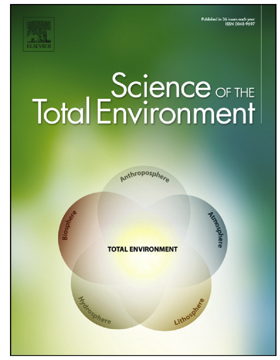
Journal Pre-proof



Projected climate changes are expected to decrease the suitability and production of olive varieties in southern Spain

Salvador Arenas-Castro, João Gonçalves, Manuel Moreno, Rafael Villar

PII: S0048-9697(19)36157-1

DOI: https://doi.org/10.1016/j.scitotenv.2019.136161

Reference: STOTEN 136161

To appear in: *Science of the Total Environment*

Received date: 24 July 2019

Revised date: 28 October 2019

Accepted date: 14 December 2019

Please cite this article as: S. Arenas-Castro, J. Gonçalves, M. Moreno, et al., Projected climate changes are expected to decrease the suitability and production of olive varieties in southern Spain, *Science of the Total Environment* (2019), https://doi.org/10.1016/j.scitotenv.2019.136161

Projected climate changes are expected to decrease the suitability and production of olive varieties in southern Spain

Salvador Arenas-Castro[a,c,*], João Gonçalves[b], Manuel Moreno[d] and Rafael Villar[c]

[a]CICGE - Centro de Investigação em Ciências Geo-Espaciais, Faculdade de Ciências, Universidade do Porto, Observatório Astronómico "Prof. Manuel de Barros", Alameda do Monte da Virgem, 4430-146 Vila Nova de Gaia, Portugal

[b]InBIO/CIBIO - Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto, Campus Agrário de Vairão, Rua Padre Armando Quintas, 4485-601 Vairão, Portugal

[c]Área de Ecología, Dpto. de Botánica, Ecología y Fisiología Vegetal, Facultad de Ciencias, Universidad de Córdoba, Campus de Rabanales, 14071 Córdoba, España

[d]IFAPA, Alameda del Obispo, Avda. Menéndez Pidal s/n, 14004 Córdoba, España

[*]**Corresponding author:** Salvador Arenas-Castro, e-mail: sarenascastro78@gmail.com

Present address: CICGE - Centro de Investigação em Ciências Geo-Espaciais, Faculdade de Ciências, Universidade do Porto, Observatório Astronómico "Prof. Manuel de Barros", Alameda do Monte da Virgem, 4430-146 Vila Nova de Gaia, Portugal

João Gonçalves: jfgoncalves@fc.up.pt

Manuel Moreno: mogam79@hotmail.com

Rafael Villar: rafael.villar@uco.es

Abstract

World olive production is based on the cultivation of different varieties that respond differently to abiotic factors. Climate change may affect the area of land suitable for olive cultivation and change production levels, thus causing serious damage to this economically-relevant and highly-productive olive grove agroecosystem. In Mediterranean regions such as Andalusia, one of the main areas of olive production, the effect of climate change seems threatening. Thus, our main aims are: (1) to examine the abiotic factors that characterise the current cultivated locations and predict the current and potential distribution of these locations; (2) to evaluate the effect of climate change (based on regional scenarios) on the future environmental suitability of each olive variety; and (3) to analyse the expected alteration in the annual olive production. We used the seven most-productive olive varieties in Andalusia and the wild olive species to develop Species Distribution Models (SDMs), coupled with soil properties, geomorphology, water balance and (bio-)climatic predictors at a fine scale. We also derived future climate projections to assess the effect of climate change on the environmental suitability and productivity of each olive variety. We found that soil pH was the most-important factor for most distribution models, while (bio-)climatic predictors - such as continentality index, summer and autumn precipitation and winter temperature - provided important contributions. In general, projections based on regional climate change scenarios point to a decrease in the area suitable for olive crops in Andalusia, due to an increase in evapotranspiration and a decrease in precipitation. These changes in suitable area are also projected to decrease olive production for almost all the olive-growing provinces investigated. Our findings may anticipate the effects of climate change on olive crops and provide early estimates of fruit production, at local and regional scales, as well as forming the basis of adaptation strategies.

Keywords: climate change, drought, environmental suitability, olive tree, olive production, Species Distribution Models

1. Introduction

The cultivation of the olive tree (*Olea europaea* subsp. *europaea*) is an ancient tradition in the Mediterranean Basin (Rallo et al., 2005; Kaniewski et al., 2012), with great importance in the ecology, economy and culture of this area (Carrión et al., 2010). The olive grove is considered as an agroecosystem with a marked multi-functionality and a significant potential to provide ecosystem services related to provisioning (e.g. olives and wood), regulation and maintenance (e.g. water regulation, CO_2 fixation) and cultural heritage (e.g. biodiversity conservation, generation of high-value agricultural landscapes) (Garbach et al., 2017; Haines-Young and Potschin, 2018). Overall, olive agroecosystems thrive on different types of soil, preferably deep soils that are light-textured and well-drained (Barranco et al., 2005). Olives also grow at different altitudes, from sea level up to 900-1000 m a.s.l. (even at 1200 m a.s.l.). Although olive trees can tolerate high levels of drought stress, drought affects tree and shoot growth, foliage formation and fruiting. Olive trees have a physiological requirement for low temperature (i.e., a vernalisation period) and can tolerate different temperature regimes depending on the geographic location, being able to withstand temperatures of -8ºC for short durations and an upper limiting temperature of around 35ºC (Krishna, 2013). Nowadays, olive groves occupy more than 5 million ha in the European area of the Mediterranean Basin and 2.6 million ha are located in Spain (DGARD-EC, 2012), of which 1.5 million ha (60%) are in Andalusia (CAPDER, 2013; MAPA, 2013).

The olive derives from the domestication of a common ancestor (*Olea europaea* var. *sylvestris* Mill.) (Terral et al., 2004; Besnard et al., 2013). The objective of the repeated cycles of selection and improvement is to obtain certain morphological and agronomic characteristics for: i) better adaptation to the environmental conditions, ii) high yield and iii) a great range of organoleptic profiles. This has produced a progressive increase in the number of varieties. It is estimated that there are more than 2000 varieties worldwide, many of which are traditional and very old with little representation in the current olive crop. In Spain, 262 different varieties have been documented (Barranco and Rallo, 2000), although only 24 are classified as important and regularly used in oil production (Barranco, 2004). In the case of Andalusia (southern Spain), 156 varieties have been described of which only seven are considered as the most relevant, constituting 90% of the Andalusian olive area. Most of the Andalusian varieties are very old and are grown in the areas where they were originally selected by farmers (Rallo et al., 2014). However, the rapid expansion of only a few varieties from nurseries that is taking place not only in Andalusia, but also worldwide, could be causing the regression of those varieties with an ancestral distribution (Diez et al., 2015). In addition, the continuous process of modernisation and intensive management to which the olive cultivation is subjected currently and the imperatives of global supply and demand are resulting in the homogenisation of the olive cultivation and a serious loss of agronomic biodiversity. This situation endangers traditional varieties, a source of genetic diversity that might be very useful under new and unforeseen scenarios of climate change, diseases or pests, or to obtain new varieties of olive trees adapted to the new and innovative cultivation techniques. Thus far, we do not know much about the requirements of the different varieties and how they can be affected by climate change.

For the Mediterranean Basin, and especially for Andalusia, it is estimated that climate change will result in substantial warming and a significant decrease in precipitation in the coming decades (Dell'Aquila et al., 2012; Gualdi et al., 2013), which might cause serious ecological, economic and social changes. Because the different olive varieties are adapted to specific climatic, edaphic and lithological conditions, the variations that could occur in a context of climate change would have a significant impact on the distribution of olive varieties and, as a consequence, their growth and productivity (Moriondo et al., 2008; Ponti et al., 2014). Some olive-growing regions where traditional varieties are cultivated - yielding fruit, and thus oil, of high quality - are located in relatively-narrow geographic niches and have specific microclimatic characteristics (Rubio de Casas et al., 2002). As such, these varieties exhibit greater vulnerability to both short-term climate variability and long-term climate change (Olesen et al., 2011). Therefore, the areas suitable for the production of the main olive varieties in Andalusia could expand or contract due to the effects of climate change (Moriondo et al., 2013). Previous re-constructions and simulations of olive-growing areas showed that a northwards expansion is expected to occur by the end of the century due to the warmer and drier conditions anticipated in the coming decades across the Mediterranean basin (Moriondo et al., 2013). Thus, given the socio-economic importance of olive groves and the need to optimise the resources invested in the production of fruits and oil, it is important to determine the current and potential distribution of areas suitable for olive cultivation. This is especially the case for the varieties with the most cultural and economic importance, to ensure high and stable yields in the future. Nowadays, Spain produces 33% of all the olive oil in the world, making it the world's leading producer, with 80% of this being produced in Andalusia. Thus, changes in environmental suitability for the different olive varieties grown in Andalusia could have a serious impact on olive production.

Here, we use Species Distribution Models (SDMs) to investigate changes in the spatial distribution of the seven most-important olive varieties cultivated in Andalusia and the wild olive tree (*O. europaea* var. *sylvestris*). Traditionally, SDMs have been used by ecologists and biologists to model the distribution and the spatial patterns of a wide range of species (Thomas et al., 2004; Elith and Leathwick, 2009; Franklin et al., 2013; Merow et al., 2014). These correlative models allow us to analyse the empirical relationships between the occurrence (or abundance) of a species and the environmental or abiotic factors that enable its existence (Elith and Leathwick, 2009). However, SDMs are also being used increasingly to model cultivated crops (Miller and Knouft, 2006; Sun et al., 2012; Estes et al., 2013), including cultivated olive trees as domesticated species and the wild olive tree as the ancestor (Besnard et al., 2013). In the latter study, the authors unravelled the geographic origins of wild olives, and then inferred the parallel expansion of human civilizations and the primary origins of the domesticated olive along the Mediterranean Basin. Thus, by using SDMs, spatial and temporal projections can be obtained, allowing us to investigate the suitability of different olive varieties for the environmental conditions, as well as their current and future potential distributions.

Our aim in this study is to know the main factors responsible for the distribution of different olive varieties and to forecast the effect of climate change on the environmentally-suitable area and on olive production in Andalusia. The specific objectives are: (1) to examine the abiotic factors that characterise the locations where the wild olive tree and seven olive varieties are currently cultivated in Andalusia, and predict their current and potential distribution; (2) to project the future distribution and assess the environmental suitability of each olive variety, by incorporating regional climate change scenarios specifically developed for the Andalusia region; and (3) to analyse the predicted suitable area for each olive variety, as a proxy of olive annual production , and its expected trend as a consequence of climate change. Using the future potential distribution areas of the main cultivated olive varieties, we were able to evaluate the potential effects of climate change on the economic activity of the region in terms of production.

2. Material and methods

2.1. Study area

The study was carried out in Andalusia (southern Spain) (Fig. 1). This region spans a total area of 87268 km² (17.4% of the Spanish territory), which explains its considerably-varied orographic and hydrographic features, climate types and high biodiversity (Myers et al., 2000). Although the maximum elevation is 3500 m a.s.l., mountains of moderate height (below 1000 m a.s.l.) predominate in the Andalusian landscape (42% of its total surface area). It has a temperate Mediterranean climate characterised by mild temperatures (annual average temperature above 16.0°C and 300 sunny days per year throughout most of its territory), with dry summers and short, mild winters. The total annual precipitation ranges from 170 mm to more than 2000 mm; it is generally concentrated in autumn, winter and spring, increasing from east to west. Depending on the altitude, the threshold temperature for growth fluctuates considerably among provinces: 12.5°C in Córdoba, 7.0°C in Jaén and 6.0°C in Granada. Warm temperatures and moderate rainfall during the fruit-ripening period favour fruit production (Minero et al., 1998), and olive harvesting takes place in late autumn and winter, usually from November to January.

Insert Fig. 1.

2.2. Olive varieties

Among the long list of olive varieties which are currently cultivated in Andalusia, we selected those catalogued as “principal” and that are the most used in Andalusian olive groves in rain-fed regimes (Rubio de Casas et al., 2002), namely: *Hojiblanca* (Hj), *Lechín de Sevilla* (Lch), *Manzanilla de Sevilla* (Mnz), *Nevadillo negro* (Nvd), *Picudo* (Pcd), *Picual* (Pcl) and *Verdial de Huévar* (Vrd) (Table 1). We also used the wild olive tree (Acebuche, Oe), closely related to the domesticated olive tree. Two varieties stand out for their importance in terms of area in Andalusia: *Picual*, which represents about 60% of the olive groves, and *Hojiblanca*, with around 20%.

Table 1. Summary of the presence-only records used in the study. Data from the Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (Government of Andalusia, Spain), except Acebuche: [a]GBIF (http://www.gbif.org).

Target	Code	Main features	Area (km^2)
Acebuche	Oe	Wild species of reference	2161[a]
Hojiblanca	Hj	Very-frequent olive-tree variety cultivated in plant nurseries	7868
Lechín de Sevilla	Lch	Frequent olive-tree variety in plant nurseries	3221
Manzanilla de Sevilla	Mnz	Frequent table olive-tree variety in plant nurseries	2654
Nevadillo negro	Nvd	Traditional olive-tree variety	1114
Picudo	Pcd	Traditional olive-tree variety	2459
Picual	Pcl	Very-frequent olive-tree variety in plant nurseries	18677
Verdial de Huévar	Vrd	Traditional olive-tree variety	865

2.3. Data collection

2.3.1. Presence input data

A total of seven olive varieties and one wild species were used for model calibration. Presence-only data for the seven cultivated varieties were collected from the CAPDER corresponding to the 1998/99 agricultural season. This is the most-complete database of olive varieties compiled so far in relation to spatial and temporal extensions. The presence-only records of the wild olive were extracted from the Global Biodiversity Information Facility database (GBIF, http://www.gbif.org) (Table 1). These data were filtered and harmonised before the modelling procedures. In total, more than 25000 occurrence points in grid cells with a resolution lower than 1 km were used to calibrate the models. A grid with 1×1 km squares was generated to standardise the processing of input data. This resolution allowed us to relate the occurrence data to climatic, lithological and topographical features. The cartographic processing, as well as the treatment of maps derived from the models, was performed in Quantum GIS (QGIS 2018) software version 2.18.11 (open source software) and ArcGIS version 10.2 (ESRI 2013).

2.3.2. Predictive variables

In Species Distribution Modelling (and Ecological Niche Modelling in general), there are several criteria to select predictors. Normally, the variable selection is based on expert knowledge, previous literature on the ecology of the target species and the construction of preliminary statistical models or exploratory analysis such as testing the associations between predictors (to reduce multicollinearity). Thus, we used all these approaches in the selection of the variables used in this study.

To know which variables can predict the distribution, suitability and productivity of olive varieties in the region (Rubio de Casas et al., 2002), we selected variables (predictors) that can be aggregated into four groups related to plant physiology and distribution, ranging from local/fine-scale attributes, i) soil properties and ii) geomorphology, to regional/coarse-scale factors related to iii) water balance and iv) (bio-)climatic conditions. Geomorphological, water balance and climatic data were obtained from the Red de Información Ambiental de Andalucía (REDIAM, Government of Andalusia, Spain), originally in 200 × 200 m units. We derived topographic attributes from the Digital Elevation Model data (DEM; 2006-2007) by using spatial analysis tools of QGIS. Soil properties were retrieved originally, at a resolution of 5 km, from the Map of Soil pH in Europe (LRMUIES-EU, 2010). All environmental variables were processed in QGIS software to the geographical coordinate system WGS 1984, in order to obtain a spatial resolution equal to that of the occurrence data (1 km^2). The initial dataset included 21 candidate predictors (Table SI1, Supplementary Material).

Considering that we used a correlative approach for modelling, and a higher correlation between predictors could increase the uncertainty and redundancy of our models, we applied a multicollinearity test to optimise and simplify the models by reducing the initial number of variables. For this, a preliminary Spearman correlation analysis was developed to check the correspondence between the occurrence data and variables. After that, and to avoid multicollinearity effects by verifying if strong linear associations existed between any selected predictors, we used Spearman's correlation coefficient (Dormann et al., 2013). Only those independent variables for each variety with Spearman correlation of <0.8 between pairs of environmental factors (Elith et al., 2006) were retained as predictors for further model processing (Fig. SI1). In addition, and considering that the olive grove require Mediterranean-like climatic and agro-ecological conditions, with locally-extreme microclimatic influence depending on the selected variety, we choose those predictors that better represent the extreme limiting factors of each variety. Thus, the final dataset included eight predictors: soil pH (SLPH; unitless), slope (SLPC; %), solar orientation (SLOR; degrees), evapotranspiration

(EVTP; mm/year), summer precipitation (PRSM; mm), autumn precipitation (PRAU; mm), average winter temperature (TPWT; °C) and the continentality index (IDCT; °C).

2.3.3. Regional climate projections for Andalusia

To understand the future distribution and assess the environmental suitability of each olive variety, we used the Local Scenarios of Climate Change of Andalusia (ELCCA) (URL: http://www.juntadeandalucia.es/medioambiente/site/rediam). These regional climate change scenarios were specifically developed for the Andalusia region to represent the changes expected in the climate in the coming decades, according to studies carried out on a planetary scale. The scenarios were produced from the Third Generation Coupled Global Climate Model (MCGs; CNCM3), for a balance across all sources (A1b; IV IPCC Report), for three periods: 2011-2040 (“Proj-2040”), 2041-2070 (“Proj-2070”) and 2071-2100 (“Proj-2100”). The baseline (current) climatic data used to run the models comprised the average values for the interval 1961-2000. From these simulations, (bio-)climatic variables (such as monthly precipitation and temperature) were derived. We then calculated aggregation statistics (the mean as well as the 5%, 50% and 95% quantiles) for all the climatic variables, to assess projected changes in the study region.

2.4. Modelling procedure

2.4.1 Model calibration and evaluation

The ensemble-forecasting framework has been established as a powerful tool for the modelling of relationships between environmental factors and spatial patterns of biodiversity for a wide range of species (Araújo and New, 2007). Thus, we calibrated static SDMs based on the ensemble-forecasting approach, and implemented in the ‘biomod2’ package (Thuiller, 2014), available at http://cran.r-project.org/web/packages/biomod2/index.html), which includes 10 modelling techniques that were calibrated (with model parameters set to default) and combined. The algorithms available are: (1) generalized linear model (GLM); (2) generalized additive model (GAM); (3) generalized boosted models (GBM); (4) classification tree analysis (CTA); (5) flexible discriminant analysis (FDA); (6) random forests (RFO); (7) artificial neural networks (ANN); (8) multivariate adaptive regression splines (MRS); (9) maximum entropy using Phillip’s Maxent software (MXP) and (10) maximum entropy in Tsuruoka’s R package (MXT).

Since only presence data were available for each olive variety, we generated a total of 10 sets of randomly-distributed pseudo-absences in the model calibration (PA; also called ‘background’ points), equal in number to the presence points (Barbet-Massin et al., 2012). The use of PA is required to overcome the lack of the ‘true-absence’ data needed for model calibration, but it also holds some advantages related, for example, to the avoidance of erroneous or false absences (Lobo et al., 2010; Barbet-Massin et al., 2012). We used a prevalence of 0.5 for each variety, no rescaling of model projections and calibration of the final full models (i.e., a final calibration round including all training points without a train/test split). A prevalence of 0.5 in the case of ‘biomod2’ (Thuiller, 2009; Thuiller, 2014) means that absences will be weighted equally to presences (i.e., the weighted sum of presences equals the weighted sum of absences). We employed hold-out cross-validation to evaluate the models, with 20 evaluation rounds for each PA set. Due to the very-large number of training points (TP; including both presences and pseudo-absences), we defined a rule for adjustment of the train/test split by setting a maximum of 3000 TP’s. By default, if a given olive variety had less than this number of TP’s, then the train/test split was set to 80%/20%; otherwise, it was adjusted to include a percentage equal to the maximum number of 3000 TP’s (Table SI2).

Two measures of model performance and discrimination ability were used: (i) the Area Under the Receiver Operating Characteristics (AUC-ROC) curve and (ii) True-skill statistic (TSS). AUC is an effective, threshold-independent measure of a model’s ability to discriminate presence from absence (Baasch et al., 2010), and ranges between 0 and 1 (here, values < 0.7 were considered poor, 0.7–0.9 moderate and > 0.9 good). We also used the TSS values as a threshold-dependent measure of model accuracy. Since TSS ranged from -1 (indicating agreement no better than random classification) to 1 (indicating perfect agreement between predictions and observations), we considered TSS values < 0.4 poor, 0.4–0.8 useful and > 0.8 good-excellent (see Text SI1, Supplementary Material).

2.4.2 Ensemble forecasting

The ‘biomod2’ R package allows rounds of modelling to be combined and ensembled in order to profit from the multi-technique calibration process. For this, we considered that all partial models included in the top 5% percentile of the AUC distribution were ensemble (in total, 105 top-ranked models). We used the average value of all the partial projections since this measure gave the best results in general (not shown).

We partitioned ensemble suitability maps (ranging from 0 to 1000), for current and projected future conditions, into binary maps of suitable/unsuitable areas by choosing the suitability threshold value that minimised the distance between the AUC-ROC curve and the (0, 1) point (Liu et al., 2005) (see Table SI3 - *Cut-off column*). This cut-off value generally gave a good balance between sensitivity (true positive rate or recall) and specificity (true negative rate).

Ensemble model projections for future conditions were obtained by replacing the predictors used in the calibration (current conditions) with regional climatic projections; that is, the future conditions for three time points: 2040, 2070 and 2100.

2.4.3 Variable importance

The importance of each predictive variable was assessed through the 'variables_importance' function of 'biomod2'. The algorithm implemented in this function randomly shuffles each variable and then model predictions are made with this 'shuffled' dataset. Then, Pearson's correlation coefficient (Pc) is calculated for the relationship between the reference predictions (not shuffled) and the 'shuffled' ones, returning the importance score (I) equal to $I = 1 - Pc$. The higher the value, the greater the influence that the variable has on the model (a value of zero assumes no influence). We calculated variable importance scores for each selected model included in the average ensemble. After this step, average importance scores by olive variety were calculated and standardised by the maximum average value encountered across all predictors (i.e., the highest-ranked variable in terms of importance always has a value of one).

2.4.4 Post-processing of model results

To evaluate the changes in the distribution of the areas environmentally suitable for each olive variety between the current (A_C) and future conditions (A_F), for the three periods available from climatic projections, we calculated the percentage change as $100 \times (A_F - A_C) / A_C$.

To assess the spatial congruence and the similarity between environmental suitability values we used Spearman's non-parametric correlation between pairs of projected current and future maps for each variety. We also calculated maps representing the adequacy of conditions for all varieties, by either summing dichotomous suitability maps (with values of either 0 or 1), thus portraying variety richness, or calculating the 95% quantile of continuous suitability values (i.e., representing those areas with greater environmental suitability).

To analyse which climatic predictor most influenced the change in suitable area, we also calculated the Spearman non-parametric correlation between the percentage change for the three projection periods (2011-2040, 2041-2070 and 2071-2100) and the importance scores.

2.4.5 Olive productivity modelling

Annual olive production data (kg of olive fruits) were available for each of the eight provinces that constitute the Andalusia region (Anuario de Estadísticas Agrarias y Pesqueras de Andalucía; https://www.juntadeandalucia.es/organismos/agriculturaganaderiapescaydesarrollosostenible/consejeria/sobre-consejeria/estadisticas/paginas/agrarias-anuario.html), for the years 2010-2014. Prior to modelling, annual production values were averaged to minimise inter-annual fluctuations (mainly derived from the climatic conditions and other factors). These averaged values of total annual production per province were considered the response variable.

We used a parsimonious univariate log-log linear model to analyse the relationship between the current area suitable for olive varieties ($\log_{10}$ area with suitable conditions) and the annual production ($\log_{10}$ average production), by province. The log-log transformation was required to linearize the relationship between these two quantities. The R^2 value, the root-mean-square error (RMSE) and the Spearman correlation between the observed and predicted values were calculated to evaluate the model. Leave-one-out cross-validation was also used to assess the predictive performance of the model. Using this model, we showed that olive production is related to the suitability of the area (for all varieties); therefore, future-suitability maps can be used to obtain projections of total fruit production. Further, we also obtained projections to assess the alteration in the trend of annual production due to changes in the environmental suitability and the distribution of the olive varieties as a consequence of climate change. To obtain production projections for the three future time points (2040, 2070 and 2100), we replaced the independent variable (i.e. $\log_{10}$ area with suitable environmental conditions) with its projections from SDMs.

3. Results

3.1. Model performance, predictor importance and response curves

Overall, the predictive performance of the average ensemble models varied from good to excellent, with evaluation measures ranging from 0.76 (*Acebuche*) to 0.95 (*Nevadillo negro*) for TSS, and from 0.95 (*Acebuche*) to 1.00 (*Nevadillo negro*, *Verdial de Huévar*) for AUC (Table SI3). In addition, the values of both sensitivity and specificity were always above 90% and 85%, respectively (see also Fig. SI4 and Text SI1 showing the relationship between AUC and TSS for all varieties).

Soil pH (SLPH) was the most-important predictor for most models (Fig. 2), while (bio-)climatic predictors such as continentality index (IDCT), average autumn precipitation (PRAU), average summer precipitation (PRSM) and average winter temperature (TPWT) provided high contributions for all varieties. The environmental predictors with the highest gain for all cases calculated only with one variable were IDCT and SLPH, which provided the most-useful information by themselves.

Insert Fig. 2.

We found a direct relationship between olive trees presence and some environmental factors (Fig. 3), according to the response curves (logistic output) produced by univariate models of the two most-important predictors per variety. Overall, bioclimatic tolerance (represented by the predictors IDCT, PRAU and TPWT) determined the olive-crop distribution limits; the exception was the wild olive, for which they were mainly determined by soil properties (SLPH) and topographic features (SLPC). For a more-detailed description of the influence of the predictors on the environmental suitability for each variety, see Text SI2 (Supplementary Material).

Insert Fig. 3.

3.2. Projections of suitable area for current and future scenarios, by variety

3.2.1. Changes in climatically-suitable areas

The total suitable area calculated from current predictions ranged from 26237 km^2 for *Picual* and 4341 km^2 for *Nevadillo*, 30% and 5% of the total study area, respectively. According to projections based on future bioclimatic scenarios, the total suitable area for the periods 2011-40, 2041-70 and 2071-100 ranged, respectively, from 26386 (~30.5%), 27862 (~32.1%) and 32779 km^2 (~37.8%) for *Picual*, to 599 km^2 (~0.7%) for *Lechín*, 223 km^2 (~0.3%) for *Manzanilla* and 0 km^2 for *Nevadillo* (Table 2).

Table 2. Projected area for current and future scenarios, by variety. Values are shown in relative units (% of suitable area with respect to the total study area; i.e., Andalusia region). The Spearman correlation shows the association between the current suitability and each future projection, with values closer to 1 representing higher similarity between them and, therefore, less potential change caused by the climate. See Table 1 for variety codes.

Variety	Projection	% of suitable area	% Difference	Spearman correlation
Hj	Current	16.88		
	Proj-2040	1.53	-90.96	0.08
	Proj-2070	6.35	-62.35	0.35
	Proj-2100	0.03	-99.82	0.18
Lch	Current	13.22		
	Proj-2040	0.69	-94.77	0.13
	Proj-2070	0.80	-93.96	0.14
	Proj-2100	0.01	-99.93	0.11
Mnz	Current	11.48		
	Proj-2040	0.82	-92.83	0.14
	Proj-2070	0.26	-97.76	-0.02
	Proj-2100	0.01	-99.89	0.05
Nvd	Current	5.01		
	Proj-2040	1.11	-77.79	0.07
	Proj-2070	0.43	-91.32	0.08
	Proj-2100	0.00	-100.00	-0.07
Oe	Current	17.29		
	Proj-2040	9.61	-44.43	0.33
	Proj-2070	10.19	-41.03	0.34
	Proj-2100	4.92	-71.53	0.32
Pcd	Current	10.75		
	Proj-2040	1.15	-89.34	0.34
	Proj-2070	1.15	-89.30	0.29

	Proj-2100	0.01	-99.94	0.22
Pcl	Current	30.26		
	Proj-2040	30.43	0.57	0.63
	Proj-2070	32.13	6.19	0.48
	Proj-2100	37.80	24.93	0.23
Vrd	Current	5.27		
	Proj-2040	5.11	-3.00	0.45
	Proj-2070	4.22	-19.94	0.47
	Proj-2100	4.11	-22.02	0.46

To evaluate changes in the distribution of environmentally-suitable areas for each olive variety between the current and future climatic conditions, we calculated the percentage change in area. Except for *Picual*, for which there was an increment in suitable area for the future scenarios (a 24.93% increase in Proj-2100), the future suitable areas predicted for each variety were significantly smaller than the current ones (Table 2). The most-dramatic trends were for *Lechín*, *Manzanilla*, *Nevadillo* and *Picudo*, with potential losses of suitable area of up to 100% for year 2100 - as in the case of *Nevadillo*. The same trend was followed by the wild olive tree, with a suitable area reduction of almost 72% for 2100.

To determine which climatic predictors influenced most the change in environmentally-suitable area for all the olive varieties, we calculated the Spearman non-parametric correlation between the percentage change for the three projection periods (ending in 2040, 2070 and 2100, respectively) and the variable importance scores (Table 3). Overall, the correlation coefficients were high and negative over the three periods, being statistically significant in the case of the predictors evapotranspiration (EVTP), average autumn precipitation (PRAU) and average summer precipitation (PRSM) for the Proj-2040 and Proj-2070 periods. This indicates that future changes in suitable area will be mainly influenced by reductions in evapotranspiration and precipitation. On the other hand, the ELCCA GCM projections indicated a substantially-drier and warmer climate throughout the whole Andalusia region for the three future time periods. More specifically, increases in the mean monthly temperature were particularly evident in the cold season, ranging from +0.8 °C in the period 2011–2040 to +2.0 °C in the period 2071–2100 (Table SI4). The projected precipitation levels were also slightly higher, by 4.78% on average during the warm season along the three time periods. In contrast, the projected precipitation was lower during the autumn months, by around 64%, 76% and 48% in periods 2011–2040, 2041–2070 and 2071–2100, respectively.

Table 3. Spearman correlation scores for the relationship between the projected % change in suitable area (across all olive varieties and for a given projection period) and the importance score of each variable (n=8), showing which factors contributed most to the projected changes. (*) *P*-value < 0.05 and (.) *P*-value < 0.1; the remaining correlations were considered statistically non-significant.

Climatic variable name	**Spearman correlation** (variable importance vs. % change)		
	% change Proj-2040	% change Proj-2070	% change Proj-2100
EVTP	**-0.64 (.)**	-0.62	-0.26
IDCT	-0.33	-0.43	-0.38
PRAU	**-0.86 (*)**	**-0.69 (.)**	-0.38
PRSM	**-0.81 (*)**	-0.60	-0.14
TPWT	-0.26	-0.29	0.07

3.2.2. Number of projected varieties by period (current vs. future)

Due to the drier and warmer climatic conditions expected in the future in Andalusia, the SDMs projected a strong impact on the potential spatial distribution of the olive varieties over the coming decades. Both the projections of the area suitable for olive cultivation based on summing dichotomous suitability maps (Fig. SI2) and the maps showing the 95% quantile of suitability values (Fig. 4) indicated a generalised loss of environmental suitability across all varieties. A general reduction in area was projected for the central portion of the study region, characterised by valleys where the effect of continentality is more notable and mountains of moderate height mainly characterised by favourable climatic conditions. The projected warmer conditions will, in turn, cause a potential increment in the evapotranspiration, continentality index and average winter temperature (Table SI4), which could also make some areas - where olives have never been grown previously - suitable for olive cultivation. For varieties *Hojiblanca*, *Lechín*, *Manzanilla*, *Nevadillo* and *Picudo*, it is predicted that the areas suitable for cultivation could extend beyond the current limits (Fig. SI2).

Insert Fig. 4.

We also tested the relationship between the percentage change in suitable area, for each variety and future projection period, and the spatial correlation between suitability values (and also between the values of the current and the three future periods) (Fig. 5 and Fig. SI3). This plot displayed a continuum of change, from large losses in suitability for the three time periods (notice the left-lower corner), especially in the case of *Nevadillo*, *Manzanilla* and *Lechín*, to higher correlation values signalling lower percentage changes in adequate area, as for *Verdial* and *Picual*. Our model projections by period suggest that it is likely that changes in habitat suitability occur both inside and outside the species´ distribution range.

Insert Fig. 5.

The models also indicate that the dynamics of change will differ widely among the Andalusian provinces (Table SI5), with some of them showing strong losses of suitable conditions (e.g., Sevilla) and others showing small increments (Almería). This increase mostly relates to the potential rise in suitable area for *Picual* (Pcl), which currently represents about 60% of the olive groves in Andalusia (Table 1).

3.3. Integrated suitable area as a proxy for olive productivity

3.3.1 Current state

The univariate log-log linear model relating the $\log_{10}$ average production (for the period 2010-2014) by province to the $\log_{10}$ area with suitable conditions across all provinces explained 67% of the variance in the measured production of the olive varieties ($R^2 = 0.67$, P-value < 0.05, RMSE = 0.49, Spearman correlation = 0.88). The leave-one-out cross-validation (LOOCV) approach also showed good accuracy for the estimation model (LOOCV $R^2 = 0.44$, LOOCV RMSE = 0.58, LOOCV Spearman correlation = 0.74). Overall, all provinces - with the exception of Huelva - generally fall inside the confidence bands (Fig. 6).

Insert Fig. 6.

3.3.2 Current vs. future

Using the same approach as above, we also assessed the expected alteration to the trend in annual production due to projected changes in environmental suitability and the potential distribution of all the olive varieties as a consequence of climate change (expressed in regional projections for the six climatic predictors). We found a decrease in olive production in the future for almost all the olive-growing provinces investigated (Cádiz, Córdoba, Huelva, Málaga and Sevilla) (Fig. 7) due to the effects of projected decreases in precipitation during the autumn months, in which a large proportion of the annual precipitation is concentrated. This suggests that the majority of impacts will be driven mostly by trends in precipitation and evapotranspiration rather than temperature. For the highly-productive provinces (i.e., Jaén, Córdoba and Sevilla), the highest projected production reduction - of 0.2% (2040), 9.1% (2100) and 29.4% (2100), respectively - depended on the future period considered (Table SI6).

On the other hand, an increase in projected production was found for two provinces, Almería (13.3% in 2100) and Granada (6.2% in 2100), mainly related to the potential expansion of the varieties *Picual* and *Verdial*. Jaén would continue being the province with the greatest production and least change for the entire projected period (to 2100). However, these predicted differences among time periods may depend on complex trade-offs among the considered climatic factors, as well as on edaphic or topographic conditions or even human management.

Insert Fig. 7.

4. Discussion

In this study, we have assessed the main abiotic factors that characterise the environmental suitability of the seven main olive varieties together with the wild olive in Andalusia (southern Spain) – a globally-important region for olive production. The most-important factors explaining the environmental suitability of the olive varieties were the continentality index (IDCT) and soil pH (SLPH), but important contributions also came from seasonal precipitation and temperature. We also predicted the current and potential distribution of each variety under the present environmental conditions, and assessed the future environmentally-suitable areas for each olive variety by incorporating regional climate change scenarios. We found, in general, a significant loss of suitable area in the future projections, relative to the current conditions, for six of the seven olive varieties studied, due especially to the drier conditions in the autumn.

Finally, as far as we know, this is the first time that an SDM-based technique has been used to predict the area suitable for olive varieties as a proxy of olive annual production, and we analysed the expected alterations of their trends in the face of climate change. We found a decrease in olive production in the future, for almost all the olive-growing provinces investigated, due to the effects of projected decreases in autumn precipitation, suggesting that the majority of impacts will be driven mostly by trends in precipitation and evapotranspiration rather than temperature. We discuss these results and their implications in depth below.

4.1. Predictors of the environmental suitability of Andalusian olive varieties

Overall, the ensemble models showed a very-good predictive performance for all the olive varieties tested (see Table SI3). Among the predictive variables used to calibrate the models, the climatic and soil properties made the highest contributions (Fig. 2). This confirms that most of the Andalusian olive varieties are well suited to the Mediterranean-type climate observed in the region. In general, olive trees perform well in mild to cool winters with a chilling period of about two months (mainly in January and February in Andalusia, but it depends on the variety) for flower bud differentiation, and in the absence of late spring frosts that may kill the blossom (buds and fruiting shoots are usually damaged by temperatures below -5ºC) (Larcher, 2000; Barranco et al., 2005). Long, sunny and warm summers properly ripen the fruit and result in a high oil content. Furthermore, the contribution of summer and autumn precipitation, in addition to the mean annual rainfall (ca. 400 to 700 mm), increases the area suitable for olive-growing.

However, although the climatic predictors explained well the environmental suitability of the olive trees, soil pH played a fundamental role at the spatial scale studied (Figs. 2 and 3). In general, olives grow well on soils that run from slightly acidic, with pH values from 5.0-6.5 (*Lechín*, *Nevadillo*, *Verdial* and the wild olive *Acebuche*), to slightly alkaline, with values of 7.0-8.5 (*Hojiblanca*, *Picudo* and *Picual*). Andalusian olive trees are also tolerant of mildly-saline conditions, but avoid extremely-saline or sodic soils (Melgar et al., 2009) that are usually related to higher pH levels as well.

Usually, climatic and soil properties are the key determinants of the distribution of olive trees at the local scale and with coarse-resolution data, while topography-related features (e.g., elevation, slope and aspect) usually show poorer predictive capacity

(Neilson, 1995; Nezer et al., 2017). Further analysis of topography when high-spatial-resolution data are available (i.e., micro-topographical features) might confirm the fundamental role that areas with highly-complex morphology play in olive distributions at finer scales. In addition, a more-detailed analysis of human intervention (i.e., management of agricultural crops, deforestation, or the subsequent soil degradation in the sloping areas where olives are usually cultivated) may be important in defining habitat suitability (Guisan and Zimmermann, 2000).

4.2. Areas suitable for olive cultivation in the face of climate change

Our future projections suggest a significant reduction in the suitable area, relative to the current conditions, for six of the seven olive varieties studied (Table 2). Previous studies have shown that an average climate warming of 1.8°C will benefit some olive-growing regions and adversely affect others, while some will remain relatively unchanged, not only in ecological terms, such as distribution or habitat suitability (Moriondo et al., 2013; Viola et al., 2013), but also regarding olive production (Olesen et al., 2011; Ponti et al., 2014; Fraga et al., 2019).

In our study, the most-dramatic trends were for the local and narrowly-distributed varieties (*Lechín*, *Manzanilla* and *Picudo*), with potential losses of suitable areas of 100% for the year 2100, as in the case of *Nevadillo*. The wild olive showed a similar trend, with losses of suitable area of almost 45%, 41% and 72% for 2040, 2070 and 2100, respectively. These changes in suitable area for all the olive varieties and for the three projection periods (to 2040, 2070 and 2100) were statistically related to an increase in evapotranspiration and a decrease in seasonal precipitation (see Table 3). This could be due especially to the drier autumn conditions, contributing to an increase in the water deficit during the summer to values potentially exceeding the limits tolerated by olive trees. These results match those of other studies where decreased precipitation and increments in annual temperatures were predicted for the Mediterranean Basin (Vergni and Todisco, 2011; Moriondo et al., 2013). More specifically, a general reduction in the suitable area was projected for the Atlantic coast and the south- eastern coast of Andalusia (mainly related to a lower chilling hours accumulation) and for areas in the north and north- east of the region (due to the occurrence of high temperatures during flowering), among the mountains of moderate altitude mainly characterised by favourable climatic conditions (Gabaldón-Leal et al., 2017). These changes could already have had a significant impact on olive cultivation since the areas that appear to be currently suitable for olive growth extend beyond the current limits of cultivation (e.g., for *Hojiblanca*, *Lechín*, *Manzanilla*, *Nevadillo* and *Picudo*; Fig. SI2).

Despite these dramatic projected changes for the main olive varieties cultivated in Andalusia, new areas may become viable at the same time due to increasingly-milder winters. However, these new areas suitable for olive cultivation may not be sufficient to compensate for the reductions projected for other parts of the region. In turn, if this trend materialises, a potential erosion of olive diversity may occur, with some areas losing the potential to have multiple varieties (Fig. 5), thus further eroding the climate-adaption potential of olive agroecosystems. Our models also revealed that great differences in dynamics between different Andalusian provinces (Table SI5) will potentially occur, with some of them showing strong losses of suitable conditions (e.g., Sevilla) and others, contrastingly, recording small increments (e.g., Almería).

4.3. Olive productivity in the face of climate change

Once we had obtained the SDM-based current and future areas suitable for each olive variety, we assessed the relationships between the suitable conditions and productivity, by province. As expected, there was a relationship between the current predicted suitable area and the average annual production for almost all provinces (Fig. 6), suggesting that the warmer and drier conditions (changes in precipitation and evapotranspiration) expected in the coming decades may determine unprecedented changes in olive production in this region (Moriondo et al., 2013; Tanasijevic et al., 2014). However, these differences in the estimates among time periods may depend on the trade-off among the considered climatic factors, the edaphic or topographic conditions or even human management. In summary, our models predicted that if a larger environmentally-suitable area is available, and therefore potentially more crop-areas, the production will be greater. We must highlight that the models only predicted areas with suitable conditions based on current cultivation patterns, and the same models may fail (or struggle) to predict sub-optimal or marginal areas where olives are currently cultivated, which would require further analysis in the future.

As in other types of crop, an accurate and early quantitative forecast of olive yields has become a valuable tool in the support of different activities - such as optimisation of the harvest, oil transformation or marketing (Orlandi et al., 2010). Different approaches to olive-yield assessment have been based on pollen emissions

(Galán et al., 2008; Oteros et al., 2014; Ramos-Román et al., 2019), long-term aerobiological data series and bioclimatic conditions (Aguilera and Ruiz-Valenzuela, 2014) or tree canopy measurements (Maselli et al., 2012; Sola-Guirado et al., 2017). However, and to our knowledge, changes in spatial and temporal patterns of olive production, in the face of global change, as a function of SDM-derived areas suitable for olive crops have never been addressed. Inclusion of the spatial distribution of olive groves in model predictions might reduce or increase the over- and under-estimations, respectively, of the adverse climate impact on olive production. Nevertheless, topographical and soil properties, as well as human interventions driven by the climatic conditions, may play an important role in defining the environmental suitability at more-local and finer scales, which will require more-detailed analysis in future studies.

The impact of climate change on the viability of olive orchards has been reported previously in other studies. While empirical or correlative-based models - generally fitted with climatic variables to predict olive yields – have been used traditionally for this purpose (Quiroga and Iglesias, 2009; Moriondo et al., 2015), recently, approaches such as process-based models have been developed to couple a dynamic olive-crop model with high-resolution climatic projections, for current and for future climate change scenarios (Fraga et al., 2019). In general, all these models have reported a negative impact of climate change on the viability of olive orchards in the south of the Iberian Peninsula. These models are able to detect early stages of change critical to the determination of yield, growing season and limiting factors, even for future climate scenarios, and therefore they could anticipate the effects of climate change (Orlandi et al., 2013; Fraga et al., 2019). However, so far, no study has addressed the association between the climate-driven spatial patterns of the different olive varieties and the olive production.

Our findings highlight the role of spatial patterns of cultivation in terms of how climate change will affect the current olive crop expansion into new areas, and therefore the fruit production at local and regional scales. Furthermore, relation of the predicted area suitable for potential olive crops expansion to olive production would help to provide early warnings to anticipate and/or mitigate the effects of climate change, thus supporting adaptive ecological and economic strategies.

Despite the good performance so far in the prediction of the spatial patterns of olive crops by correlative models, which are mainly calibrated by interpolated climatic or geomorphological data at coarse resolutions, additional studies are needed to improve the predictive ability of models. For that, the incorporation of more-accurate environmental data in modelling approaches - in terms of spatial resolution, but also in terms of temporal resolution such as phenological and seasonal phases (e.g., from satellite remote sensing) - would improve both the anticipation of olive crop expansion and production monitoring. Improvement of the conventional climate change monitoring schemes with more-accurate statistical approaches and predictors (Estes et al., 2013) would also help to prioritise areas suitable for crop monitoring. In turn, this would allow measures to be taken to reduce the impact not only on crop stability and production, but also on natural ecosystems impacted by crop expansion.

5. Conclusions: recommendations for improvement

Climate-based models used to determine the areas suitable for cropping represent an important tool for assessing and anticipating the effects of future climate change on spatial and temporal production patterns of olive crops. We found that the most-important factors related to the environmental suitability of most of the seven olive varieties studied were the continentality index (IDCT) and soil pH (SLPH), but seasonal precipitation and temperature also provided useful information. The future projections indicate, in general, a significant reduction in the suitable area and olive productivity, in comparison with the current conditions, for six of the seven olive varieties studied, due particularly to drier conditions in autumn. Also, our results may allow early detection of the climate change effects on olive crop expansion into new areas as well as early estimates of fruit production, at local and regional scales, and therefore the development of adaptation strategies. Thus, nursery cultivation of traditional varieties should be encouraged in potentially-suitable areas, to avoid substitution by other varieties with lower environmental suitability.

A model-based approach using finer-scale environmental data by incorporating specific variables – that would allow early detection of spatial and temporal changes in species distribution patterns and production in the face of global change - may provide valuable findings that improve decision-making processes. We conclude that this methodology may be applied to other olive-production areas and other cultivation systems to predict the effects of climate change at scales ranging from regional to sub-continental. Therefore, this study offers useful tools that politicians, land managers and the owners of olive crops can use to planning and anticipate future climate change effects across space and time.

CRediT authorship contribution statement

Salvador Arenas-Castro: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **João Gonçalves:** Formal analysis, Investigation, Methodology, Visualization, Writing - review & editing. **Manuel Moreno:** Data curation, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Rafael Villar:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing, Supervision.

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.

Acknowledgements

We thank the Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (Government of Andalusia, Spain) for providing olive data. Dr. Salvador Arenas-Castro was financially supported by the fellowship ENGAGE-SKA POCI-01-0145-FEDER 022217, at the CICGE-Research Centre for Geo-Space Science, Faculty of Sciences, University of Porto (Portugal). Dr. João F. Gonçalves was funded by the Individual Scientific Employment Stimulus Program (2017) by the Portuguese Foundation for Science and Technology (FCT CEEC-2017). Part of this study was performed within the context of the Master Thesis of Manuel Moreno in the *Máster en Geomática, Teledetección y Modelos espaciales aplicado a la gestión forestal* (University of Córdoba, Spain).

References

Aguilera, F., Ruiz-Valenzuela, L., 2014. Forecasting olive crop yields based on long-term aerobiological data series and bioclimatic conditions for the southern Iberian Peninsula. Spanish J. Agric. Res. 12. http://dx.doi.org/10.5424/sjar/2014121-4532.

Araújo, M.B., New, M., 2007. Ensemble forecasting of species distributions. Trends Ecol. Evol. 22, 42–47. https://doi.org/https://doi.org/10.1016/j.tree.2006.09.010.

Baasch, D.M., Tyre, A.J., Millspaugh, J.J., Hygnstrom, S.E., Vercauteren, K.C., 2010. An evaluation of three statistical methods used to model resource selection. Ecol. Modell. 221, 565–574. https://doi.org/10.1016/j.ecolmodel.2009.10.033.

Barbet-Massin, M., Jiguet, F., Albert, C.H., Thuiller, W., 2012. Selecting pseudo-absences for species distribution models: how, where and how many? Methods Ecol. Evol. 3, 327–338. https://doi.org/10.1111/j.2041-210X.2011.00172.x.

Barranco, D., 2004. Variedades y patrones, in: Andalucía, M.-P. y J. de (Ed.), El Cultivo Del Olivo.

Barranco, D., Rallo, L., 2000. Olive cultivars in Spain. Horttechnology 10, 107–110.

Barranco, D., Ruiz, N., Campo, M.G., 2005. Frost Tolerance of Eight Olive Cultivars. Hort. Science. 40.

Besnard, G., Khadari, B., Navascues, M., Fernandez-Mazuecos, M., El Bakkali, A., Arrigo, N., Baali-Cherif, D., Brunini-Bronzini de Caraffa, V., Santoni, S., Vargas, P., Savolainen, V., 2013. The complex history of the olive tree: from Late Quaternary diversification of Mediterranean lineages to primary domestication in the northern Levant. Proceedings. Biol. Sci. 280. https://doi.org/10.1098/rspb.2012.2833.

CAPDER, Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible (Government of Andalusia, Spain)., 2013.

Carrión, Y., Ntinou, M., Badal, E., 2010. Olea europaea L. in the North Mediterranean Basin during the Pleniglacial and the Early–Middle Holocene. Quat. Sci. Rev. 29, 952–968. https://doi.org/10.1016/j.quascirev.2009.12.015.

Dell'Aquila, A., Calmanti, S., Ruti, P., Struglia, M.V., Pisacane, G., Carillo, A., Sannino, G., 2012. Effects of seasonal cycle fluctuations in an A1B scenario over the Euro-Mediterranean region. Clim. Res. 52, 135–157. https://doi.org/10.3354/cr01037.

DGARD-EC (Directorate-General for Agriculture and Rural Development). The influence of the Common Agricultural Policy on agricultural landscapes., 2012.

Diez, C.M., Trujillo, I., Martinez-Urdiroz, N., Barranco, D., Rallo, L., Marfil, P., Gaut, B.S., 2015. Olive domestication and diversification in the Mediterranean Basin.

New Phytol. 206, 436–447. https://doi.org/10.1111/nph.13181.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography (Cop.). 36, 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x.

Elith, J., H. Graham, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A., Li, J., G. Lohmann, L., A. Loiselle, B., Manion, G., Moritz, C., Nakamura, M., Nakazawa, Y., McC. M. Overton, J., Townsend Peterson, A., J. Phillips, S., Richardson, K., Scachetti-Pereira, R., E. Schapire, R., Soberón, J., Williams, S., S. Wisz, M., E. Zimmermann, N., 2006. Novel methods improve prediction of species' distributions from occurrence data. Ecography (Cop.). 29, 129–151. https://doi.org/10.1111/j.2006.0906-7590.04596.x.

Elith, J., Leathwick, J.R., 2009. Species Distribution Models: Ecological Explanation and Prediction Across Space and Time. Annu. Rev. Ecol. Evol. Syst. 40, 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159.

Estes, L.D., Bradley, B.A., Beukes, H., Hole, D.G., Lau, M., Oppenheimer, M.G., Schulze, R., Tadross, M.A., Turner, W.R., 2013. Comparing mechanistic and empirical model projections of crop suitability and productivity: implications for ecological forecasting. Glob. Ecol. Biogeogr. 22, 1007–1018. https://doi.org/10.1111/geb.12034.

Fraga, H., Pinto, J.G., Viola, F., Santos, J.A., 2019. Climate change projections for olive yields in the Mediterranean Basin. Int J Climatol. 1–13. https://doi.org/10.1002/joc.6237.

Franklin, J., Davis, F.W., Ikegami, M., Syphard, A.D., Flint, L.E., Flint, A.L., Hannah, L., 2013. Modeling plant species distributions under future climates: how fine scale do climate projections need to be? Glob. Chang. Biol. 19, 473–483. https://doi.org/10.1111/gcb.12051.

Gabaldón-Leal, C., Ruiz-Ramos, M., de la Rosa, R., León, L., Belaj, A., Rodríguez, A., Santos, C., Lorite, I.J., 2017. Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in southern Spain. Int. J. Climatol. 37, 940–957. https://doi.org/10.1002/joc.5048.

Galán, C., García-Mozo, H., Vázquez, L., Ruiz, L., Díaz de la Guardia, C., Domínguez-Vilches, E., 2008. Modeling Olive Crop Yield in Andalusia, Spain. Agron. J. 100, 98–104. https://doi.org/10.2134/agronj2006.0345.

Garbach, K., Milder, J.C., DeClerck, F.A.J., Montenegro de Wit, M., Driscoll, L., Gemmill-Herren, B., 2017. Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. Int. J. Agric. Sustain. 15, 11–28. https://doi.org/10.1080/14735903.2016.1174810.

Gualdi, S., Somot, S., Li, L., Artale, V., Adani, M., Bellucci, A., Braun, A., Calmanti, S., Carillo, A., Dell'Aquila, A., Déqué, M., Dubois, C., Elizalde, A., Harzallah, A., Jacob, D., L'Hévéder, B., May, W., Oddo, P., Ruti, P., Sanna, A., Sannino, G., Scoccimarro, E., Sevault, F., Navarra, A., 2013. The CIRCE Simulations: Regional Climate Change Projections with Realistic Representation of the Mediterranean Sea. Bull. Am. Meteorol. Soc. 94, 65–81. https://doi.org/10.1175/BAMS-D-11-00136.1.

Guisan, A., Zimmermann, N.E., 2000. Predictive habitat distribution models in ecology. Ecol. Modell. 135, 147–186. https://doi.org/https://doi.org/10.1016/S0304-3800(00)00354-9.

Haines-Young, R., Potschin, M., 2018. CICES (Common International Classification of Ecosystem Services) V5.1 and Guidance on the Application of the Revised Structure.

Sun, J.-S., Zhou, G.-S., and Sui, X.-H., 2012. Climatic suitability of the distribution of the winter wheat cultivation zone in China. Eur. J. Agron. 43, 77–86. https://doi.org/https://doi.org/10.1016/j.eja.2012.05.009.

Kaniewski, D., Van Campo, E., Boiy, T., Terral, J.-F., Khadari, B., Besnard, G., 2012. Primary domestication and early uses of the emblematic olive tree: palaeobotanical, historical and molecular evidence from the Middle East. Biol. Rev. Camb. Philos. Soc. 87, 885–899. https://doi.org/10.1111/j.1469-185X.2012.00229.x.

Krishna, K.R., 2013. Agroecosystems: Soils, Climate, Crops, Nutrient Dynamics and Productivity. Apple Academic Press.

Larcher, W., 2000. Temperature stress and survival ability of Mediterranean sclerophyllous plants. Plant Biosyst. - An Int. J. Deal. with all Asp. Plant Biol. 134, 279–295. https://doi.org/10.1080/11263500012331350455.

Liu, C., Berry, P.M., Dawson, T.P., Pearson, R.G., 2005. Selecting thresholds of occurrence in the prediction of species distributions. Ecography (Cop.). 28, 385–393. https://doi.org/10.1111/j.0906-7590.2005.03957.x.

Lobo, J.M., Jiménez-Valverde, A., Hortal, J., 2010. The uncertain nature of absences and their importance in species distribution modelling. Ecography (Cop.). 33, 103–114. https://doi.org/10.1111/j.1600-0587.2009.06039.x.

LRMUIES-EU, 2010. Land Resources Management Unit, Institute for Environment and Sustainability, European Commission.

MAPA (Ministry of Agriculture, Fisheries and Food), 2013.

Maselli, F., Chiesi, M., Brilli, L., Moriondo, M., 2012. Simulation of olive fruit yield in Tuscany through the integration of remote sensing and ground data. Ecol. Modell. 244, 1–12. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2012.06.028.

Melgar, J.C., Mohamed, Y., Serrano, N., García-Galavís, P.A., Navarro, C., Parra, M.A., Benlloch, M., Fernández-Escobar, R., 2009. Long term responses of olive trees to salinity. Agric. Water Manag. 96, 1105–1113. https://doi.org/https://doi.org/10.1016/j.agwat.2009.02.009.

Merow, C., Smith, M.J., Edwards Jr, T.C., Guisan, A., McMahon, S.M., Normand, S., Thuiller, W., Wüest, R.O., Zimmermann, N.E., Elith, J., 2014. What do we gain from simplicity versus complexity in species distribution models? Ecography (Cop.). 37, 1267–1281. https://doi.org/10.1111/ecog.00845.

Miller, A.J., Knouft, J.H., 2006. GIS-based characterization of the geographic distributions of wild and cultivated populations of the Mesoamerican fruit tree Spondias purpurea (Anacardiaceae). Am. J. Bot. 93, 1757–1767. https://doi.org/10.3732/ajb.93.12.1757.

Minero, F.J.G., Candau, P., Morales, J., Tomas, C., 1998. Forecasting olive crop production based on ten consecutive years of monitoring airborne pollen in Andalusia (southern Spain). Agric. Ecosyst. Environ. 69, 201–215. https://doi.org/https://doi.org/10.1016/S0167-8809(98)00105-4.

Moriondo, M., Stefanini, F.M., Bindi, M., 2008. Reproduction of olive tree habitat suitability for global change impact assessment. Ecol. Modell. 218, 95–109. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2008.06.024.

Moriondo, M., Trombi, G., Ferrise, R., Brandani, G., Dibari, C., Ammann, C.M., Lippi, M.M., Bindi, M., 2013. Olive trees as bio-indicators of climate evolution in the Mediterranean Basin. Glob. Ecol. Biogeogr. 22, 818–833. https://doi.org/10.1111/geb.12061.

Moriondo, M., Ferrise, R., Trombi, G., Brilli, L., Dibari, C., Bindi, M., 2015. Modelling olive trees and grapevines in a changing climate. Environ. Model. Softw. 72, 387–401. https://doi.org/https://doi.org/10.1016/j.envsoft.2014.12.016.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858. https://doi.org/10.1038/35002501.

Neilson, R.P., 1995. A Model for Predicting Continental-Scale Vegetation Distribution and Water Balance. Ecol. Appl. 5, 362–385. https://doi.org/10.2307/1942028.

Nezer, O., Bar-David, S., Gueta, T., Carmel, Y., 2017. High-resolution species-distribution model based on systematic sampling and indirect observations. Biodivers. Conserv. 26, 421–437. https://doi.org/https://doi.org/10.1007/s10531-016-1251-2.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112. https://doi.org/https://doi.org/10.1016/j.eja.2010.11.003.

Orlandi, F., Avolio, E., Bonofiglio, T., Federico, S., Romano, B., Fornaciari, M., 2013. Potential shifts in olive flowering according to climate variations in Southern Italy. Meteorol. Appl. 20, 497–503. https://doi.org/10.1002/met.1318.

Orlandi, F., Carlo, S., Tommaso, B., Luigia, R., Bruno, R., Marco, F., 2010. Yield modelling in a Mediterranean species utilizing cause–effect relationships between temperature forcing and biological processes. Sci. Hortic. (Amsterdam). 123, 412–417. https://doi.org/https://doi.org/10.1016/j.scienta.2009.09.015.

Oteros, J., Orlandi, F., García-Mozo, H., Aguilera, F., Dhiab, A. Ben, Bonofiglio, T., Abichou, M., Ruiz-Valenzuela, L., del Trigo, M.M., de La Guardia, C.D., 2014. Better prediction of Mediterranean olive production using pollen-based models. Agron. Sustain. Dev. 34, 685–694. https://doi.org/10.1007/s13593-013-0198-x.

Ponti, L., Gutierrez, A.P., Ruti, P.M., Dell\textquoterightAquila, 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. 111, 5598–5603. https://doi.org/10.1073/pnas.1314437111.

Quiroga, S., Iglesias, A., 2009. A comparison of the climate risks of cereal, citrus, grapevine and olive production in Spain. Agric. Syst. 101, 91–100. https://doi.org/https://doi.org/10.1016/j.agsy.2009.03.006.

Rallo, L., Barranco, D., Caballero, J.M., Río, C. Del, Martín, A., Tous, J., Trujillo, I., 2005. Antecedentes y presentación. Variedades de olivo en españa, Junta de Andalucia, M.A.P.A. y Ediciones Mundi-Prensa.

Rallo, L., Barranco, D., Castro-García, S., Connor, D.J., del Campo, M., Rallo, P., 2014. High-Density Olive Plantations, in: Horticultural Reviews Volume 41. John Wiley & Sons, Ltd, pp. 303–384. https://doi.org/10.1002/9781118707418.ch07.

Ramos-Román, M.J., Jiménez-Moreno, G., Anderson, R.S., García-Alix, A., Camuera, J., Mesa-Fernández, J.M. and Manzano, S., 2019. Climate controlled historic olive tree occurrences and olive oil production in southern Spain. Glob. Planet. Change. 182, 1–9. https://doi.org/10.1016/j.gloplacha.2019.102996.

Rubio de Casas, R., Balaguer, L., Manrique, E., Pérez-Corona, M.E., Vargas, P., 2002. On the historical presence of the wild olive Olea europaea L. var. sylvestris (Miller) Lehr. in the Eurosiberian North of the Iberian Peninsula. An Jard Bot Madr. 59, 342–344.

Sola-Guirado, R.R., Castillo-Ruiz, F.J., Jiménez-Jiménez, F., Blanco-Roldan, G.L., Castro-Garcia, S., Gil-Ribes, J.A., 2017. Olive Actual "on Year" Yield Forecast Tool Based on the Tree Canopy Geometry Using UAS Imagery. Sensors (Basel). 17, 1743. https://doi.org/10.3390/s17081743.

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/https://doi.org/10.1016/j.agwat.2014.05.019.

Terral, J.-F., Alonso, N., Capdevila, R.B. i, Chatti, N., Fabre, L., Fiorentino, G., Marinval, P., Jordá, G.P., Pradat, B., Rovira, N., Alibert, P., 2004. Historical biogeography of olive domestication (Olea europaea L.) as revealed by geometrical morphometry applied to biological and archaeological material. J. Biogeogr. 31, 63–77. https://doi.org/10.1046/j.0305-0270.2003.01019.x.

Thomas, C.D., Cameron, A., Green, R.E., Bakkenes, M., Beaumont, L.J., Collingham, Y.C., Erasmus, B.F.N., de Siqueira, M.F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A.S., Midgley, G.F., Miles, L., Ortega-Huerta, M.A., Townsend Peterson, A., Phillips, O.L., Williams, S.E., 2004. Extinction risk from climate change. Nature 427, 145–148. https://doi.org/10.1038/nature02121.

Thuiller, W., Lafourcade, B., Engler, R., Araújo, M. B., 2009. BIOMOD – a platform for ensemble forecasting of species distributions. Ecography. 32, 369–373.

https://doi:10.1111/j.1600-0587.2008.05742.x.

Thuiller, W., 2014. Editorial commentary on “BIOMOD - optimizing predictions of species distributions and projecting potential future shifts under global change.” Glob. Chang. Biol. 20, 3591–3592. https://doi.org/10.1111/gcb.12728.

Vergni, L., Todisco, F., 2011. Spatio-temporal variability of precipitation, temperature and agricultural drought indices in Central Italy. Agric. For. Meteorol. 151, 301–313. https://doi.org/https://doi.org/10.1016/j.agrformet.2010.11.005.

Viola, F., Caracciolo, D., Pumo, D., Noto, L.V., 2013. Olive Yield and Future Climate Forcings. Procedia Environ. Sci. 19, 132–138. https://doi.org/https://doi.org/10.1016/j.proenv.2013.06.015.

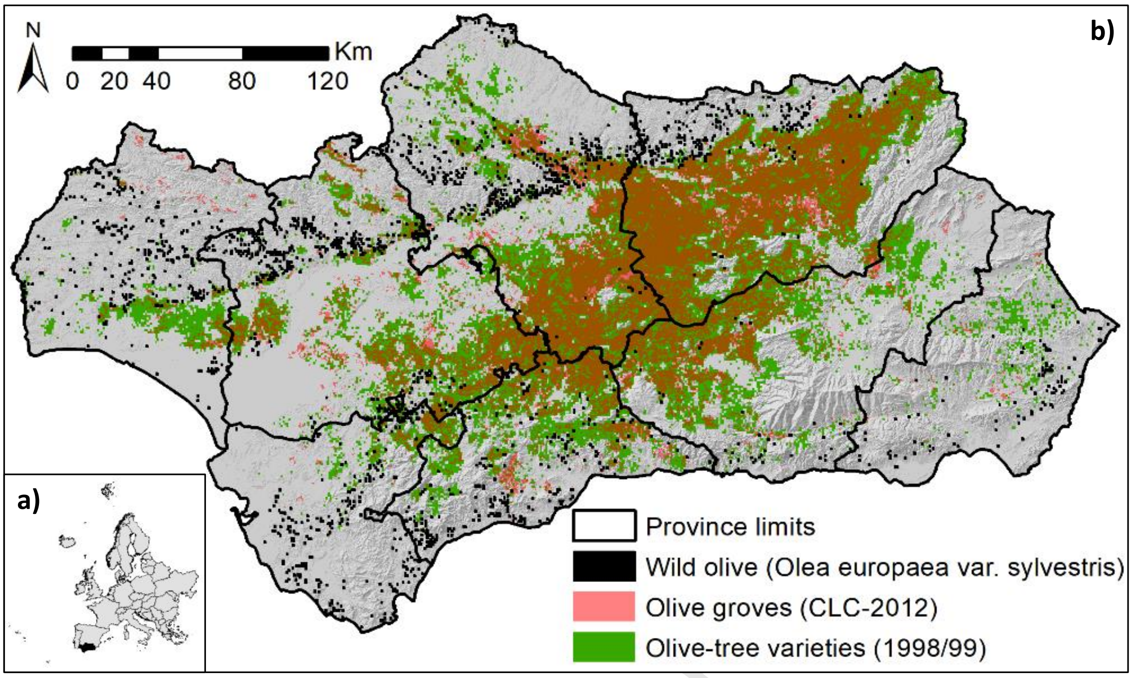


Fig. 1. Study area. a) Andalusia region in the European context; b) 'Olive groves' land cover class (Corine Land Cover 2006 Level 3 nomenclature), and the total area occupied by the seven olive-tree varieties (1 km pixel size).

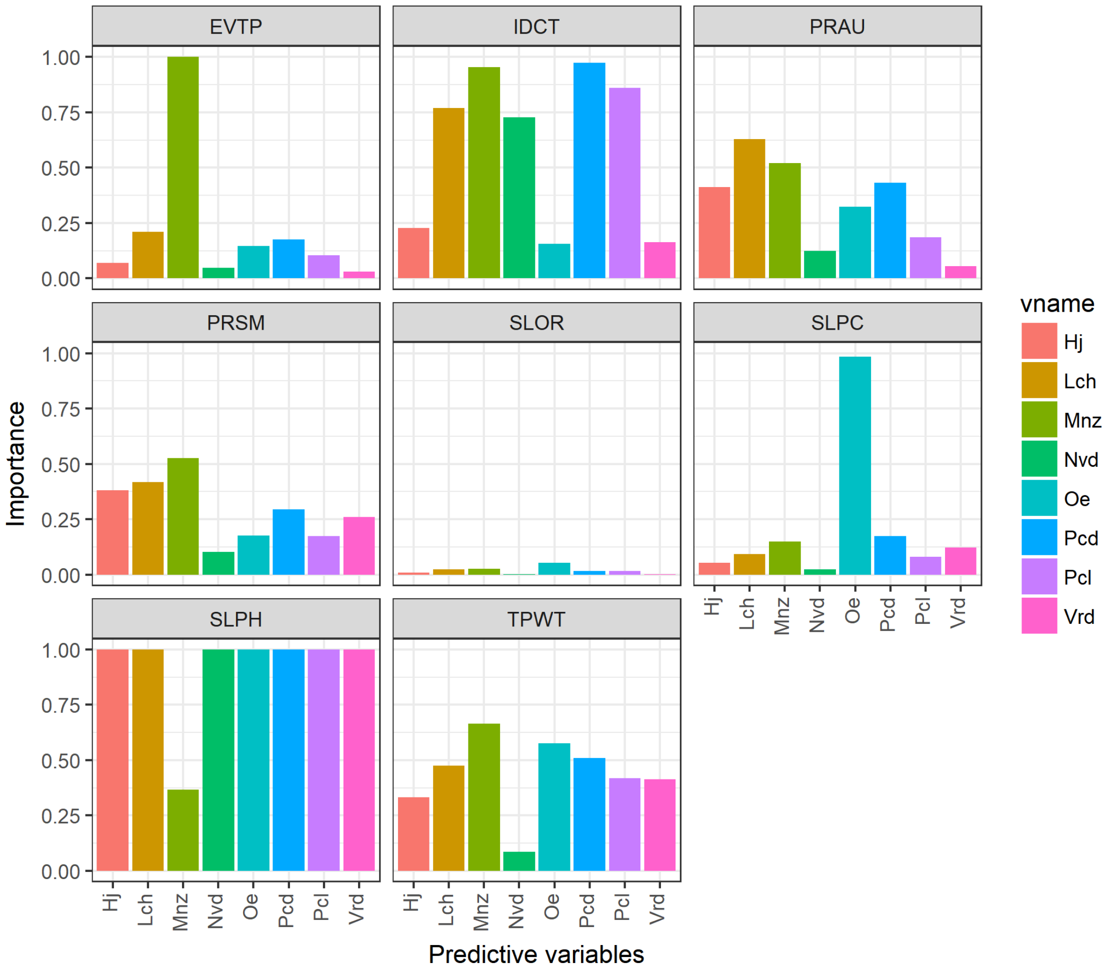


Fig. 2. Variable importance by predictor and olive variety. Evapotranspiration (EVTP), continentality index (IDCT), autumn precipitation (PRAU), summer precipitation (PRSM), solar orientation (SLOR), Slope (SLPC), pH (SLPH), and the average winter temperature (TPWT). Olive varieties are: *Hojiblanca* (Hj), *Lechín de Sevilla* (Lch), *Manzanilla de Sevilla* (Mnz), *Nevadillo negro* (Nvd), *Picudo* (Pcd), *Picual* (Pcl), and *Verdial de Huévar* (Vrd) (Table 1). We also used the wild olive-tree species (*Olea europaea var. sylvestris*; Oe).

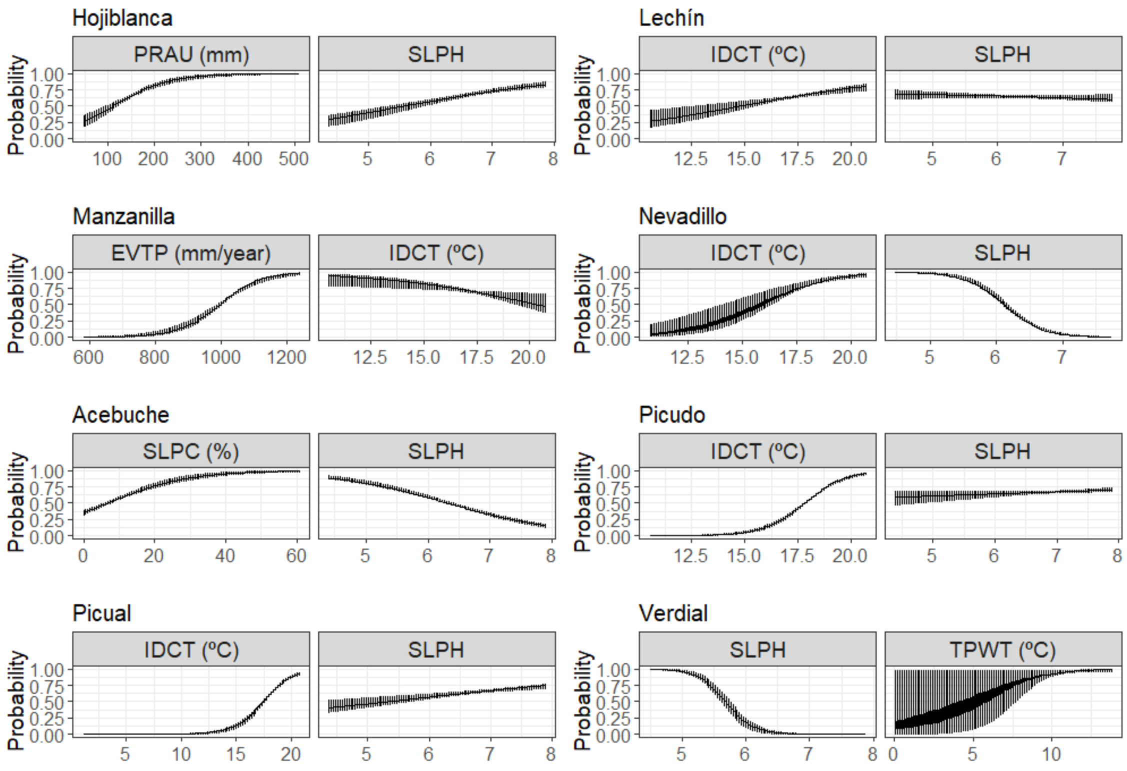


Fig. 3. Maxent-based response curves showing the relationships between the probability of presence of each variety and two most important predictors. The mean response (n= 20 models) is represented with a black line while the standard-deviation is represented with a grey shadow.

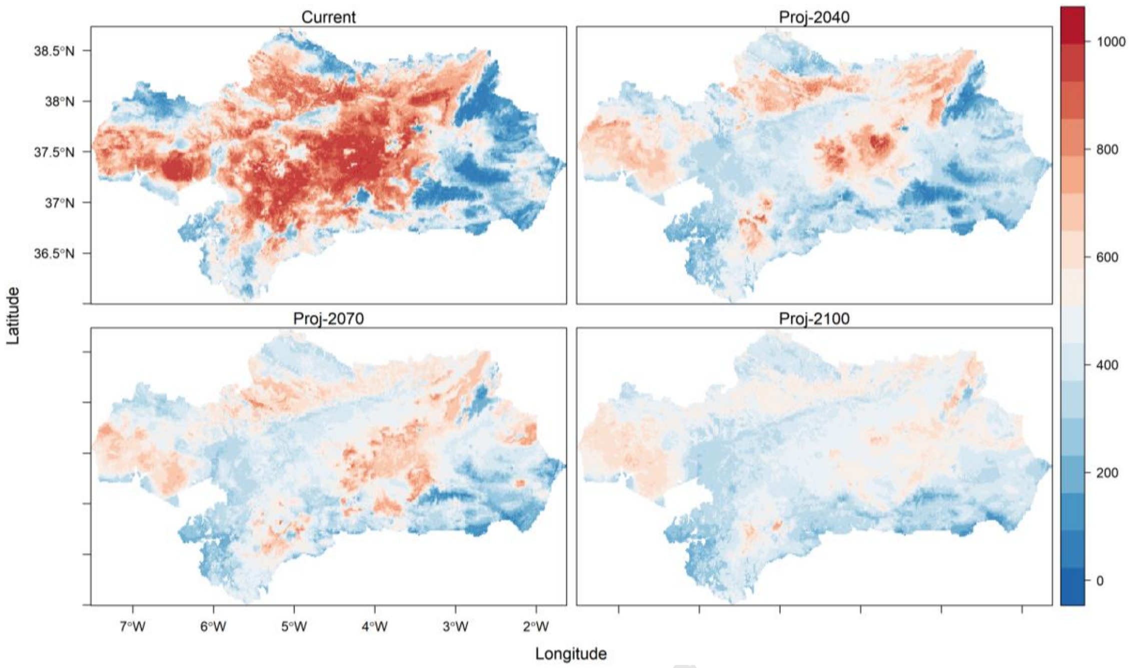


Fig. 4. 95% quantile ("highly-suitable areas") across all varieties by period (current vs. future). Values closer to 1000 (red tones) have higher likelihood to be suitable to at least one olive variety.

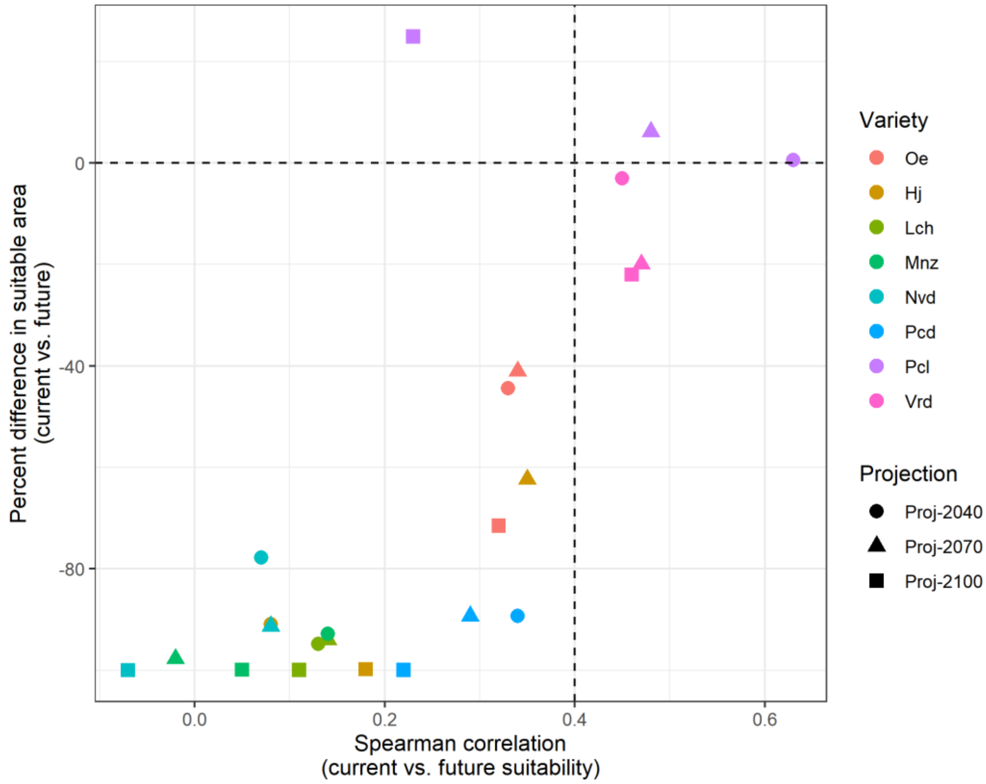


Fig. 5. Scatterplot showing the relation between % change in suitable area for each variety and future projection period, and the spatial correlation between suitability values (also between current and the three future periods). Notice the left-lower corner with higher differences in suitability related to larger losses in suitability. Higher correlation values generally signal lower percentual changes in adequate area.

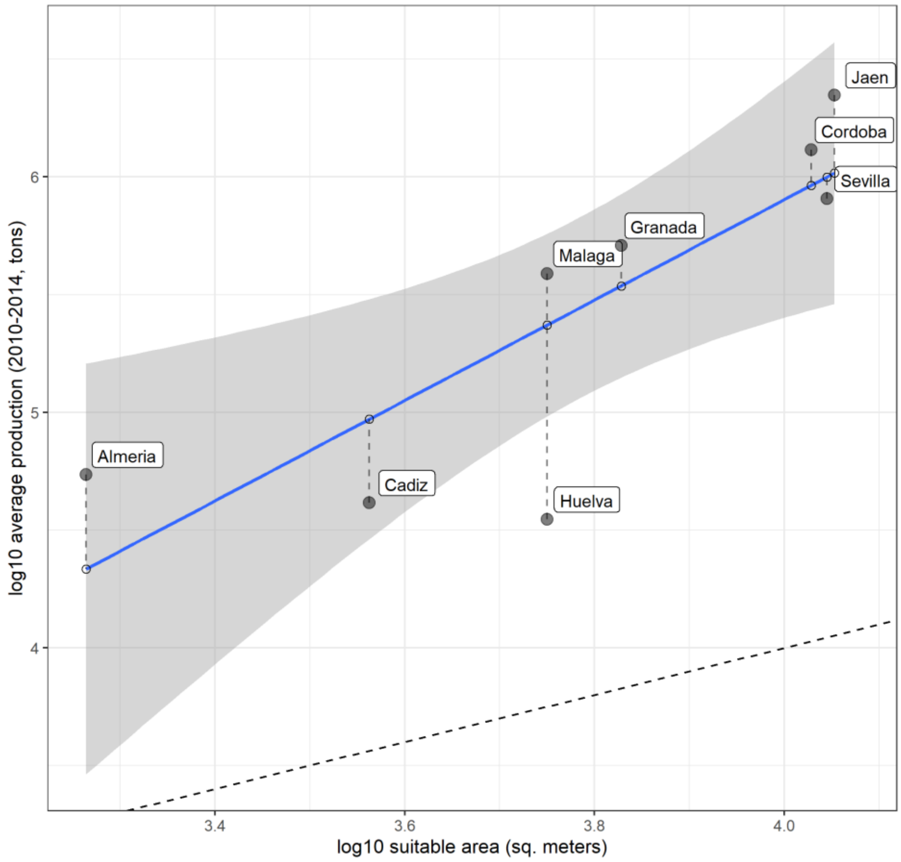


Fig. 6. Log-log model relating suitable area for at least one olive variety (in $\log_{10}$ sq. meters) and average annual production ($\log_{10}$ tons).

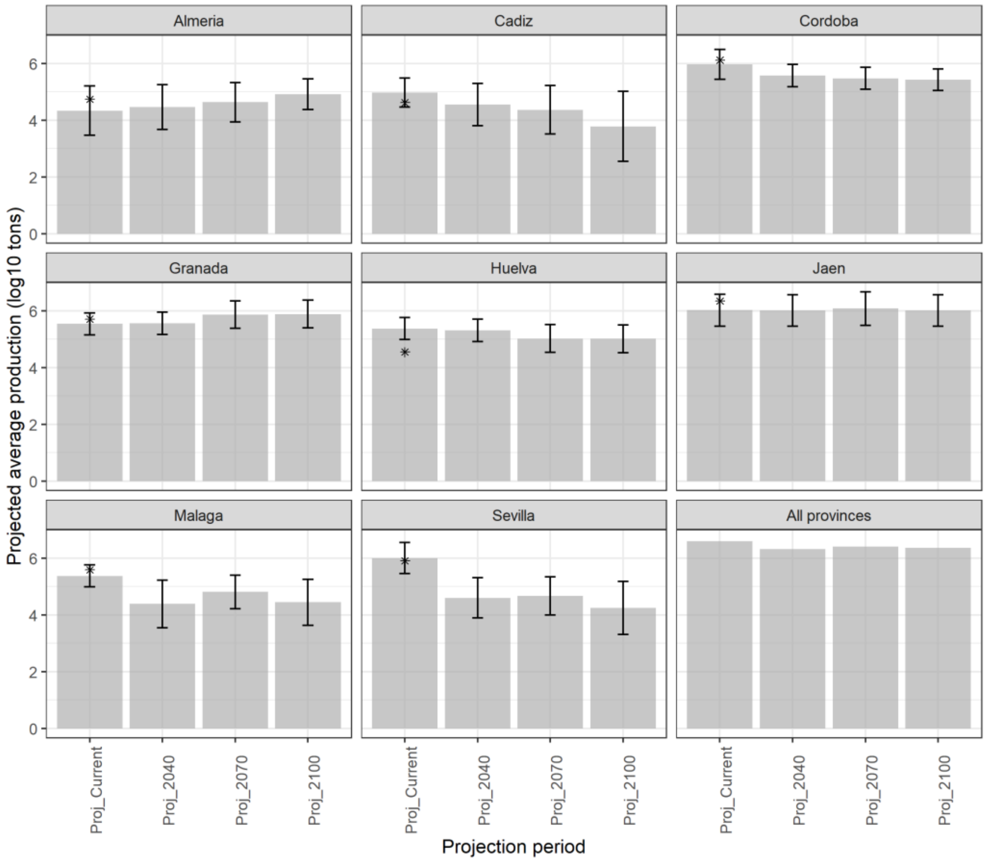
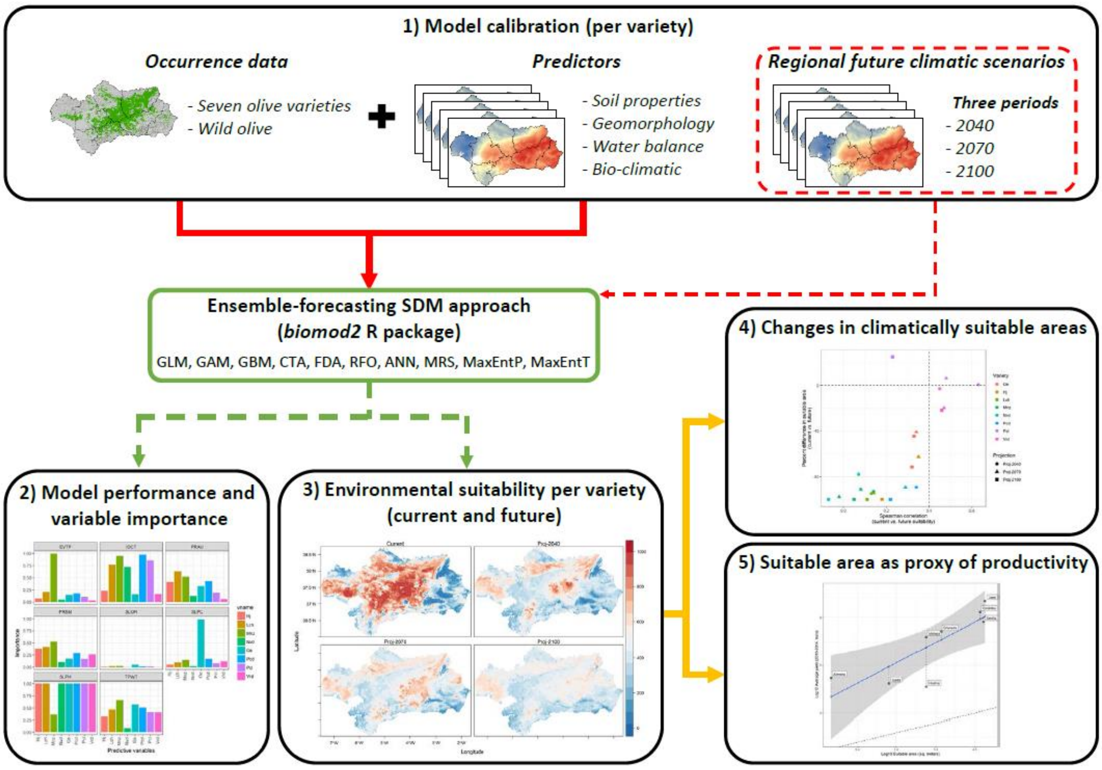


Fig. 7. Projected trends in annual production (in $\log_{10}$ tons) by province obtained by the log-log model using modelled suitable area as predictor. Note: the (*) above the projected current production is the observed average log10 value between 2010 and 2014. Bars represent the parametric prediction intervals assuming that future observations have the same error variance.

Graphical abstract



Highlights

- Climate change will significantly reduce the suitable area of main olive varieties
- Drier and warmer conditions in summer and autumn are the main drivers of change
- SDM-based environmentally-suitable area can predict olive production and its trend
- Framework potentially applicable to other olive grove areas and cultivation systems

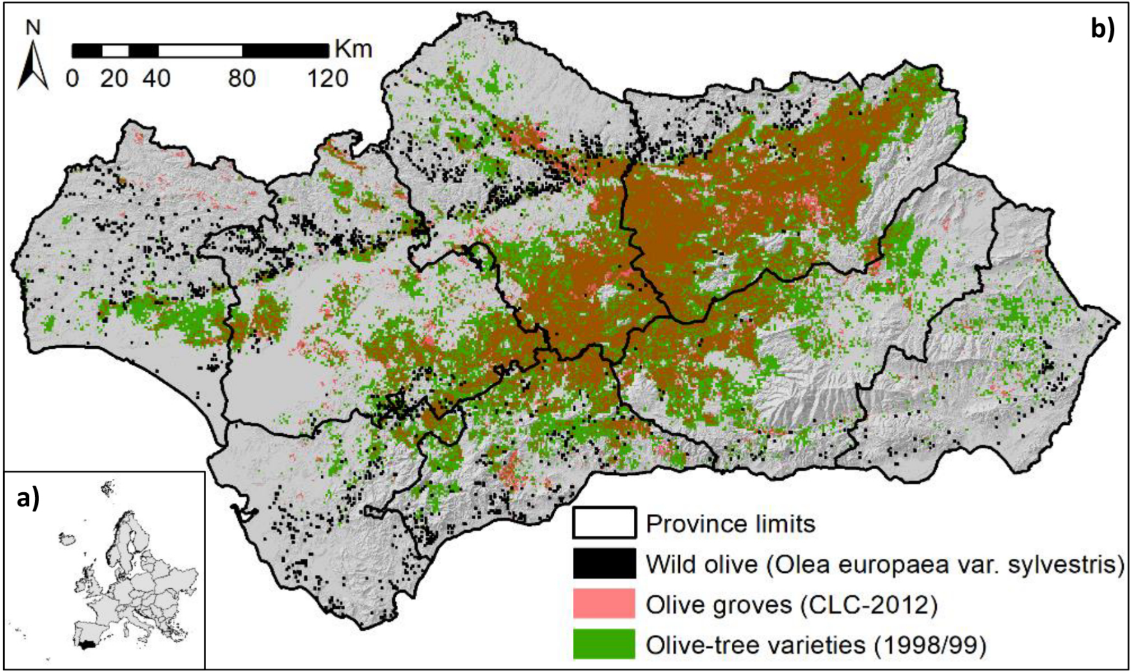

b)
N
Km
0 20 40 80 120
a)
Province limits
Wild olive (Olea europaea var. sylvestris)
Olive groves (CLC-2012)
Olive-tree varieties (1998/99)

Figure 1

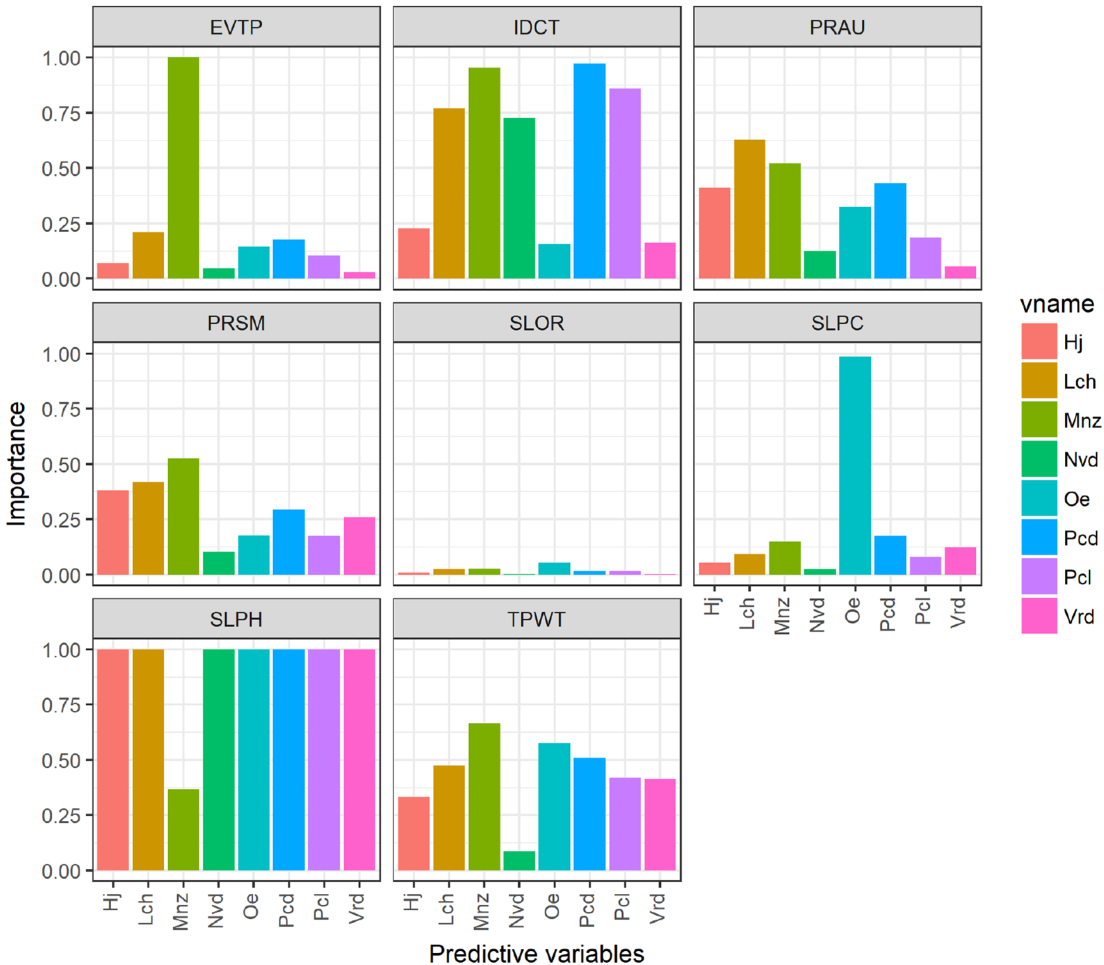
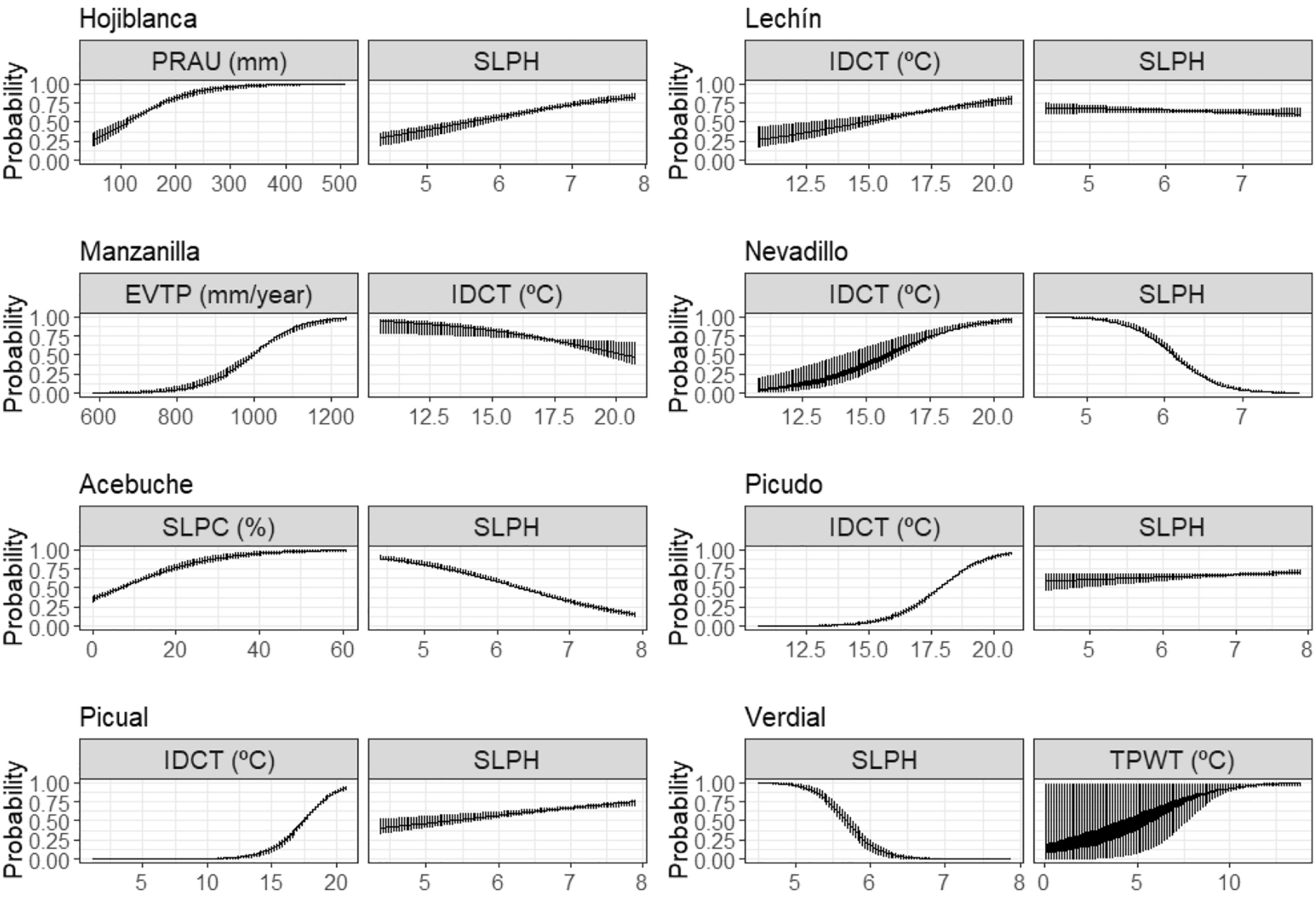

EVTP
IDCT
PRAU
PRSM
SLOR
SLPC
SLPH
TPWT
Importance
Predictive variables
vname
Hj
Lch
Mnz
Nvd
Oe
Pcd
Pcl
Vrd
1.00
0.75
0.50
0.25
0.00

Figure 2



Hojiblanca
PRAU (mm)
SLPH
Lechín
IDCT (ºC)
SLPH
Manzanilla
EVTP (mm/year)
IDCT (ºC)
Nevadillo
IDCT (ºC)
SLPH
Acebuche
SLPC (%)
SLPH
Picudo
IDCT (ºC)
SLPH
Picual
IDCT (ºC)
SLPH
Verdial
SLPH
TPWT (ºC)
Probability

Figure 3

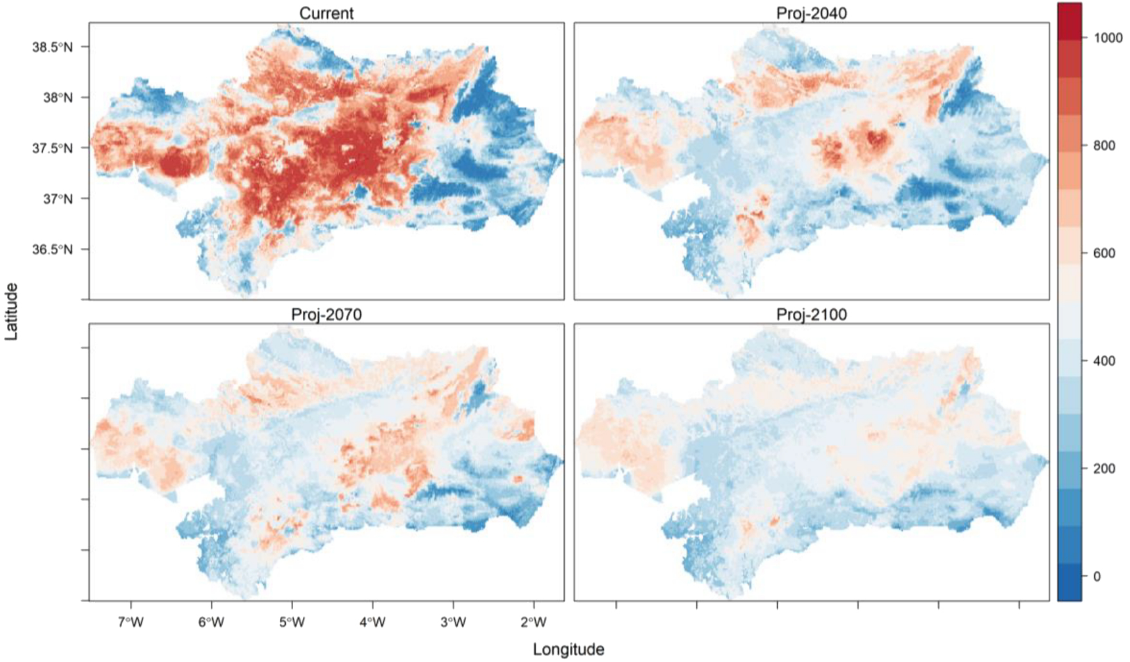

Current
Proj-2040
Proj-2070
Proj-2100
38.5°N
38°N
37.5°N
37°N
36.5°N
Latitude
7°W
6°W
5°W
4°W
3°W
2°W
Longitude
1000
800
600
400
200
0

Figure 4

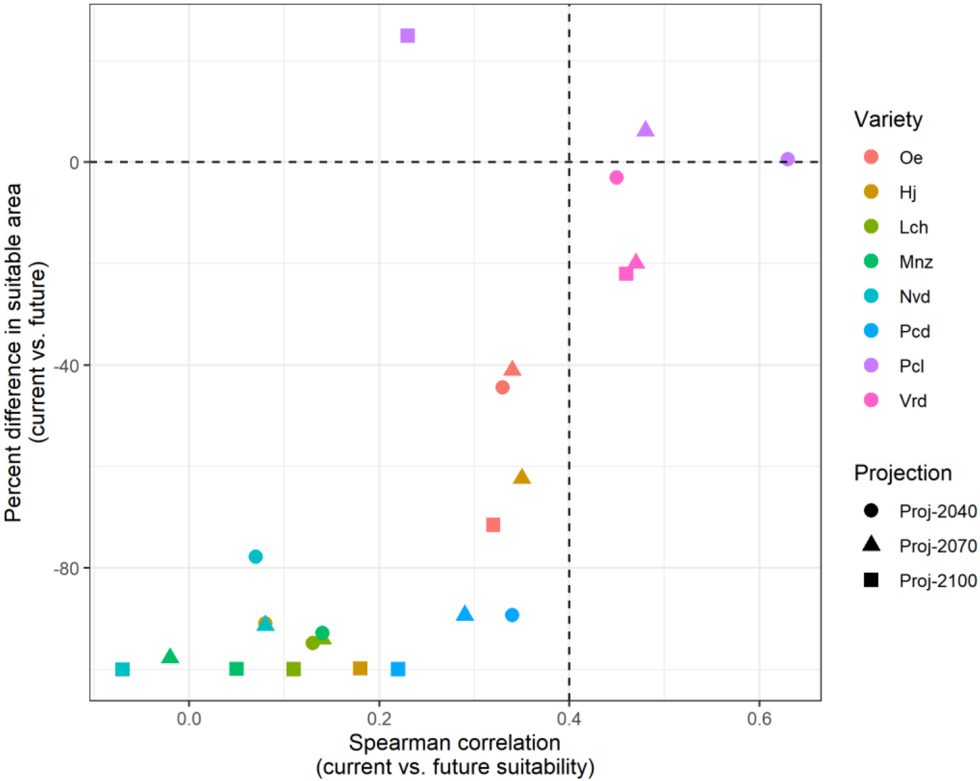
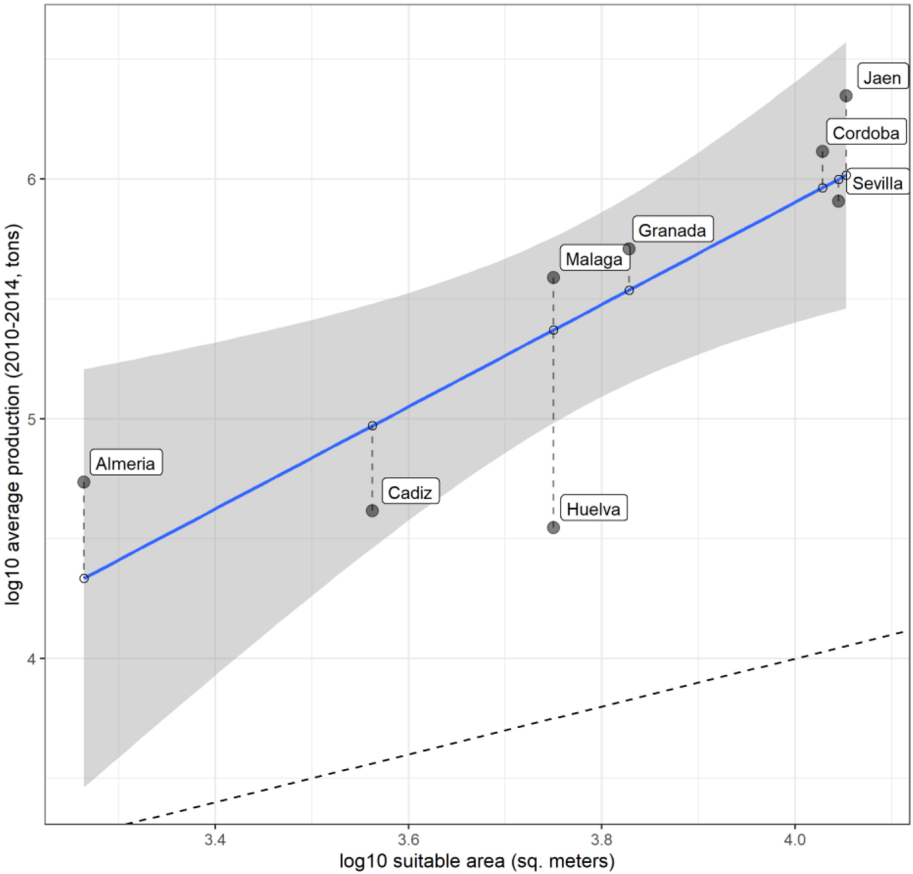
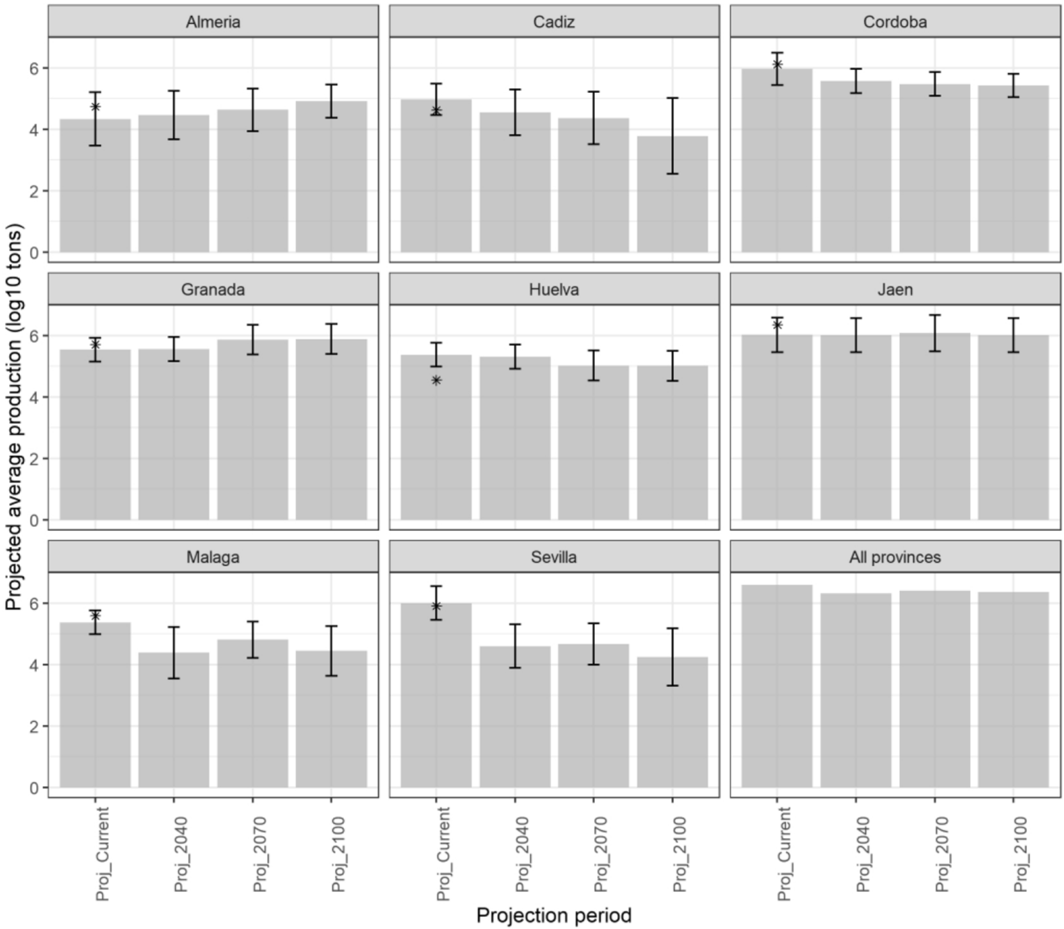

Percent difference in suitable area
(current vs. future)
0
-40
-80
0.0
0.2
0.4
0.6
Spearman correlation
(current vs. future suitability)
Variety
Oe
Hj
Lch
Mnz
Nvd
Pcd
Pcl
Vrd
Projection
Proj-2040
Proj-2070
Proj-2100

Figure 5



Jaen
Cordoba
Sevilla
Granada
Malaga
Almeria
Cadiz
Huelva
6
5
4
3.4
3.6
3.8
4.0
log10 average production (2010-2014, tons)
log10 suitable area (sq. meters)

Figure 6



Almeria
Cadiz
Cordoba
Granada
Huelva
Jaen
Malaga
Sevilla
All provinces
Projected average production (log10 tons)
0
2
4
6
Proj_Current
Proj_2040
Proj_2070
Proj_2100
Projection period

Figure 7