-Martínez's bioclimatic indices (Rivas-Martínez et al. 2011; 2017), our work confirms the strong predictive capability of bioclimatology for studies on climate change and its impacts on plant communities. It can be observed that the continentality index tends to increase in the future in both the two-time scenarios proposed and for both RCPs. Average values for the whole DO could change from 17.4 at present to 19.2 under the pessimistic scenario (year 2070, RCP 8.5). This means that the territories included in the DO could be more continental than today if this trend is maintained in the future.

The compensated thermicity index also tends to increase in the future, motivated by the confirmed rise in temperatures. The rate of change is approximately 20–30 units for each time scenario and RCP considered. Thus, in 2070 and

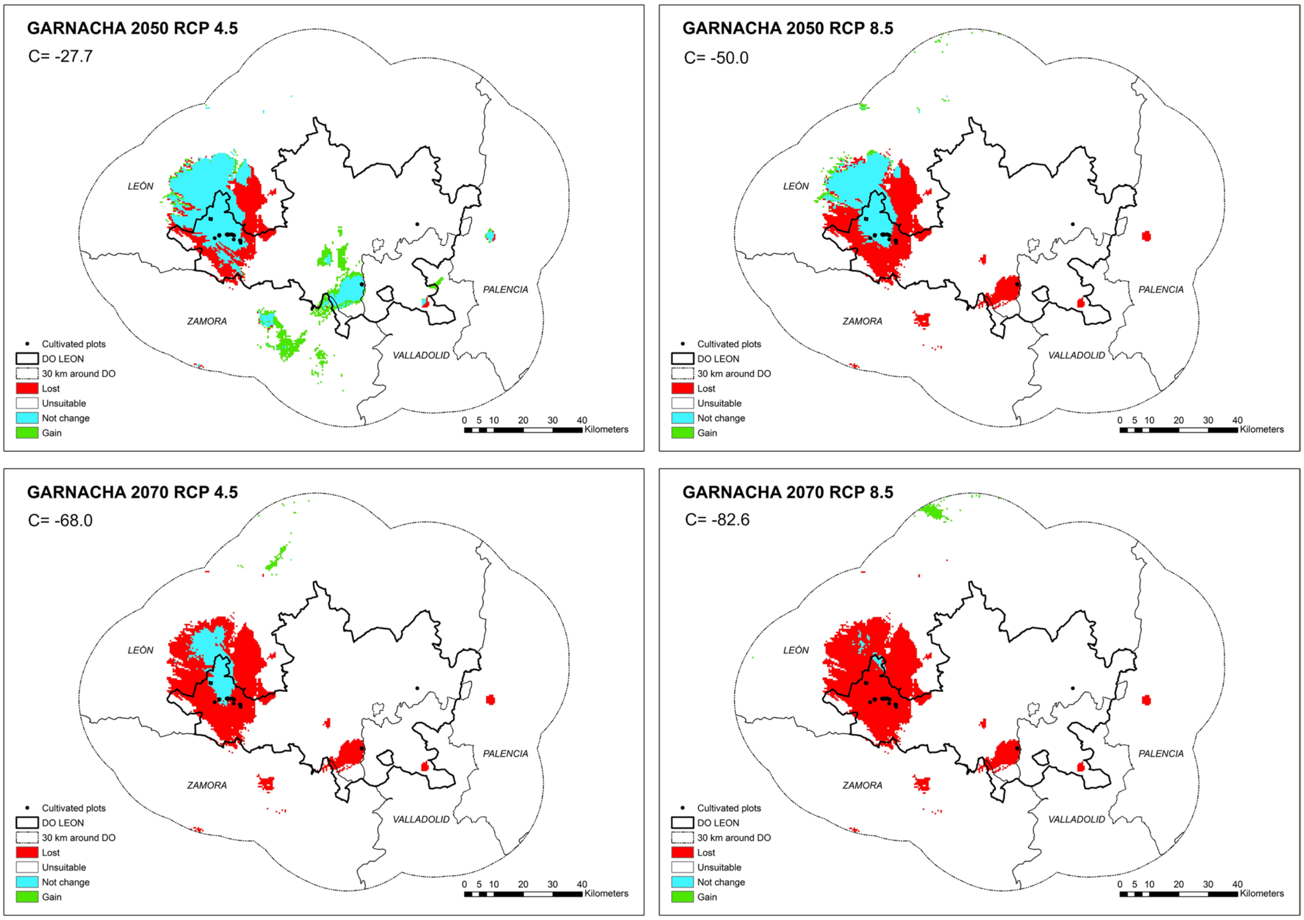

Fig. 3 Predicted changes in suitable areas and value of range change (*C*) for Garnacha variety under climate change scenarios

in RCP 8.5, all the territory under study could have a meso-Mediterranean character. These results confirm that the viticultural areas in Spain are typically lower supra- and meso-Mediterranean (del Río et al. 2021a).

Unlike the previous indices, the future trend of the annual ombrothermic index will be to decrease, in line with the generalized increase in temperature and decline in rainfall. The results reveal that the ombrotype in the study area will be dry in most of the climate change scenarios considered. The southern areas exhibited the lowest values for this bioclimatic index, indicating drier conditions. The results indicate that irrigation may be necessary in some areas in the DO in the future in order to maintain the plantations of the current grape varieties.

Growing season precipitation stands out as one of the most influential bioclimatic variables for viticulture under current conditions in north-western Spain (Blanco-Ward et al. 2007). GSP reveals also as a significant factor when evaluating the appropriateness and economic viability of a particular region for the cultivation of grapevines and wine production (Santos et al. 2012a). A decrease was detected in this variable in the two-time scenarios and for both RCPs in this study. Decreases in GSP have also been reported by Piña-Rey et al. (2020) in five DO areas in north-western Spain and by Chacón-Vozmediano et al. (2021) in La Mancha DO. Malheiro et al. (2010) highlighted the significance of the projected decreases in the GSP for southern Europe (Spain, Italy, and Portugal). The same authors also suggested that the future aridity and the rise in cumulative thermal stress during the growing season are expected to have negative effects on wine grapes in Spain. In this line, Cardell et al. (2019a) reported that a severe decrease in rainfall in spring would be a limiting factor for the growth of vineyards in current winemaking regions in Spain.

Average values of the temperature range during ripening could increase by about 1 °C in the most pessimistic scenario in relation to current conditions. These results are in line with those proposed by Morales-Castilla et al. (2020) who reported that changes in DTR may affect the world's winegrowing regions unevenly; for example, mild increases in southern Europe versus slight decreases in central Europe.

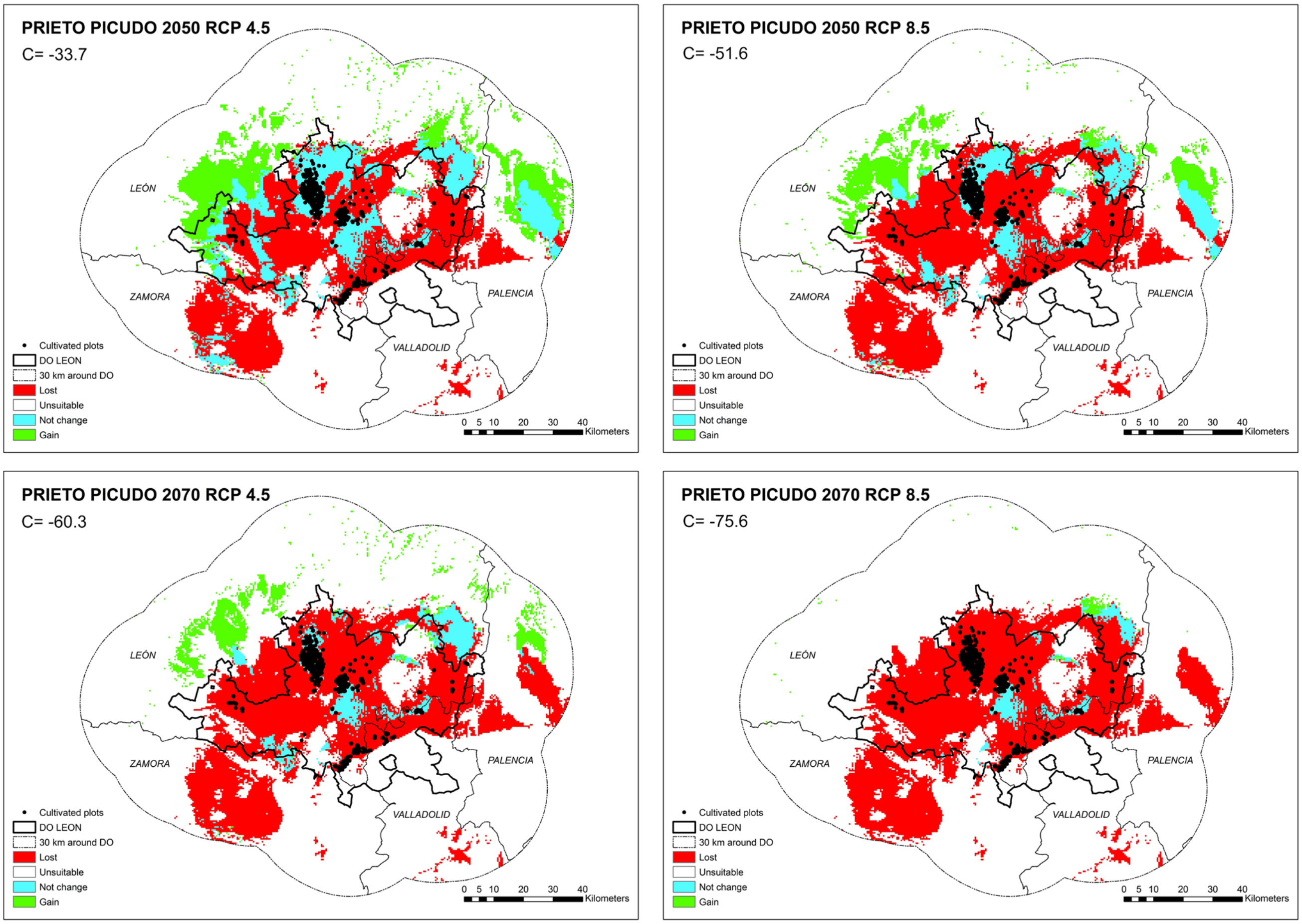

Fig. 4 Predicted changes in suitable areas and value of range change (*C*) for Prieto Picudo variety under climate change scenarios

Values for the hydrothermic index of Branas tend to be slightly higher than at present in all the climate change scenarios analyzed. Piña-Rey et al. (2020) also detected minor differences in this index between the RCP 4.5 and RCP 8.5 scenarios for the period 2061–2095. This index provides information on the probability of mildew attacks in vineyards (Lorenzo et al. 2013). Values of Branas below 2500 are generally associated with a low risk of mildew contamination, while values exceeding 5100 indicate a high risk (Malheiro et al. 2010). The average values for this predictor for the whole DO León in all the scenarios considered will be below 2500, indicating a low potential risk of mold infestation.

Although it is not the objective of this study, it is worth noting that the trends observed in the bioclimatic indices could also affect aspects such as phenology, grape ripening, grape quality, and yield, as has been mentioned in the introduction section. For instance, earlier phenology due to climate change not only means earlier harvesting but also in warmer conditions, which can lead to uneven ripening and negatively impact grape composition and quality (Chacón-Vozmediano et al. 2021).

3.2 Changes in future suitable areas for vineyards

Figures 2, 3, 4, 5, 6, and 7 show the projected changes in habitat suitability for vineyards and the value of the range change (*C*) under the four climate change projections studied (two time horizons × two RCPs) compared to present conditions. Suitable locations for each variety under present conditions can be checked in del Río et al. (2021a). Table 4 displays the area (km^2) with appropriate requirements for the cultivation of vineyards in current conditions and the climate change projections studied. This table also shows the final percentage of future habitat suitability (lost or gained) compared to today.

Our predictions suggest that viticulture in the DO León could be negatively affected by climate change. Future forecasts reveal a significant loss of habitat suitability within the limits of the DO for all the grape varieties analyzed (with the exception of the Mencía variety), with statistically significant differences between current and future conditions. These findings are associated with the abovementioned decreases in rainfall and rise in temperature, which will imply a lower IO and GSP and a higher ITC, especially in the 2070 horizon

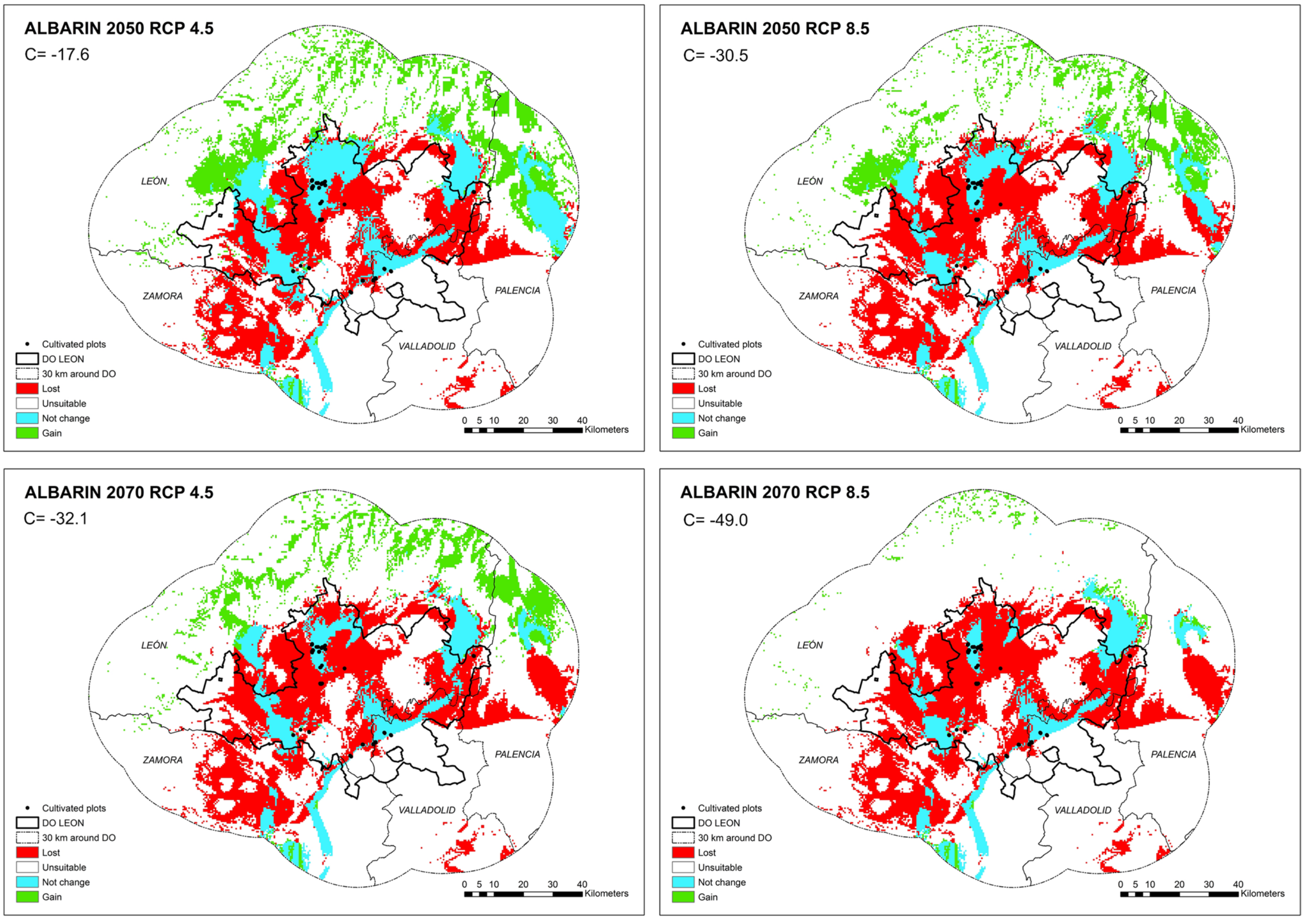

Fig. 5 Predicted changes in suitable areas and value of range change (C) for Albarín variety under climate change scenarios

where the most significant changes may be seen. Our findings are in agreement with other authors who suggested that the progressive water shortage and warmer conditions will adversely affect viticulture in southern Europe (Malheiro et al. 2010; Moriondo et al. 2013; Cardell et al. 2019b; Morales-Castilla et al. 2020). The adverse consequences of climate change on some Spanish winegrowing regions have also recently been reported by Sánchez et al. (2019), Chacón-Vozmediano et al. (2021), and Ramos et al. (2021).

The loss of future habitat suitability within the limits of the DO could be offset to some extent with new potentially suitable areas for cultivation for the varieties analyzed around the study area. New potential viticultural zones can be seen in territories located to the north of the DO limits and at higher altitudes than at present. These displacements could compensate for decreases in rainfall. This is especially noteworthy for the Albarín and Tempranillo varieties, with around 30% and 40% respectively of new areas suitable for cultivation in 2050. Several researches in wine regions in southern Europe (Malheiro et al. 2010; Moriondo et al. 2011, 2013; Koufos et al. 2018; Lazoglou et al. 2018) have also noted this displacement towards northern regions and higher elevations in their original ranges and the contraction within the region due to climate change. More specifically, Fraga et al. (2012) and Piña-Rey et al. (2020) suggested for the Iberian Peninsula the extension of new potential viticultural areas in northwest Spain. Sánchez et al. (2019) also pointed out that favorable areas for growing grapes will move towards the north-western parts of the DO Sierra de Salamanca.

Analyzing the results for each variety, Verdejo could suffer the greatest loss of area suitable for cultivation in the 2050 horizon and for both emission scenarios. Only 15–20% of the current areas appropriate for planting this grape variety may be maintained in the future (Fig. 2 and Table 4), mainly corresponding to areas that are cultivated today. Unlike other varieties, the increases in potential new areas will be around 10%.

As can be seen in Fig. 3 and Table 4, the Garnacha variety could lose practically all its optimal areas for cultivation in 2070. Nevertheless, it should be noted that it is the least cultivated grape in the DO León, with vineyards located in its western areas.

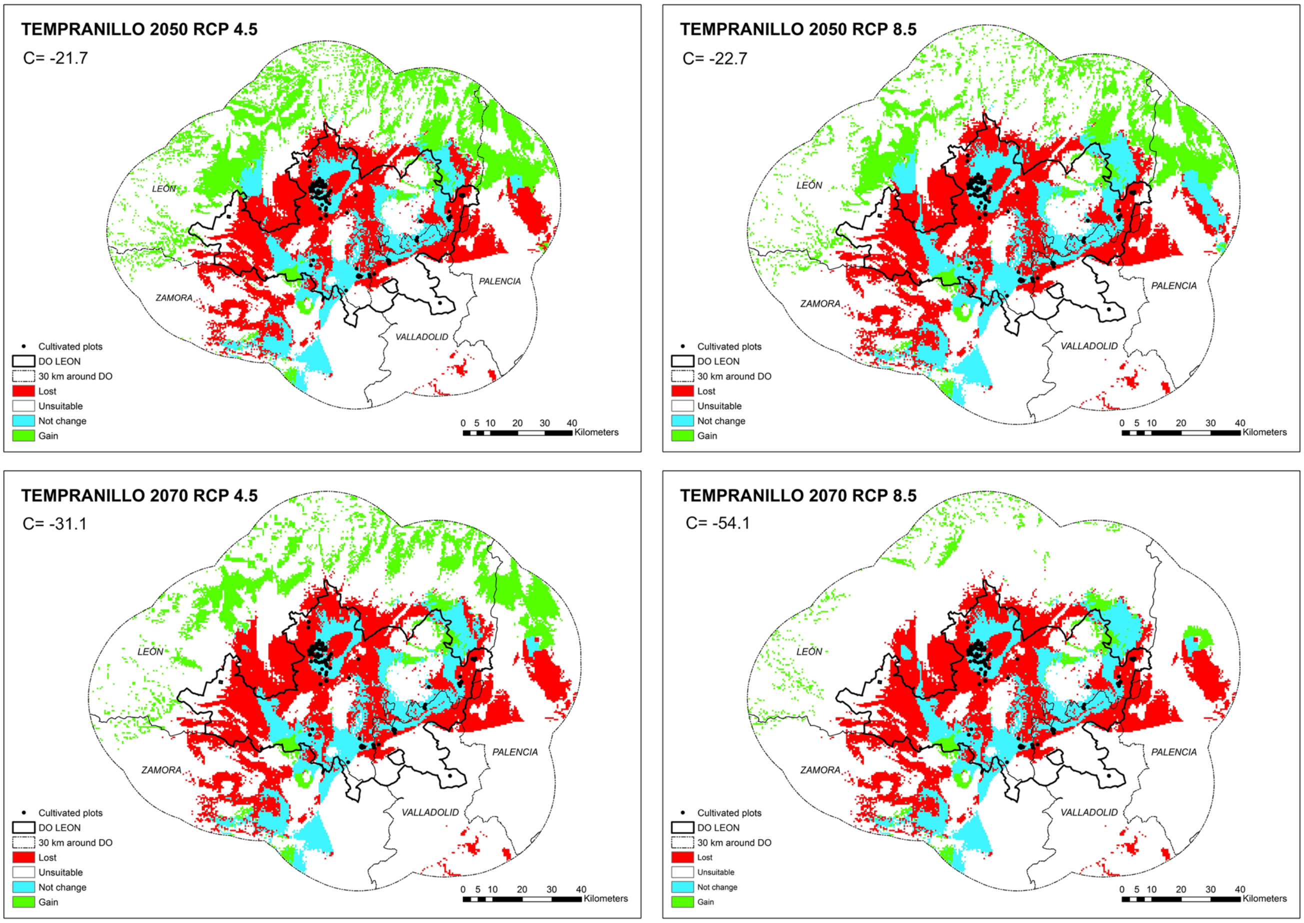

Fig. 6 Predicted changes in suitable areas and value of range change (*C*) for Tempranillo variety under climate change scenarios

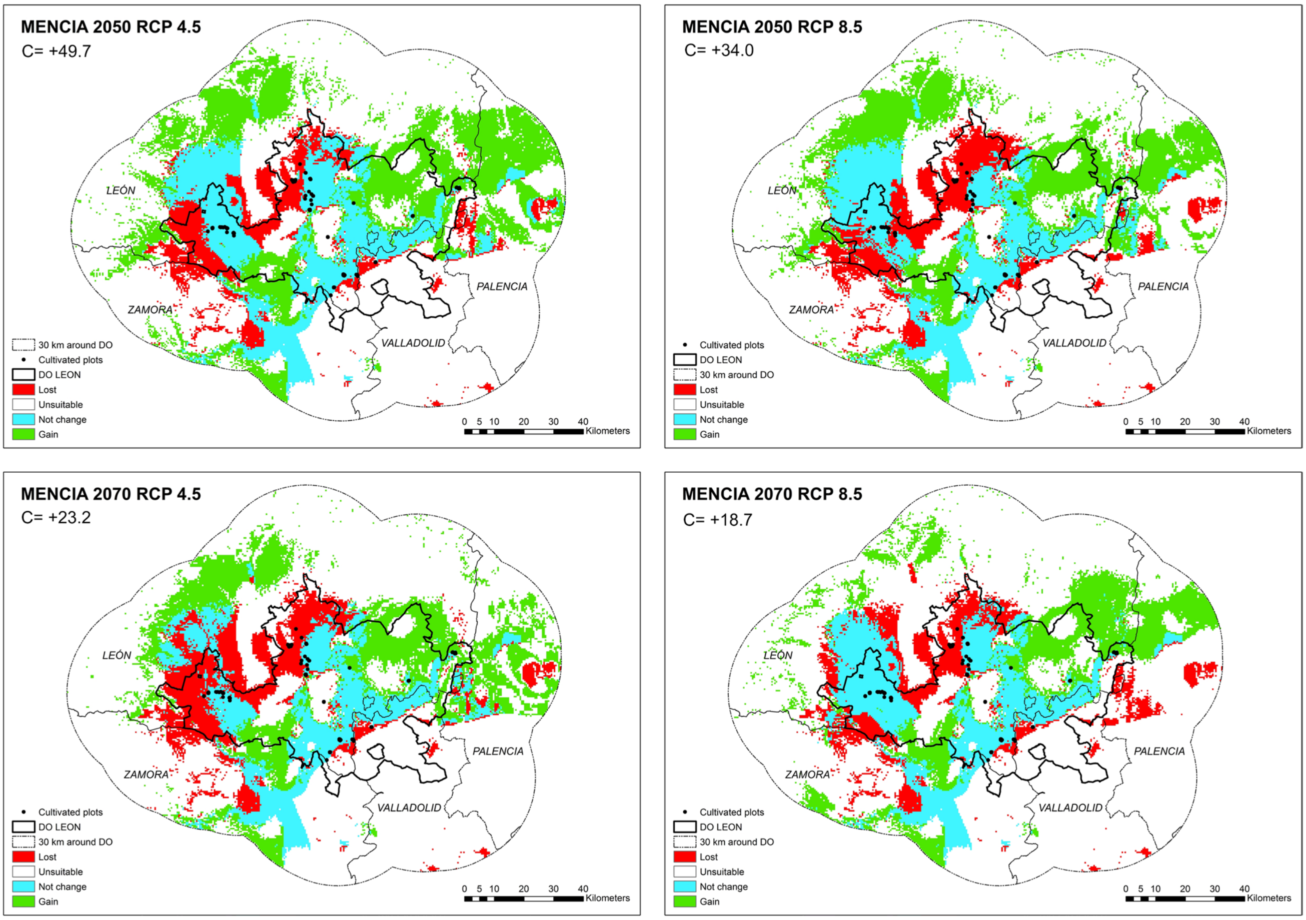

Fig. 7 Predicted changes in suitable areas and value of range change (*C*) for Mencía variety under climate change scenarios

Table 4 Squared kilometers forecasted by the ensemble models for each variety under current and climate change scenarios and final percentage (%) of habitat suitability lost (−) or gained (+) compared to nowadays

	Current	2050				2070			
		RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
	km^2	km^2	Final %	km^2	Final %	km^2	Final %	km^2	Final %
Albarín	4131.75	3048.75	−26.21	2256.25	−45.39	2158.50	−47.76	1123.00	−72.82
Garnacha	1117.00	982.75	−12.02	476.50	−57.34	241.00	−78.42	51.25.00	−95.41
Mencía	3466.25	5488.75	+58.35	4856.00	+40.09	5662.25	+27.54	4252.00	+22.67
Picudo	4302.50	2513.25	−41.59	1567.75	−63.56	1103.50	−74.35	292.25	−93.21
Tempranillo	4301.00	3358.25	−21.92	3315.00	−22.92	2950.50	−31.40	1978.50	−54.00
Verdejo	2625.00	770.25	−70.66	675.50	−74.27	571.50	−78.23	430.50	−83.60

Projections for the autochthonous grape variety Prieto Picudo are also unfavorable as its habitat suitability may be reduced by up to 93% in the most pessimistic scenario (2070, RCP 8.5) (Fig. 4 and Table 4). Less negative results will be seen in the shorter term (2050 scenario), as new suitable areas for its cultivation could be extended towards the north and northwest of the DO (around 17–26% in comparison to the current potential area).

Similarities can be observed between the habitat suitability maps for Albarín and Tempranillo (Figs. 5 and 6), which (together with Mencía) are the varieties least affected by climate change in terms of variations in the distribution of suitable areas for plantation. Although there is evidence of a loss of habitat suitability within the limits of the DO, new areas are expected to become suitable for the cultivation of these varieties. This is especially the case of Tempranillo, whose potential area increases by about 40% for the 2050 scenario to the north of the DO.

It is verified that Mencía is the variety whose behavior differs most significantly in response to climate change. In that way, del Río et al. (2021a) also highlighted Mencía as being the most different variety due to its soil and bioclimatic requirements. Unlike the above results, this variety will be least affected in terms of losses of habitat suitability if the projected climate change occurs. Indeed, notable increases in potential areas for vineyard cultivation can be seen towards northern latitudes and even within the limits of the study area (Fig. 7 and Table 4). Potential areas for the cultivation of this grape variety may be greater than at present for all the future scenarios analyzed, with the greatest increases in the 2050, RCP 4.5 scenario, and the lowest in the more pessimistic scenario (2070, RCP 8.5). This result agrees with our previous research, which confirmed that plantations of this variety could expand up to 3500 km^2 (including the 30 km buffer) under current climate conditions. This is the typical and characteristic variety par excellence in the DO Bierzo, located in the west of the León province and representing 75% of the vineyards in this DO. The El Bierzo region is included in the meso-Mediterranean thermotype and is characterized by having higher temperatures than the rest of the province. The Mencía variety is therefore very well adapted to high temperatures. The confirmed trend towards a warmer climate in the future could favor the maintenance/extension of its potential areas for cultivation in the territory in the study.

The range change (C) analysis confirmed these results, revealing losses in overall range (negative values) for all grape varieties except Mencía. The highest negative values and therefore the highest losses of range were confirmed for Verdejo in 2050 (both RCPs) and Garnacha in 2070 (both RCPs) (Fig. 8). C values for each variety and climate change scenario are also included in Figs. 2, 3, 4, 5, 6, and 7.

In summary, this research underlines that, although the results may differ depending on the variety analyzed, viticulture in the DO León is projected to undergo significant changes, which may represent important challenges for the winemaking sector in the coming years. The study also confirms the importance of climate on the distribution of vineyards and its importance when selecting suitable areas for growing grapevines. In agreement with Piña-Rey et al. (2020), it is essential to assess the climate suitability for a given grapevine cultivar under current and future climate conditions in order to implement effective mitigation and adaptation policies to maintain the future suitability of viticulture.

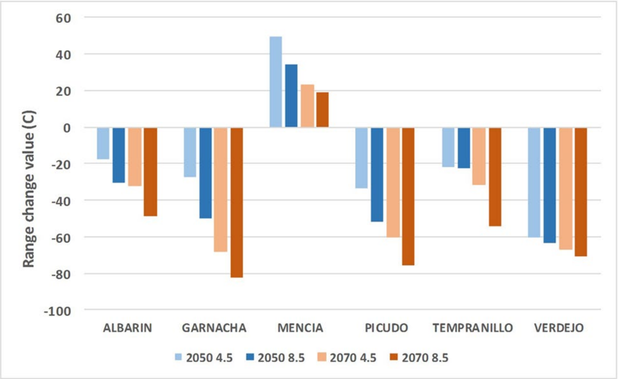

Fig. 8 Results for the future range change under climate change scenarios analyzed

As in many other areas in the world, adaptation strategies are required to preserve the present varieties and maintain their habitat suitability, although the effectiveness of each measure strongly depends on the local situation and the sign of regional climate change (Santos et al. 2012b). Several practices have been proposed in the literature, including the efficient use of irrigation, the search for better-adapted varieties, the displacement of crops to more northerly latitudes (as has been confirmed in the present study), changes in management practices and training systems, varietal/clonal and rootstock selection, increasing the level of water retention with organic matter in the ground, pest, and disease control, and use of intraspecific diversity (Santos et al. 2012b; Helder and João A 2018; Van Leeuwen et al. 2019; Fraga 2020; Morales-Castilla et al. 2020; Santillán et al. 2020; Marín et al. 2021; Naulleau et al. 2021; Santos et al. 2021; Romero et al. 2022).

In agreement with Alonso and O'Neill (2011), the perspective and perception of winegrowers in regard to climate change and its impacts on viticulture could be useful for a number of stakeholders in the wine industry in order to make adaptations and minimize the effects of climate change. In this regard, a survey consisting of personal interviews was conducted among producers and institutions involved in the DO León to find out society's perception of climate change. The results, although preliminary, show that both producers and institutions consider climate change to be a current problem that is having or could have a negative effect on wine production, and that they are very or fairly concerned about it. Drought, rising temperatures, alteration of the vegetative cycle of the vineyard, deforestation, environmental pollution, and lower yields are some of the problems that the interviewees point out as the most serious in the area, some of which are directly derived from the effects of climate change. The search for new cultivation areas, the use of irrigation, or changes in management practices could be part of the solution to these problems.

4 Conclusions

The main aim of this research was to test and prove the usefulness of bioclimatology for evaluating the potential impacts of climate change on the spatial suitability for vineyard cultivation. Our approach involves integrating both conventional agroclimatic indices and new bioclimatic ones that have proven to be essential for the characterization and demarcation of vineyards into species distribution models to assess suitable areas for viticulture under climate change projections.

The methodology proposed was tested under different climate change scenarios using ensemble forecasting models which include several bioclimatic indices and soil predictors at a fine spatial resolution on the vineyards of the DO León (NW Spain).

The results revealed increases in the continentality index (IC), compensated thermicity index (ITC), hydrothermic index of Branas (IB), and temperature range during ripening (DTR) in all the future scenarios analyzed in comparison to current conditions, while the values for the annual ombrothermic index (IO) and growing season precipitation (GSP) will tend to decrease in future. It has been noted that the pattern of changes up until 2070 could be more pronounced than 2050.

A significant loss of habitat suitability was observed within the limits of the DO for the grape varieties analyzed. Similarities were found between the maps of habitat suitability for Albarín and Tempranillo which, together with Mencía, will be the varieties least affected by climate change in terms of modifications in the distribution of suitable areas for its plantation. The loss of suitability within the limits of the DO could be offset to some extent with new potential areas in territories located to the north of the DO, as has been reported for other European viticultural regions.

Different practices and strategies should therefore be applied in order to maintain the current grape varieties and to promote economic activity in this area as a means of preventing the demographic decline detected in it.

Our results confirm once again the strong predictive capability of bioclimatology for studies on climate change and its impacts on plant communities. Moreover, the methodology proposed in can be applied to any wine region in the world.

Finally, authors suggest that the local and regional evaluation of climate suitability for a given grapevine cultivar can help in the design and application of efficient strategies for adapting and mitigating with the purpose of maintaining the future suitability of viticulture. This research could therefore help policymakers and winegrowers to select and establish effective adaptation actions to anticipate or mitigate the effects of climate change and also avoid depopulation and favor demographic settlement in rural areas.

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Author contributions SdR: conceptualization, methodology, data curation, formal analysis, investigation, writing original draft, writing-review and editing, visualization, project administration, supervision. RAE: methodology, formal analysis, software, statistics, writing-review and editing. RAR: formal analysis, visualization, writing-review and editing. RAN: formal analysis, visualization, writing-review and editing. PRF: formal analysis, visualization, writing-review and editing. AGP: formal analysis, software, visualization, writing-review and editing. AP: conceptualization, methodology, writing-review and editing.

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Declarations

Competing interests The authors declare no competing interests.

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