

Research Paper

Climate change is expected to severely impact Protected Designation of Origin olive growing regions over the Iberian Peninsula

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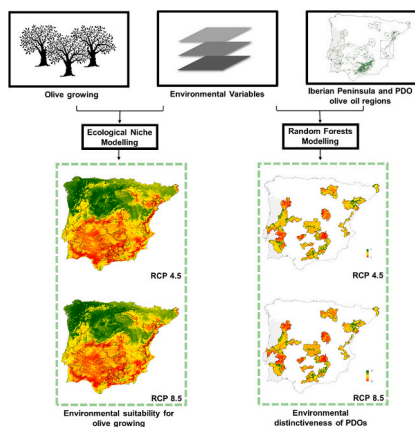
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HIGHLIGHTS

- Environmental conditions are characterized for olive growing in Iberia.
- Climate, soils and olive cultivars are responsible for the distinctive PDO olive oils.
- Climate change shifts olive environmental suitability north of the Iberian Peninsula.
- PDO regions lose environmental distinctiveness due to new climate regimes.
- Adaptation strategies call for the introduction of new cultivars in some PDOs.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The Iberian Peninsula is the world's largest olive (*Olea europaea* subsp. *europaea* L.) producing region due to its high environmental suitability for olive growing, consistently accounting for about half of the global share. Moreover, it includes a range of olive-producing regions with Protected Designation of Origin (PDO), aimed to safeguard and promote the distinctive geographical status of agricultural products linked to unique environmental characteristics. Despite the olive industry's economic importance, the impact of climate change

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on the environmental suitability and the environmental distinctiveness of olive-producing regions is still far from being understood.

OBJECTIVE: The objective of our work was twofold. First, to evaluate changes in the spatial distribution patterns of environmental suitability for olive growing both within and outside PDOs across the Iberian Peninsula under two climate change scenarios within a 2050 time horizon. Second, to evaluate the ability of PDOs to retain their distinctive environmental characteristics in response to new climate regimes.

METHODS: The study area was framed using 1×1 km square plots. We used an Ecological Niche Modelling approach, firstly, to model the environmental correlates of environmental suitability for olive growing and, secondly, to forecast their relative change within and outside PDOs. The estimated change in environmental suitability for olive growing was calculated as the percentage variation between the present and each climate change scenario. Additionally, a Random Forests Modelling approach was employed, firstly, to model the environmental correlates of PDOs and, secondly, to evaluate their environmental distinctiveness based on the probability of belonging to a given PDO. The estimated change in environmental distinctiveness of PDOs was calculated as the percentage variation between present and future in the probability of belonging to the same PDO.

RESULTS AND CONCLUSIONS: Our results suggest significant climate-driven range shifts of environmental suitability toward northern latitudes, leading to widespread reductions in southern latitudes both within and outside PDO olive-growing regions. Climate change will also severely affect the idiosyncratic environmental envelope of most PDOs, leading to the loss of their environmental distinctiveness.

SIGNIFICANCE: Our study demonstrates that climate change's impact on olive growing in the Iberian Peninsula might be stronger than previously thought. We propose exploiting the existing genotypic and phenotypic diversity related to climate - or climate diversity - as a way to adapt *O. europaea* crops to shifting climates and, in turn, allow olive growers to continue to grow in their current location for many years to come.

1. Introduction

Olive (*Olea europaea* subsp. *europaea* L.) is one of the most widespread permanent crops globally (FAO, 2022) with about 11.6 million hectares being occupied by olive trees (DeAndreis, 2022). This crop is especially prevalent in Mediterranean regions, which are particularly suitable for oliviculture (Moriondo et al., 2013). In parallel, these regions are widely recognized as global biodiversity hotspots (Myers et al., 2000). Olive growing is thus one of the major sources of environmental pressure in Mediterranean ecosystems worldwide, mainly related to the ever-increasing surface of the land devoted to this crop following the unprecedented global demand for olive products, including both olive oil and table olives.

Although olive trees show a widespread distribution in Mediterranean climate regions (Moriondo et al., 2013), some olive products (mostly olive oil) are characterized by some geographic distinctiveness, due to their singular environmental characteristics. In such cases, provided that every stage of the manufacturing process takes place within a delimited region, olive products can be granted a Protected Designation of Origin (PDO; EU, 2012). PDO olive products are mainly related to the use of traditional cultivars, which are adapted to local environmental conditions, including both climate and soil properties (EU, 2012). As such, there is a clearly established association between the characteristics of the final food product and the environmental distinctiveness of a given PDO. In Europe, which accounts for more than half of the total area of the world devoted to olive growing (IOC, 2022), there are more than one hundred ($n = 114$) PDO regions for olive products, mainly for olive oils (EC, 2022).

Climate change is suggested to have severe impacts on the spatial distribution patterns of environmentally suitable areas for olive growing (Moriondo et al., 2013; Tanasijevic et al., 2014; Ponti et al., 2014). Regardless of whether the objective proposed by the Paris Agreement of limiting global temperature increase to 2°C is achieved, in the coming years almost all olive growing regions will continue to experience large shifts in the local climate (Moriondo et al., 2013; Tanasijevic et al., 2014; Arenas-Castro et al., 2020). Climate change is thus expected to alter the potential future distribution of olive growing. However, whether and how climate change will impact the environmental suitability for olive growing areas and the distinctive environmental characteristics of PDOs is still far from being understood.

Here, we performed a spatially explicit Ecological Niche Modelling approach to project the environmental suitability for olive growing

throughout the Iberian Peninsula. Namely, we modelled environmental suitability for olive growing under two distinct climate change scenarios, the stabilization scenario (that is, Representative Concentration Pathway RCP 4.5) and the business-as-usual scenario (RCP 8.5), within the 2050 time horizon. We followed two complementary approaches to evaluate the impact of climate change on Iberian olive growing areas and PDO olive oil regions. First, we projected the spatial distribution patterns of environmentally suitable areas to assess potential future changes in the distribution of olive growing areas across the Iberian Peninsula, both within and outside PDOs. Second, we projected the climate conditions that PDOs will display in the face of climate change to evaluate their ability to retain their distinct environmental conditions.

Our study suggests that climate change causes unprecedented impacts on the olive industry, not only by altering the spatial distribution patterns of environmentally suitable areas for olive growing but also by threatening the ability of PDO regions to retain their current distinctive environmental conditions.

2. Material & methods

2.1. Study area

The Iberian Peninsula comprises two countries, Spain and Portugal, where olive distribution is concentrated in the central-southern part (Fig. 1). Specifically, this distribution is encompassed predominantly within 34 continental regions granted with Protected Designation of Origin status (Fig. 1; Supplementary Table S1). In Portugal, there are 6 registered PDOs spanning from the north to the south, whereas in Spain there are 28 continental PDOs, mostly located in the south and centre, with a few on the eastern side of the country. The assessment of environmental impacts is key in the study area, especially because the Iberian Peninsula and associated PDOs cover a wide range of soil and climate conditions, ranging from humid, mild, or cold areas to dry, warm areas, with considerable and progressive variations across them.

2.2. Data collection

2.2.1. Olive occurrence

The current distribution of olive growing areas was extracted from Corine Land Cover 2018 (EU, 2018), a data set that provides a classification of land cover on the scale of 1:10,000. First, we retained the land cover class representing cultivated areas with olive trees (CLC "2.2.3

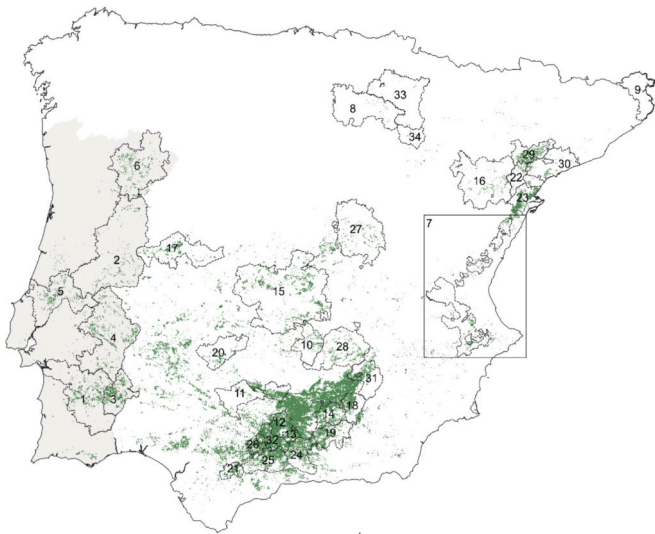


Fig. 1. - Study area: olive growing distribution across the Iberian Peninsula (in green) and numbered PDO olive oil regions of the Iberian Peninsula: 1 - Azeite do Alentejo Interior, 2 - Azeites da Beira Interior, 3 - Azeite de Moura, 4 - Azeites do Norte Alentejano, 5 - Azeites do Ribatejo, 6 - Azeite de Trás-os-Montes, 7 - Aceite de la Comunitat Valenciana, 8 - Aceite de la Rioja, 9 - Aceite de L'Empordà, 10 - Aceite Campo de Calatrava, 11 - Montoro-Adamuz, 12 - Baena, 13 - Priego de Córdoba, 14 - Sierra Mágina, 15 - Montes de Toledo, 16 - Aceite del Bajo Aragón, 17 - Gata-Hurdes, 18 - Sierra de Cazorla, 19 - Montes de Granada, 20 - Aceite Monterrubio, 21 - Sierra de Cádiz, 22 - Aceite de Terra Alta, 23 - Aceite del Baix Ebre-Montsià, 24 - Poniente de Granada, 25 - Antequera, 26 - Estepa, 27 - Aceite de La Alcarria, 28 - Aceite Campo de Montiel, 29 - Les Garrigues, 30 - Siurana, 31 - Sierra de Segura, 32 - Aceite de Lucena, 33 - Aceite de Navarra, 34 - Aceite Sierra del Moncayo. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Olive groves") limited to the Iberian Peninsula. Then, an olive occurrence map was generated by computing the centroids of each 10 km UTM square grid with the olive tree presence according to Corine, using Quantum GIS software version 3.22 (Fig. 1; QGIS.org, 2022). This step is essential, considering that the package 'sdm' represents the data on species occurrence as points (see below).

2.2.2. Protected designation of origin

Information on the geographical delimitation of PDO olive oil regions was obtained from Spanish and Portuguese governmental structures, respectively, the Spanish Ministerio de Agricultura, Pesca y Alimentación (MAPA, 2017) and the Portuguese Direção-Geral de Agricultura e Desenvolvimento Rural (DGADR, 2016). Since no detailed spatially explicit information was available for Portugal (e.g., shapefile data), we followed a simple two-step procedure to determine the Portuguese PDOs. First, we retrieved spatial information regarding the delimitation of Portuguese municipalities from the national open data portal of the Agência para a Modernização Administrativa (AMA, 2022); then, we selected those municipalities geographically representing the PDOs in their entirety, according to the information from Direção-Geral de Agricultura e Desenvolvimento Rural (DGADR, 2016), and generated shapefiles for each PDO region using Quantum GIS software. In a few cases, where the PDO occupied the municipality only partially, we considered the whole municipalities' extension as part of the PDOs. The spatial information data of the PDO regions were extracted on a 1:25.000 scale (see Supplementary Table S1).

2.3. Predictive variables

To determine the environmental correlates of the current distribution of olive growing throughout the Iberian Peninsula, we selected two

sets of variables, both of which are widely recognized as being relevant for olive distribution. These sets of variables ranged from local-scale (i.e., soil properties) to regional-scale drivers (bioclimatic conditions). Soil properties (i.e., soil pH) were extracted from the website of the Joint Research Centre of the European Union at a resolution of 250 m (EC, 2010). Bioclimatic data were extracted from WorldClim (Fick and Hijmans, 2017) and ClimateEU datasets (Marchi et al., 2020). We started with a set of 24 variables (a full list of the variables is available in Supplementary Table S2), considering all the bioclimatic variables in the WorldClim dataset and most of those in the ClimateEU dataset (those not repeating information from the WorldClim). The bioclimatic variables from WorldClim had a spatial resolution of 30 s (~1 km²). The variables of ClimateEU and the Joint Research Centre were resampled to match the resolution of the WorldClim dataset, using the "resample" (i.e., bilinear) function in the "raster" package (Hijmans, 2020).

To soften multicollinearity problems, we calculated the Variance Inflation Factor for all variables and excluded those with the highest VIF (VIF > 10; Naimi et al., 2014). As a result, we retained for further analysis the following ten variables: Mean Diurnal Range (bio2), Isothermality (bio3), Mean Temperature of Wettest Quarter (bio8), Mean Temperature of Driest Quarter (bio9), Precipitation of Warmest Quarter (bio18), Precipitation of Coldest Quarter (bio19), annual heat:moisture index (AHM), summer heat:moisture index (SHM), number of frost-free days (NFFD) and European Soil pH (pH).

2.4. Climate projections

We considered two Representative Concentration Pathways (RCP) climate scenarios, RCP 4.5 and RCP 8.5. RCP 4.5 is defined as a stabilization scenario, assuming that the concentration of greenhouse gases, particularly carbon dioxide, will peak around the year 2040, declining afterward. For this scenario, temperatures are expected to increase between 1.1 °C and 2.6 °C and radiative forcing levels stabilize at 4.5 W/m² in 2100. On the other hand, RCP 8.5 is defined as a high-emission business-as-usual scenario, assuming that greenhouse gas emissions will continuously increase throughout the 21st century without relevant mitigation measures (IPCC, 2022). In this scenario, temperatures are expected to rise between 2.6 °C and 4.8 °C, while radiative forcing levels reach 8.5 W/m² in 2100 and continue to rise thereafter. Climate projections were analysed for the medium-term time horizon spanning from 2020 to 2050. This 30-year period allows for the assessment of climate trends and variability over a significant timeframe and was based on its relevance to understanding climate change impacts within the study area. For both RCP climate change scenarios, we forecast our model to the several General Circulation Models (GCM; Goberville et al., 2015) available in the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012): CC (CCSM4), GF (GFDL-CM3), HE (HadGEM2-ES), IN (INMCM4), IP (IPSL-CM5A-LR) and MP (MPI-ESM-LR). This reduces uncertainties and leads to more reliable results under alternative future trends of changing climate (Supplementary Table S3; Tang et al., 2018). The climate projections were generated at a spatial resolution of 30 s, which corresponds to approximately 1 km² grid cells.

2.5. Modelling procedure

2.5.1. Climate change impacts on environmental suitability for olive growing

To project the spatial distribution patterns of environmentally suitable areas for olive growing in the Iberian Peninsula, both within and outside PDOs, and under the two RCP emission forcing scenarios, we first modelled current olive occurrence patterns using all predictive variables described above, resorting to an Ecological Niche Model (ENM). To calibrate the model, we selected an ensemble modelling approach, combining eight algorithms (Araújo and New, 2007): Classification and Regression Trees (Loh, 2011), Random Forests (Breiman, 2001), Mixture Discriminant Analysis (Hastie and Tibshirani, 1996),

Generalized Linear Models (McCullagh and Nelder, 1989), Generalized Additive Models (Hastie and Tibshirani, 1986), Multivariate Adaptive Regression Spline (Friedman, 1991), Support Vector Machines (Hearst et al., 1998) and Boosted Regression Trees (Ridgeway, 1999). The ensemble model was subjected to a 10-fold cross-validation procedure that was replicated 3 times and subsequently run using ten 70 % to 30 % data partitions to calibrate and evaluate the models (Guisan et al., 2017). The model captures the ecological niche of the species, projecting it into the geographic space. The final ensemble projection for each GCM and RCP was built using a TSS-weighted mean of each model (true skill statistic; Allouche et al., 2006). Finally, we computed an average projection across all GCMs for each RCP scenario (Supplementary Fig. S1 and Fig. S2). To evaluate the model adjustment, we resorted to the Area Under the Receiver Operating Characteristic curve (AUC; Hosmer et al., 2013), the true skill statistic (TSS; Allouche et al., 2006), sensitivity (proportion of correctly classified occurrences) and specificity (proportion of correctly classified absences).

We obtained environmental suitability maps for the species, projected into 1 km² cells under present and future environmental conditions. We used a quantile-based approach to classify these predictions into three classes: low (below the 33rd percentile), medium (33rd to 66th percentile), and high (above the 66th percentile). Therefore, each pixel was assigned a category based on these thresholds. Besides, the changes in suitability per cell, from present to future, were calculated as the difference between present and future class probabilities, with values ranging from -1 to +1 indicating, respectively, a loss and a gain in environmental suitability for olive growing. We adopted a similar procedure to assess the magnitude of change in environmental drivers on olive suitability under different RCP scenarios. First, we quantified the relative importance of each environmental variable from the ENM framework, normalizing these values to 100 % to establish a baseline understanding of each variable in predicting current suitability. We then averaged the values of each environmental variable, for each PDO, for current and future scenarios (RCP 4.5 and RCP 8.5). The magnitude of change was assessed using the percentage variation between present and future scenarios, and then by applying a weighting step where the percentage change for each variable was multiplied by its relative importance previously determined. The resulting weighted changes were then adjusted to a 100 % scale to ensure comparisons.

2.5.2. Climate change impacts on the environmental distinctiveness of PDOs

The same predictive variables used in the ENM were also used to characterize and project the distinctive environmental characteristics of PDOs under the two RCP scenarios. A set of Random Forests Models (Breiman, 2001), which was calibrated in the present and projected for the time period of 2050, was used to characterize the environmental envelope of each PDO. These models were trained to identify each of the 34 PDO regions. The methodology consists of running an ensemble of 10 models where each model was trained on a random selection of 70 % of the data and the remaining 30 % was used for validation. This maximizes the chance that every observation was included in at least one of the models in the set. The class probabilities (i.e., the probability of belonging to a PDO) of the ensemble model were obtained by averaging the individual class probabilities of all models. A ten-fold cross-validation with 3 repetitions was used to fine-tune the model parameters: the number of variables randomly sampled as candidates at each split and the number of trees. The best combination of parameters for the model sets was then used to train the final models. As a result of the modelling procedure, we obtained maps with the environmental envelope of PDOs projected in 1 × 1 km square cells for the present and future bioclimatic conditions. Similar to the procedure used for the output of the ENM, we calculated the changes per cell based on the difference between present and future class probabilities. The values range from -1 to +1, where positive values indicate a gain in environmental distinctiveness of PDOs, and negative values indicate a loss. To assess the environmental similarity between PDOs, the mean conditions of each environmental

variable for each PDO were obtained. A Principal Components Analysis was then run resorting to the PDO environmental mean values, obtaining a set of PDO clusters resorting to a k-Nearest Neighbour clustering algorithm. Additionally, we repeated the procedure mentioned in the previous section to understand the magnitude of change in environmental drivers for the PDO distinctiveness under different scenarios (RCP 4.5 and RCP 8.5).

All the analyses were carried out in the R environment, version 3.6.1 (R Core Team, 2019). We applied the R packages “usdm” (using the “vifstep” method for variable selection; Naimi et al., 2014) for the variable screening procedure, and “sdm” (Naimi and Araújo, 2016) to conduct the ENM. Additionally, we also applied the R package “randomForest” to run the Random Forests model (Naimi and Araújo, 2016; Liaw and Wiener, 2002), the base package “stats” to run the Principal Components Analysis and the R package “class” to run the k-Nearest Neighbour (Venables and Ripley, 2002).

3. Results

3.1. Climate change impacts on environmental suitability for olive growing

The ensemble modelling, projecting the environmental suitability of olive growing in the Iberian Peninsula, both within and outside PDOs, had a meanAUC value of 0.794, falling just short of the “excellent” threshold of model performance (0.8; Hosmer Jr et al., 2013). Additionally, results show a moderate discriminative power with respect to the TSS metric (0.516). Besides, the scores from sensitivity (0.787) and specificity (0.729) reveal a relative efficiency at correctly classifying, respectively, occurrences and absences. The suitability of olive is steadily lower with increasing values of precipitation during the warmest quarter (bio18). Inversely, it is markedly higher with the increase of summer heat:moisture index (SHM) and the number of frost-free days (NFFD; see Supplementary Fig. S3a for the relative importance of variables and Supplementary Fig. S4 for the response curves of all variables). Taking as a baseline the current environmental conditions (Supplementary Fig. S5; Supplementary Fig. S6), climate change will have a marked impact on the spatial distribution patterns of suitable areas for olive growing. Specifically, the results indicate a strong decrease in the environmental suitability for olive growing, most notably in the southern Iberian Peninsula, as a result of latitudinal shifts toward the north of the southern range boundaries (Fig. 2 on the left panel; Supplementary Table S4; Supplementary Fig. S7). The geographically shifting climate envelopes, on the other hand, will prompt northern latitudes of the Iberian Peninsula to experience more favourable environmental conditions for olive growing (Fig. 2 on the left panel; Supplementary Table S4; Supplementary Fig. S7). As for olive growing areas within PDOs, and regarding the magnitude of change in olive suitability under the RCP 4.5 scenario, results show that environmental drivers contributed diversely across each PDO (Fig. 3). Generally, precipitation during the warmest quarter (bio18) had the highest contribution score, followed by the annual heat-moisture index (AHM), then in minor contributions the Mean Temperature of Wettest Quarter (bio8), Mean Temperature of Driest Quarter (bio9) and Precipitation of Coldest Quarter (bio19; Fig. 3). Similar results were obtained for the RCP 8.5 scenario (Supplementary Fig. S8).

3.2. Climate change impacts on the environmental distinctiveness of PDOs

The Random Forests models used to characterize the environmental envelope of each PDO in a climate change context presented an accuracy score of 92 %, indicating a high model performance. Both soil and bioclimatic conditions influenced the environmental distinctiveness of Iberian PDOs. The Precipitation of Coldest Quarter (bio19) was detected as the most important variable, followed by the soil pH (pH) and the Precipitation of Warmest Quarter (bio18; Supplementary Fig. S3b).

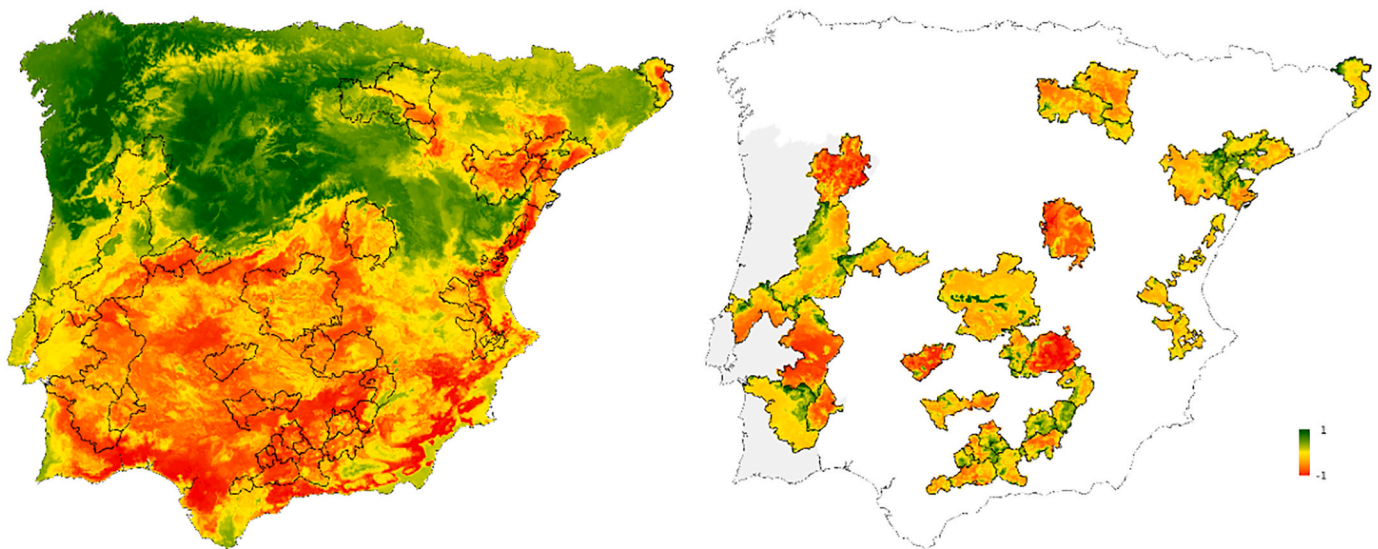


Fig. 2. Environmental suitability variation of olive growing across the Iberian Peninsula, within and outside PDOs (on the left panel), and environmental distinctiveness variation for each PDO (on the right panel), both under the RCP 4.5 climate scenario. The values -1 correspond to losses and values 1 correspond to gains, whether in suitability (on the left panel) or distinctiveness (on the right panel).

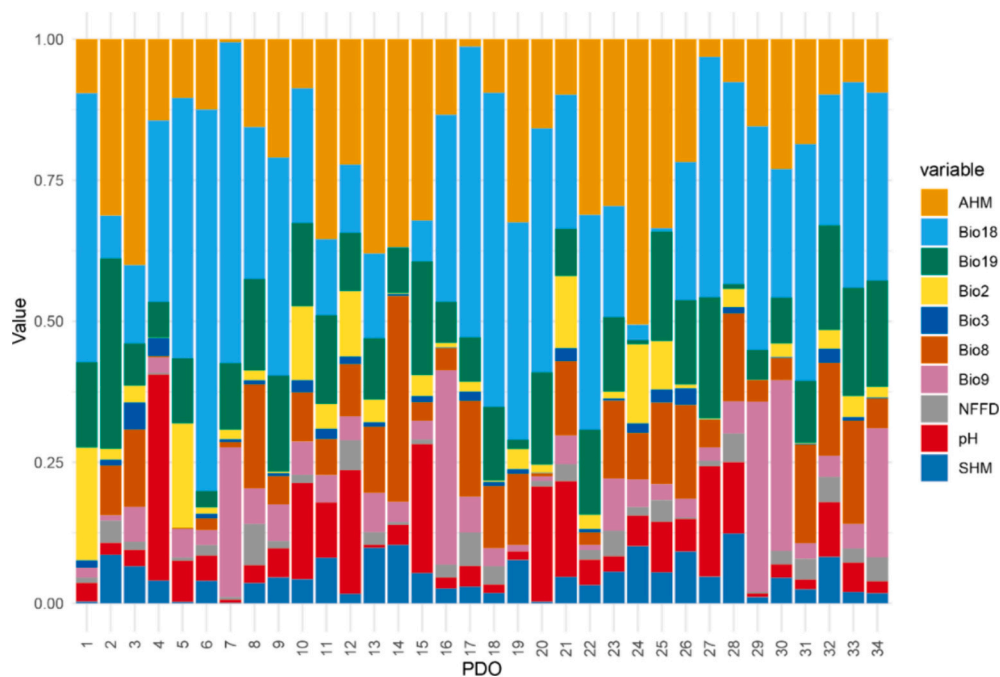


Fig. 3. Relative variable importance for changes in olive growing environmental suitability in each PDO under the RCP 4.5 climate scenario.

Results show that southern PDOs will be less likely to retain their geographically associated environmental envelopes irrespective of the evaluated climate change scenario (Fig. 2 on the right panel, Fig. 4, Supplementary Table S5; Supplementary Fig. S9). As we move further to the north, there is a smaller effect of climate change on the environmental distinctiveness of PDOs (Fig. 2 on the right panel, Fig. 4, Supplementary Table S5; Supplementary Fig. S9). The Principal Component Analysis used to examine the underlying factors contributing to the environmental distinctiveness of PDOs identified two components (PC1 and PC2) explaining 67 % of the total variance, with 4 geographically recognizable clusters (Supplementary Fig. S10). Regarding the magnitude of change in PDO distinctiveness, results show a high variation in contribution across PDOs, from the selected environmental drivers under the RCP4.5 scenario (Fig. 5). Generally, the annual heat-moisture

index (AHM), Precipitation of Warmest Quarter (bio18), and Precipitation of Coldest Quarter (bio19) contributed highly and similarly to changes in distinctiveness, while the Mean Temperature of Wettest Quarter (bio8), Mean Temperature of Driest Quarter (bio9), and summer heat:moisture index (SHM) had minor contributions (Fig. 5). Similar results were obtained for the RCP 8.5 scenario (Supplementary Fig. S11).

4. Discussion

We investigated the impact of climate change on olive growing areas in the Iberian Peninsula, both within and outside Protected Designation of Origin (PDO) regions, under two contrasting climate change scenarios for the 2050 time horizon. To achieve this challenging goal, we used two

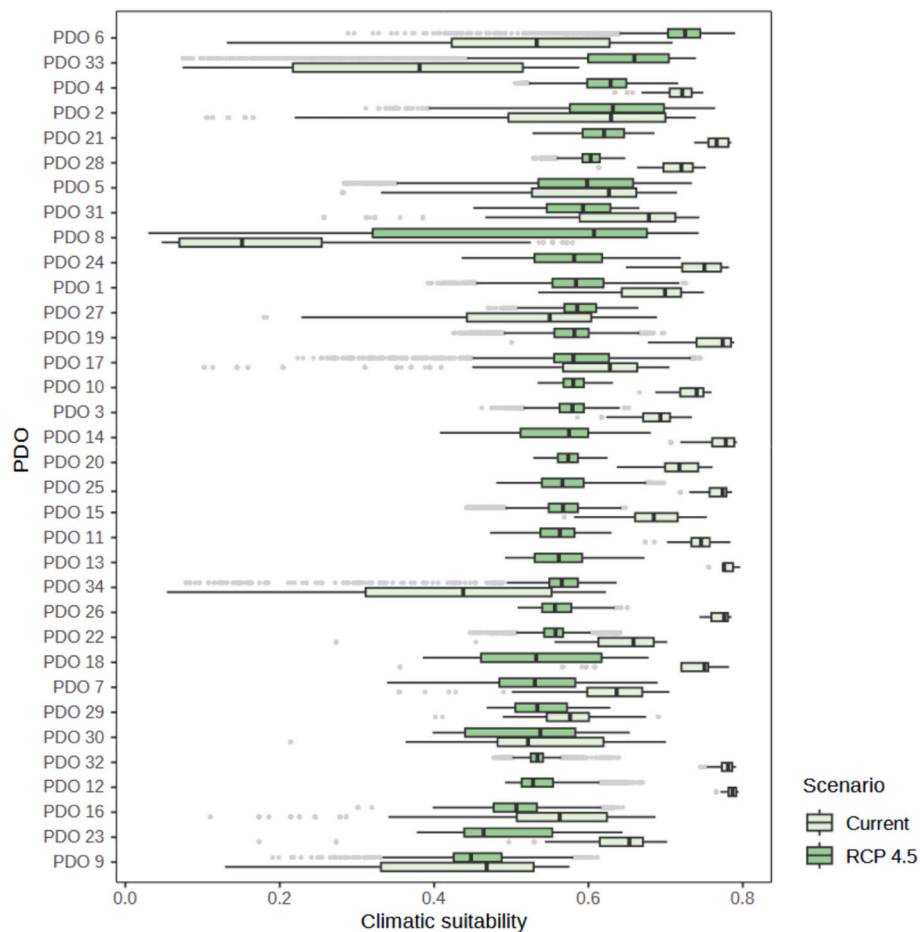


Fig. 4. Environmental distinctiveness in each PDO under the current and RCP 4.5 climate scenarios.

complementary approaches. On the one hand, we modelled current and projected future bioclimatic conditions in the Iberian Peninsula, including the ability of PDOs to retain environmentally suitable areas for olive growing. On the other hand, we modelled current and projected future bioclimatic conditions characterising PDOs to assess their ability to retain their environmental distinctiveness. Both approaches suggest severe impacts of climate change. More specifically, climate change will significantly reduce the environmental suitability for olive growing areas, particularly in the south of the Iberian Peninsula, as a consequence of generalized northward shifts of suitable areas. Furthermore, it will significantly impact the environmental distinctiveness of most PDOs, leading even to the disappearance of many of them, particularly in southernmost latitudes. Taking into consideration the high socio-economic relevance of the olive industry and the role of PDOs within it, our work suggests that the potential impacts of climate change will be even stronger than previously thought, going beyond alterations in the spatial distribution patterns of environmentally suitable areas for olive growing and reductions in crop productivity.

4.1. Climate change impacts on environmental suitability for olive growing

In close agreement with the existing literature, we found that climate change will have a strong impact on the spatial distribution patterns of environmentally suitable areas for olive growing (Tanasijevic et al., 2014; Ponti et al., 2014; Arenas-Castro et al., 2020). Thus, while suitable areas will decrease in the southernmost latitudes, the opposite trend is predicted in the northernmost latitudes (Moriondo et al., 2013; Tanasijevic et al., 2014; Arenas-Castro et al., 2020). To a large extent, this is

related to the generalized northward shifts in environmental variables that characterize suitable areas for olive growing in Mediterranean-like climate regions, including temperature and precipitation patterns (Tanasijevic et al., 2014; Ponti et al., 2014; Arenas-Castro et al., 2020). Specifically, low summer precipitation (bio18) contributes to reduced soil moisture levels, thereby minimizing the risk of waterlogging. Additionally, the increase in days without frost (NFFD) lowers the possibility of plant tissue damage. The summer heat:moisture index (SHM), reflecting combined summer temperature and moisture levels, is critical for olive growth and fruit ripening, which affects oil yield (Connor and Fereres, 2010). Interestingly, low summer precipitation (bio18) is one of the most influential drivers in olive suitability shift across the Iberian Peninsula, together with annual heat:moisture index (AHM), meaning that changes in these aspects are crucial for understanding olive growth capacity and adaptation (Tanasijevic et al., 2014). Remarkably, the sign and extent of projected range shifts in suitable areas, and the drivers contributing to that shift, did not differ significantly between both RCP 4.5 and RCP 8.5, suggesting the robustness of predictors across scenarios and pervasive impacts of climate change even in moderate climate change scenarios. However, our work goes beyond the existing literature by determining the effects of climate-driven range shifts in suitable areas for olive growing within and outside PDOs. Thus, we found that – as a consequence of the generalized northward shifts of all those variables that determine environmental suitability for olive-growing – climate change is expected to significantly reduce environmental suitability for olive growing in the Iberian Peninsula, particularly in the southernmost latitudes. In fact, this will inclusively impact the PDO regions of the southern Peninsula. For example, “Aceite de la Comunitat Valenciana” (PDO number 7) in Spain and the “Azeites do Ribatejo” (PDO number 5)

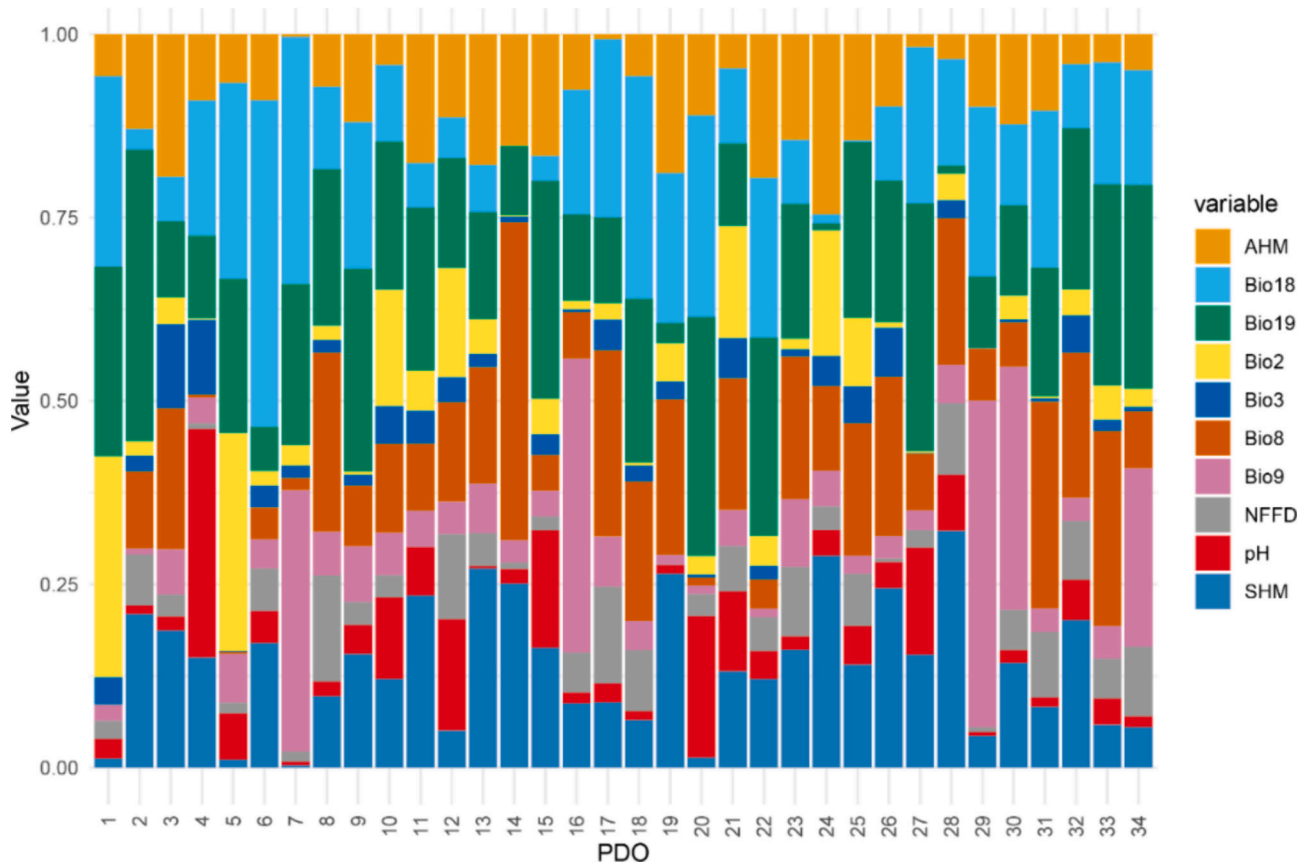


Fig. 5. Relative variable importance for changes in PDO distinctiveness under the RCP 4.5 climate scenario.

in Portugal are both suggested to show an overall decrease in environmental suitability for olive growing in both climate change scenarios (using median values), of 0.77 ± 0.22 (RCP 4.5) and 0.74 ± 0.26 (RCP 8.5), and 0.79 ± 0.41 (RCP 4.5) and 0.78 ± 0.4 (RCP 8.5), respectively (Supplementary Table S4). Conversely, northernmost latitudes will show an overall climate-driven increase in environmental suitability for olive growing. This includes PDO regions such as “Aceite de Navarra” (PDO number 33) in Spain and “Azeite de Trás-os-Montes” (PDO number 6) in Portugal, both of which are expected to increase their environmental suitability for olive growing by 0.78 ± 0.75 (RCP 4.5) and 0.8 ± 0.7 (RCP 8.5), and 0.85 ± 0.59 (RCP 4.5) and 0.85 ± 0.43 (RCP 8.5), respectively (Supplementary Table S4).

4.2. Climate change impacts on the environmental distinctiveness of PDOs

By definition, PDOs are closely related to the set of environmental variables that characterize a particular geographical region (EU, 2012). In fact, this distinctive environmental envelope is a key driver of the added value of PDO products whose qualities are specifically linked to the area of production. To date, the existing literature has focused primarily on characterising the environmental envelope of current olive growing locations to forecast the distribution of suitable areas for decades to come (see references above). For the first time, we suggest that the impact of climate change on the olive industry goes further by altering the environmental distinctiveness of PDOs from the Iberian Peninsula, one of the most important olive growing regions in the world (IOC, 2022). Forecasts, in fact, predict generalized climate-driven impacts on most PDOs regardless of the RCP scenario, although these impacts are expected to be slightly stronger in PDOs from the southernmost latitudes. Because our suitability models suggest the lack of a spatial pattern in the environmental distinctiveness of PDOs across the Iberian Peninsula, we hypothesize that this response pattern could be related to

the predicted higher rates of range shifts in temperature and precipitation regimes as latitude increases. Precipitation of Coldest Quarter has emerged as a key factor contributing to the environmental distinctiveness of PDOs, as it is critical for replenishing soil moisture, which impacts plant health and fruit quality (Connor and Fereres, 2010). Variations in the soil pH (pH) affect nutrient availability in the soil (Connor and Fereres, 2010). Additionally, the Precipitation of Warmest Quarter (bio18) impacts olive growth and fruit development, affecting both yield and quality (Connor and Fereres, 2010). These variations in all variables can have consequences on the flavour profiles and quality of olive oils (Connor and Fereres, 2010), which underscore the diversity of olive oils originating from distinct PDOs. This variability was observed in our findings regarding the impact of environmental drivers on PDO distinctiveness. However, our results show that while olive suitability was primarily influenced by a few variables with larger contributions, PDO distinctiveness was affected by a greater number of variables, each generally with individual contribution within each PDO, which highlights the complex, region-specific interactions between climatic factors and the unique characteristics of each PDO. Interestingly, in the model of environmental distinctiveness of PDOs, the variables pH, SHM, and bio9 exhibit a greater relative importance compared to their role in the environmental suitability for olive growing model. This discrepancy could be attributed to the broader scope of the environmental suitability for olive growing model, which encompasses interspecific diversity across all cultivars of olive species. Forecasts indeed predict that some of the southernmost PDOs will exhibit severe changes in their environmental envelopes, with some of them losing their distinctiveness almost completely. Such is the case, for example, with “Sierra de Cádiz” (PDO number 21) in Spain and “Azeite de Moura” (PDO number 3) in Portugal, where forecasts predict reductions in environmental distinctiveness (using median values) to 0.12 ± 0.18 (RCP 4.5) and 0.07 ± 0.09 (RCP 8.5), and to 0.07 ± 0.1 (RCP 4.5) and

0.04 ± 0.05 (RCP 8.5), respectively (Supplementary Table S5). For PDOs from northernmost latitudes, forecasts predict comparatively lower decreases in their environmental distinctiveness. This is the case, for example, of “Azeite de L’Empordà” (PDO number 9) in Spain and “Azeites da Beira Interior” (PDO number 2) in Portugal, both of which are expected to decrease their environmental distinctiveness by 0.38 ± 0.68 (RCP 4.5) and 0.27 ± 0.61 (RCP 8.5), and by 0.34 ± 0.63 (RCP 4.5) and 0.32 ± 0.62 (RCP 8.5), respectively (Supplementary Table S5). Furthermore, there are some PDOs that show local increases in environmental distinctiveness, which are possibly related to areas of higher altitude (data not shown). The main point is that, even if a PDO increases its overall environmental suitability for olive growing (e.g., those to the north), there is still a great loss of environmental distinctiveness. This means that although it is suitable for the cultivation of olive trees, the climate will be quite different from current conditions. Briefly, we can categorize the factors that influenced the environmental distinctiveness of PDOs into four groups. The northeastern PDOs were primarily affected by factors related to temperature and precipitation during specific periods of the year (i.e., bio8 and bio18). Meanwhile, the center-southern PDOs were essentially impacted by pH levels, temperature variations throughout the day and annual heat and moisture conditions (i.e., pH, bio2 and AHM). The southwestern PDOs were mainly influenced by factors linked to temperature and heat and moisture conditions during summer (i.e., bio3, bio9 and SHM) while northwestern PDOs were not particularly affected by any of the analysed factors.

4.3. PDOs and climate change adaptation

By dramatically altering the climate conditions of virtually all olive-growing regions throughout the Iberian Peninsula, climate change undeniably poses a major challenge to the olive industry. Currently, a critical concern is that olive yield and quality will decline unless relevant stakeholders, including farmers and researchers alike, can devise strategies to adapt the olive industry to shifting climates. Among possible solutions, selecting olive cultivars able to tolerate the new temperature and precipitation regimes imposed by climate change is increasingly gaining ground. Ideally, using these cultivars would allow farmers to continue growing olive trees in their current locations, both within and outside of the PDOs (Alfieri et al., 2019). Olive is, in fact, known to harbour a high diversity of cultivars linked to a high variation in a number of characteristics, including cold tolerance and reproductive phenology (Connor and Fereres, 2010). In the Iberian Peninsula, more than 320 different varieties have been documented, although only 36 are classified as economically relevant (Barranco and Rallo, 2000; DGAV, 2022; Jordão, 2014). Intraspecific diversity, as suggested by other authors, can then be suitable to adapt olive growing to shifting climates over time without moving across space (Morales-Castilla et al., 2020). This approach, however, will require updated and rigorous spatially explicit distribution maps of olive varieties to predict their specific resilience to climate change and, in turn, to suggest which varieties will be best for which regions in the future. Unfortunately, this information is currently absent for most olive varieties in the Iberian Peninsula, with the exception of some economically relevant varieties (e.g., Hojiblanca and Picual) in Spain’s Andalusia region (Arenas-Castro et al., 2020).

Nevertheless, such an approach is hardly adaptable to PDOs unless relevant stakeholders, including farmers, consumers, and policy makers, are willing to accept new varieties adapted to future conditions. This is mostly because, as stated above, PDOs are closely linked to the set of environmental variables that characterize a particular geographical region, allowing to grow only varieties with special characteristics related to the location (EU, 2012). Farmers with PDOs are, in fact, subjected to exclusively growing certain varieties if they want to continue to sell their products linked to a PDO. Such is the case, for example, with “Baena” (PDO number 12) and “Azeite do Alentejo Interior” (PDO number 1) in Spain and Portugal, which are obligated to grow primarily either

“Picudo” and “Galega Vulgar”, respectively, to preserve the geographical indication of their olive products (mostly olive oil). This being the case, all those producers within PDOs for which forecasts predict that olive yield and quality of current varieties will decline under new climate regimes are at a crossroads. Thus, they will have to choose between growing the varieties they know (thereby assuming climate-driven crop yield and quality losses) or embracing new varieties adapted to future climate conditions while rejecting any geographical indication for their olive products. In our opinion, olive farmers, just as other farmers devoted to any other crop, should not be confronted with this challenging decision. Paraphrasing Wolkovich et al. (2018), at a time when climate change demands resiliency and sustainability, investing in diversity and its by-products – this is, adaptability, flexibility, and resilience – is critical to maintaining crop yield and quality. Therefore, exploiting the current diversity of olive varieties should be explicitly considered and integrated into climate adaptation programs both within and outside PDOs. In any case, such in-place adaptation should undoubtedly preserve current local products and the know-how of local producers for the next generation of olive farmers.

CRedit authorship contribution statement

Inês Guise: Writing – original draft, Methodology, Data curation, Conceptualization. **Bruno Silva:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Frederico Mestre:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **José Muñoz-Rojas:** Writing – review & editing, Funding acquisition. **Maria F. Duarte:** Writing – review & editing, Funding acquisition. **José M. Herrera:** Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Scripts and Dataset (Reference data) (Figshare)

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Appendix A. Supplementary data

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References

- Alfieri, S.M., Riccardi, M., Menenti, M., Basile, A., Bonfante, A., De Lorenzi, F., 2019. Adaptability of global olive cultivars to water availability under future Mediterranean climate. *Mitig. Adapt. Strateg. Glob. Chang.* 24, 435–466. <https://doi.org/10.1007/s11027-018-9820-1>.
- Allouche, O., Tsoar, A., Kadmon, R., 2006. Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *J. Appl. Ecol.* 43 (6), 1223–1232. <https://doi.org/10.1111/j.1365-2664.2006.01214.x>.
- AMA, 2022. Concelhos de Portugal. Agência Para a Modernização Administrativa. <https://dados.gov.pt/pt/datasets/concelhos-de-portugal/> accessed 12 May 2022.
- Araújo, M.B., New, M., 2007. Ensemble forecasting of species distributions. *Trends Ecol. Evol.* 22, 42–47. <https://doi.org/10.1016/j.tree.2006.09.010>.
- Arenas-Castro, S., Gonçalves, J.F., Moreno, M., Villar, R., 2020. Projected climate changes are expected to decrease the suitability and production of olive varieties in southern Spain. *Sci. Total Environ.* 709, 136161 <https://doi.org/10.1016/j.scitotenv.2019.136161>.
- Barranco, D., Rallo, L., 2000. Olive cultivars in Spain. *HortTechnology* 10 (1), 107–110. <https://doi.org/10.21273/HORTTECH.10.1.107>.
- Breiman, L., 2001. Random forests. *Mach. Learn.* 45, 5–32. <https://doi.org/10.1023/A:1010933404324>.
- Connor, D.J., Fereres, E., 2010. The physiology of adaptation and yield expression in olive. In: *Horticultural Reviews*, vol. 31. John Wiley & Sons, Inc. <https://doi.org/10.1002/9780470650882.ch4>.
- DeAndreis, P., 2022. One-third of global olive oil production comes from intensive farming. *Olive Oil Times*. <https://www.oliveoiltimes.com/production/one-third-of-global-olive-oil-production-comes-from-intensive-farming/112809> (accessed 15 November 2022).
- DGADR, 2016. DOP - Denominação de Origem Protegida (Produtos agrícolas e géneros alimentícios). <https://tradicional.dgadr.gov.pt/pt/produtos-por-regime-de-qualidade/dop-denominacao-de-origem-protegida> accessed 10 May 2022.
- DGAV, 2022. Registo Nacional de Variedades de Fruteiras. https://www.dgav.pt/wp-content/uploads/2022/08/DGAV_RNVF-2022_2Edi.pdf accessed 21 September 2023.
- EC, 2010. Soil pH in Europe. European Commission, Joint Research Centre (JRC). <http://data.europa.eu/89h/jrc-esdac-22>.
- EC, 2022. Geographical indications registers. *Agricult. Rural Dev.* <https://agriculture.ec.europa.eu/farming/geographical-indications-and-quality-schemes/geographical-indications-registers-en> (accessed 9 May 2022).
- EU, 2012. Regulation (EU) no 1151/2012 of the European Parliament and of the Council of 21 November 2012 on Quality Schemes for Agricultural Products and Foodstuffs. European Union: Brussels, Belgium. Official Journal of the European Union. <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:343:0001:0029:en:PDF>. accessed 26 May 2022.
- EU, 2018. Copernicus Land Monitoring Service. European Environment Agency (EEA).
- FAO, 2022. FAOSTAT - Food and agriculture data. <http://www.fao.org/faostat> accessed 22 July 2022.
- Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* 37 (12), 4302–4315. <https://doi.org/10.1002/joc.5086>.
- Friedman, J.H., 1991. Multivariate adaptive regression splines. *Ann. Stat.* 19, 1–67. <https://doi.org/10.1214/aos/1176347963>.
- Goberville, E., Beaugrand, G., Hautekèete, N.C., Piquot, Y., Luczak, C., 2015. Uncertainties in the projection of species distributions related to general circulation models. *Ecol. Evol.* 5 (5), 1100–1116. <https://doi.org/10.1002/ece3.1411>.
- Guisan, A., Thuiller, W., Zimmermann, N.E., 2017. *Habitat Suitability and Distribution Models: With Applications in R*, 1st ed. Cambridge University Press. <https://doi.org/10.1017/9781139028271>.
- Hastie, T.J., Tibshirani, R.J., 1986. *Generalized additive models (1st Editio)*. Routledge. <https://doi.org/10.1201/9780203753781>.
- Hastie, T., Tibshirani, R., 1996. Discriminant analysis by Gaussian mixtures. *J. R. Stat. Soc. B. Methodol.* 58, 155–176. <https://doi.org/10.1111/j.2517-6161.1996.tb02073.x>.
- Hearst, M.A., Dumais, S.T., Osuna, E., Platt, J., Scholkopf, B., 1998. Support vector machines. *IEEE Intell. Syst. Appl.* 13 (4), 18–28. <https://doi.org/10.1109/5254.708428>.
- Hijmans, R.J., 2020. Raster: geographic data analysis and modeling. R package version 3.1–5. <https://cran.r-project.org/package=raster>.
- Hosmer Jr., D.W., Lemeshow, S., Sturdivant, R.X., 2013. *Applied Logistic Regression*, 3rd ed. John Wiley & Sons. <https://doi.org/10.1002/0471722146>.
- IOC, 2022. The world of olive oil. IOC News. <https://www.internationaloliveoil.org/the-world-of-olive-oil/> (accessed 7 June 2022).
- IPCC, 2022. In: Pörtner, H.O., Roberts, D.C., Tignor, M., Poloczanska, E.S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B. (Eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA. <https://doi.org/10.1017/9781009325844>.
- Jordão, P., 2014. *Boas práticas no Olival e no Lagar*, 1st ed. Instituto Nacional de Investigação Agrária e Veterinária, I.P. (INIAV, I.P.), Oeiras, Portugal.
- Liaw, A., Wiener, M., 2002. Classification and regression by randomForest. *R News* 2 (3), 18–22.
- Loh, W.Y., 2011. Classification and regression trees. *Wiley Interdiscip. Rev. Data Min. Knowledge Discov.* 1, 14–23. <https://doi.org/10.1002/widm.8>.
- MAPA, 2017. *Calidad Diferenciada*. <https://www.mapa.gob.es/es/cartografia-y-sig/ide/descargas/alimentacion/calidad-diferenciada.aspx> accessed 13 May 2022.
- Marchi, M., Castellanos-Acuña, D., Hamann, A., Wang, T., Ray, D., Menzel, A., 2020. ClimateEU, scale-free climate normals, historical time series, and future projections for Europe. *Scientific Data* 7, 428. <https://doi.org/10.1038/s41597-020-00763-0>.
- McCullagh, P., Nelder, J.A., 1989. *Generalized Linear Models*, 2nd ed. Chapman & Hall. <https://doi.org/10.1201/9780203753736>.
- Morales-Castilla, I., García de Cortázar-Atauri, I., Cook, B.I., Lacombe, T., Parker, A., Van Leeuwen, C., Wolkovich, E.M., 2020. Diversity buffers winegrowing regions from climate change losses. *Proc. Natl. Acad. Sci.* 117 (6), 2864–2869. <https://doi.org/10.1073/pnas.1906731117>.
- Moriondo, M., Trombi, G., Ferrise, R., Brandani, G., Dibari, C., Ammann, C.M., Lippi, M., Bindi, M., 2013. Olive trees as bio-indicators of climate evolution in the Mediterranean Basin. *Glob. Ecol. Biogeogr.* 22 (7), 818–833. <https://doi.org/10.1111/geb.12061>.
- Myers, N., Mittermeier, R.A., Mittermeier, C.G., Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. *Nature* 403, 853–858. <https://doi.org/10.1038/35002501>.
- Naimi, B., Araújo, M.B., 2016. Sdm: a reproducible and extensible R platform for species distribution modelling. *Ecography* 39 (4), 368–375. <https://doi.org/10.1111/ecog.01881>.
- Naimi, B., Hamm, N.A.S., Groen, T.A., Skidmore, A.K., Toxopeus, A.G., 2014. Where is positional uncertainty a problem for species distribution modelling? *Ecography* 37 (2), 191–203. <https://doi.org/10.1111/j.1600-0587.2013.00205.x>.
- Ponti, L., Gutierrez, A.P., Ruti, P.M., Dell'Aquila, A., 2014. Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers. *Proc. Natl. Acad. Sci. USA* 111 (15), 5598–5603. <https://doi.org/10.1073/pnas.1314437111>.
- QGIS.org, 2022. QGIS Geographic Information System. QGIS Association. <http://www.qgis.org>.
- R Core Team, 2019. R: a language and environment for statistical computing. In: *R foundation for statistical computing (3.6.1)*. <https://www.r-project.org/>.
- Ridgeway, G., 1999. The state of boosting. *Comput. Sci. Stat.* 31, 172–181.
- Tanasijevic, L., Todorovic, M., Pereira, L.S., Pizzigalli, C., Lionello, P., 2014. Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. *Agric. Water Manag.* 144, 54–68. <https://doi.org/10.1016/j.agwat.2014.05.019>.
- Tang, Y., Winkler, J.A., Viña, A., Liu, J., Zhang, Y., Zhang, X., Li, X., Wang, F., Zhang, J., Zhao, Z., 2018. Uncertainty of future projections of species distributions in mountainous regions. *PLoS One* 13, e0189496. <https://doi.org/10.1371/journal.pone.0189496>.
- Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* 93 (4), 485–498. <https://doi.org/10.1175/BAMS-D-11-00094.1>.
- Venables, W.N., Ripley, B.D., 2002. *Modern Applied Statistics with S, Fourth edition*. Springer, New York. ISBN 0-387-95457-0.
- Wolkovich, E.M., García De Cortázar-Atauri, I., Morales-Castilla, I., Nicholas, K.A., Lacombe, T., 2018. From pinot to Xinomavro in the world's future wine-growing regions. *Nat. Clim. Chang.* 8 (1), 29–37. <https://doi.org/10.1038/s41558-017-0016-6>.