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ORIGINAL ARTICLE

Contribution of spatially explicit models to climate change adaptation and mitigation plans for a priority forest habitat

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Abstract Climate change will impact forest ecosystems, their biodiversity and the livelihoods they sustain. Several adaptation and mitigation strategies to counteract climate change impacts have been proposed for these ecosystems. However, effective implementation of such strategies requires a clear understanding of how climate change will influence the future distribution of forest ecosystems. This study uses maximum entropy modelling (MaxEnt) to predict environmentally suitable areas for cork oak (*Quercus suber*) woodlands, a socio-economically important forest ecosystem protected by the European Union Habitats Directive. Specifically, we use two climate change scenarios to predict changes in environmental suitability across the entire geographical range of the cork oak and in areas where stands were recently established. Up to 40 % of current environmentally suitable areas for cork oak may be lost by 2070, mainly in northern Africa and southern Iberian Peninsula. Almost 90 % of new cork oak stands are predicted to lose suitability by the end of the century, but future plantations can take advantage of increasing suitability in northern Iberian Peninsula and

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France. The predicted impacts cross-country borders, showing that a multinational strategy, will be required for cork oak woodland adaptation to climate change. Such a strategy must be regionally adjusted, featuring the protection of refugia sites in southern areas and stimulating sustainable forest management in areas that will keep long-term suitability. Afforestation efforts should also be promoted but must consider environmental suitability and land competition issues.

Keywords Afforestation · Climate change impacts · Conservation planning · Dehesa · Environmental niche modelling · Montado

1 Introduction

Global climate change is affecting ecosystems worldwide (Parmesan 2006; Parmesan and Yohe 2003). Forest ecosystems are particularly susceptible to shifts in natural disturbance regimes induced by climate change (Dale et al. 2001; Trumbore et al. 2015). For example, changes in the intensity, frequency and duration of wildfires or droughts can negatively affect tree growth and recruitment, increase tree defoliation and, ultimately, induce tree mortality (Allen et al. 2010; Caldeira et al. 2015; Lindner et al. 2010; Walck et al. 2011). Adaptation and mitigation strategies against climate change are crucial to counteract such effects. However, effective implementation of such strategies requires accurate identification of areas that may remain environmentally suitable for forest species and areas with potential for afforestation (Aitken et al. 2008; Millar et al. 2007; Settele et al. 2014). This is particularly important in climate change hotspots, such as the Mediterranean Basin (Giorgi 2006), where the development of forest adaptation and mitigation strategies is a pressing challenge (Doblas-Miranda et al. 2015; Scarascia-Mugnozza et al. 2000).

Cork oak (*Quercus suber*) woodlands are agro-silvo-pastoral systems of high socio-economic and conservation value, typical of the Western Mediterranean Basin. They cover approximately 1.5 million ha across Portugal, Spain, Italy and France and 1 million ha in North Africa between Morocco, Algeria and Tunisia (Bugalho et al. 2011; Diáz et al. 1997). Cork oak woodlands have a relatively open, savannah-like tree structure (about 30 to 60 trees per ha) and a heterogeneous shrub-grassland matrix understory (Bugalho et al. 2009). These woodlands host plant and animal species of high conservation value (Correia et al. 2015a; Diáz et al. 1997), including endemic or threatened species such as Iberian imperial eagle *Aquila adalberti*, Black stork *Ciconia nigra* or Iberian *Lynx lynx pardinus*. Cork oak woodlands are classified under the European Union Habitats Directive (92/43/CEE) and are included in the Natura 2000 network of protected areas (Berrahmouni et al. 2009). Cork oak woodlands also have a very high socio-economic value, mostly derived from cork and livestock production (Bugalho et al. 2009; Pereira and Tomé 2004). Cork can be harvested every 9 to 12 years without significant damage to the tree or affecting the biodiversity of these woodlands (Leal et al. 2011). Cork is mainly used for wine bottle stoppers (over 70 % of production), although there has been a recent increase in other applications such as insulation materials and pavements (Bugalho et al. 2009; Bugalho et al. 2011). Approximately 300,000 t of cork is harvested across the western Mediterranean Basin annually (Berrahmouni et al. 2007). Cork is the sixth most important non-timber forest product worldwide, with an estimated export value of US$329 million, and processed cork products generate an annual revenue of US$ 2 billion (Berrahmouni et al. 2007).

Current threats to cork oak woodlands include a lack of natural oak regeneration and high adult oak mortality, eventually leading to declines in tree density and area loss (Plieninger et al. 2010; Santos and Thorne 2010). Climate change will exacerbate these threats through an increase in temperatures and frequency of droughts (Acácio et al. 2016; Besson et al. 2014; Caldeira et al. 2015), both of which will contribute to an increase in the frequency and severity of wildfires (Acácio et al. 2007; Godinho et al. 2016), especially in areas with inadequate management (Bugalho et al. 2011; Godinho et al. 2016).

Here, we use environmental niche models (ENMs) to predict changes in environmental suitability across the geographic range of cork oak woodlands in response to climate change. Our objectives were to (i) quantify changes in environmental suitability across the cork oak geographic range using two climate change scenarios, (ii) assess whether ongoing afforestation efforts have taken place in those areas most likely to remain environmentally suitable for the species, using Portugal as a case study and (iii) discuss potential climate change adaptation and mitigation strategies for cork oak woodlands at regional and global scales.

2 Methods

2.1 Cork oak distribution data

Cork oak distribution was obtained by geo-referencing or collecting geo-referenced data in national forestry and biodiversity inventories. Data were collected for all the countries where the species occurs naturally (Fig. 1): Portugal (Autoridade Florestal Nacional 2009), Spain (Dirección General de Medio Natural y Política Forestal 2009), France (Institut National de l'Information Géographique et Forestiére 2010), Italy (Vessella and Schirone 2013), Morocco (Haut Commissariat aux Eaux et Forêts et à la Lutte Contre la Désertification 2005), Algeria (Barry et al. 1974) and Tunisia (Khaldi 2004). The spatial resolution of the data differed among countries, so the complete distribution dataset was up-scaled to a 5 arcmin resolution grid. This

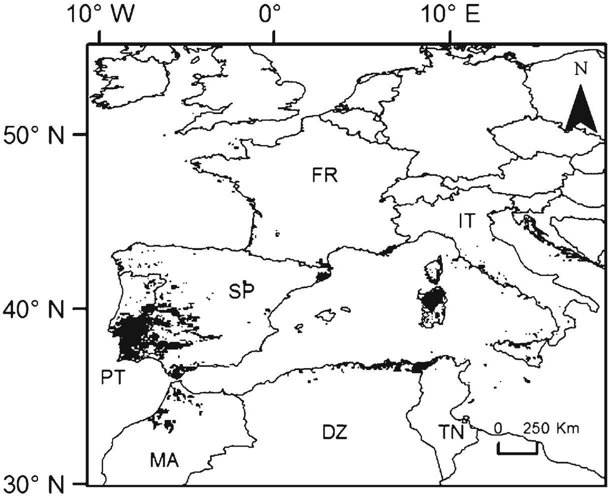

Fig. 1 Present distribution of the cork oak *Quercus suber*. Areas where the species occurs are highlighted in *black* and country codes identify the countries where the species currently occurs: Portugal (*PT*), Spain (*SP*), France (*FR*), Italy (*IT*), Morocco (*MA*), Algeria (*DZ*) and Tunisia (*TN*)

process served to homogenize the spatial resolution of the distribution data and match it to the resolution of the climate data used (see below).

We also obtained information on the location of cork oak stands recently planted in Portugal (Autoridade Florestal Nacional 2009), the country with the largest area of cork oak woodland, in order to evaluate the adequacy of the geographic location of new afforestation considering climate change scenarios.

2.2 Environmental data

Climate data representing current (1950–2000) and future (2061–2080) conditions were downloaded from the WorldClim database (http://www.worldclim.org/) at 5 arcmin resolution. Future climatic conditions were derived from four global circulation models (GCMs—ACCESS1-0, CCSM4, HadGEM2-ES and MPI-ESM-LR) and two representative concentration pathway scenarios (RCP 4.5 and 8.5). These scenarios were chosen to represent moderate (RCP 4.5, average increase of 1.8 °C by 2100) and extreme (RCP 8.5 , average increase of 3.7 °C by 2100) warming trends (Stocker et al. 2013). We collected data from the standard set of 19 bioclimatic variables (Hutchinson et al. 2009) available in the WorldClim database. Furthermore, we calculated additional variables potentially relevant for cork oak: number of frost days (New et al. 2000) and indices of annual and seasonal aridity (Zomer et al. 2008). Two soil-related variables, soil type and soil pH, were collected from the Harmonized World Soil Database, also at 5 arcmin resolution (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012).

Twelve environmental variables (Table 1) were then selected for model calibration purposes based on the biological knowledge of the species' requirements (Pausas et al. 2009). The choice of proximal variables (i.e. variables that closely relate to the physiological limits of the species) is often recommended for modelling species distributions as it allows for more robust predictions and facilitates model interpretability (Buckley et al. 2010; Kearney and Porter 2009; Synes and Osborne 2011). Several of the potentially relevant environmental variables were highly correlated (Table S1 in Online Resource 1) which could affect model outcomes (Dormann et al. 2013; Merow et al. 2013). To minimize this, we generated environmental variable subsets which only contained variables with a correlation coefficient $< |0.7|$ using the *ENMeval* library (Muscarella et al. 2014) for R software package (R Core Team 2016). Model AUC and AIC scores (Table S2 in Online Resource 1) were then used to select the best subset of environmental variables for modelling purposes.

2.3 Modelling framework

Cork oak suitable areas were identified using a maximum entropy (MaxEnt) modelling framework and implemented in library *dismo* (Hijmans et al. 2015) for R software package v3.2 (R Core Team 2016). MaxEnt modelling is a widely used method for modelling species distributions (Merow et al. 2013) and has often been recommended over other available methods (Elith et al. 2006). Furthermore, it has recently been shown that the MaxEnt approach is analogous to a Poisson regression and thus mathematically equivalent to a generalized linear modelling (GLM) approach (Renner and Warton 2013).

Models were fitted using only linear and quadratic features to make model responses more interpretable (Merow et al. 2014; Merow et al. 2013). This approach has also been

Table 1 List of environmental variables tested for modelling the cork oak distribution

Environmental variable	Variable code	Description
Number of frost days	**Frost**	**Number of frost days in a year, calculated following** New et al. (2000)
Minimum temperature of coldest month	T_Min	Minimum temperature of the coldest month, obtained from Worldclim database
Total annual precipitation	P_total	Total annual precipitation, obtained from Worldclim database
Total spring precipitation	P_spr	Total spring precipitation, calculated as the sum of precipitation for the months of March, April and June
Total winter precipitation	P_win	Total winter precipitation, calculated as the sum of precipitation for the months of December, January and February
Annual aridity index	Arid	Annual aridity index, calculated following Zomer et al. (2008)
Spring aridity index	**Arid_spr**	**Aridity index calculated for the months of March, April and May**
Winter aridity index	Arid_win	Aridity index calculated for the months of December, January and February
Temperature seasonality	**T_seas**	**Calculated as the standard deviation of mean daily temperatures ×100, obtained from Worldclim database**
Precipitation seasonality	**P_seas**	**Calculated as the coefficient of variation of weekly precipitation estimates. Obtained from Worldclim database**
Soil type class	**Soil_class**	**Major soil grouping classes, obtained from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012)**
Soil pH class	**Soil_ph**	**Soil pH classes, obtained from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012)**

This set of environmental variables was selected based on biological knowledge of the species (Pausas et al. 2009). Variables included in the final model are highlighted in bold

recommended to obtain more realistic estimates of current and future potential distributions (Jimenez-Valverde et al. 2008; Thuiller et al. 2004), which are important for conservation purposes. Background points were selected from the whole study region but excluded areas where the cork oak is known to be present. Models were replicated 100 times by selecting 75 % of data records for calibration and 25 % for validation, using a sub-sampling approach. Each model run returned a prediction of current suitable areas for cork oak on a logistic scale varying from 0 to 1. Response curves for each environmental variable are available in Fig. Fig. S1 (Online Resource 1). Future predictions were also obtained on a logistic scale based on model response curves by applying environmental data representing future conditions to each model run.

Consensus maps were then calculated for present and future climate scenarios using an unweighted average of the logistic predictions obtained from model replicates using the *raster* library (Hijmans 2015) for R software package v3.2 (R Core Team 2016). Areas with a suitability score under 0.25 were considered as potentially unsuitable for the cork oak based on the average value of the 'equal training sensitivity plus specificity' threshold, which has been recommended as a good threshold selection approach (Jimenez-Valverde and Lobo 2007). Suitable areas were then assigned to one of two suitability classes based on logistic prediction scores: low (0.25 to <0.5) and high (≥0.5). These maps were used to estimate range-wide and country-level changes in the extent of suitable areas between present and future scenarios as well as the percentage of new stands likely to remain suitable in the future. The estimates of change in the extent of suitable area correspond to the environmental predictions of suitable area loss (measured in total grid cell area) and not observed cork oak range extent lost. Finally, Corine Land Cover 2006 raster maps (version 16) were used to determine the current land use in areas of high future suitability for the cork oak and explore the viability of different scenarios for the establishment of cork oak plantations. All map visualization, analysis and plotting was done using ArcGIS v10.0 (ESRI 2011).

3 Results

3.1 Model assessment

The final model included six environmental variables: number of frost days, spring aridity index, temperature seasonality, precipitation seasonality, soil type and soil pH (Table 1). The model with this set of variables had the highest AUC test score (0.944) and the lowest AIC score. Number of frost days was the highest contributing environmental variable (34.9 %), followed by precipitation seasonality (23.9 %). The remaining environmental variables included in the model had an overall contribution to the model which was inferior to 15 % (Table 2).

3.2 Global range analysis

Current predictions indicate that the large majority of cork oak woodlands (~75 %) are in areas of high suitability across their range (Fig. 2). Future predictions indicate an overall decrease in environmental suitability for the cork oak across its current range (average suitability decrease of 0.1 for RCP 4.5 and 0.3 for RCP 8.5, Fig. S2 in Online Resource 1). Our results suggest that suitability will decline in most countries where the species occurs (except in France) due to a northward shift of suitable environmental conditions (Fig. 2). Such changes will lead to a potential loss of suitable areas that varies between ~2000 (RCP 4.5) and 13,000 km^2 (RCP 8.5), corresponding to ~5–40 % of currently occupied areas (Fig. 3). Moreover, only ~5000 (RCP 8.5) to 11,000 km^2 (RCP 4.5), which account for ~20 to 35 % of currently occupied areas, are likely to remain highly suitable. Thus, in the future, a large proportion of the area currently occupied (between ~65 and 80 %) is likely to have a low suitability for the species.

Area losses resulting from decreasing environmental suitability may be compensated with afforestation in novel suitable areas (Fig. 2). The models predict that these new suitable areas correspond to ~51,000 km^2 under the RCP 4.5 scenario and to ~58,000 km^2 under the RCP 8.5 scenario. This represents approximately twice the area currently occupied by cork oak woodlands. However, the conversion of most of these areas to cork oak woodland faces considerable policy and socio-economic challenges including competition with current land

Table 2 Environmental variables included in the final MaxEnt model and their contributions to the model predictions

Environmental variable	Percent contribution	Permutation importance
Number of frost days	34.9	39.1
Precipitation seasonality	23.9	30.5
Soil type class	12.4	2.4
Soil pH class	10.7	3.6
Temperature seasonality	9.4	3.5
Spring aridity index	8.6	20.9

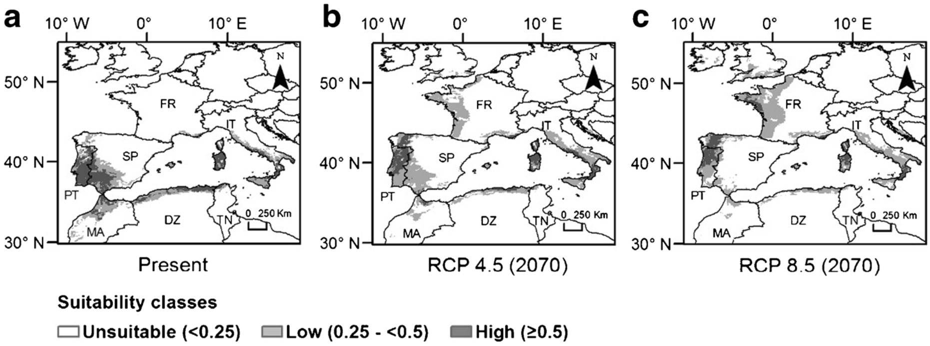

Fig. 2 Cork oak environmentally suitable areas as predicted by MaxEnt models for present (**a**) and future scenarios (year 2070) based on RCP 4.5 (**b**) and RCP 8.5 (**c**). Country codes identify the nations where the species currently occurs: Portugal (*PT*), Spain (*SP*), France (*FR*), Italy (*IT*), Morocco (*MA*), Algeria (*DZ*) and Tunisia (*TN*)

uses and alternative management options. Most of the potential new suitable areas are currently occupied by native forests and agricultural land (~25,000 to 30,000 km^2, Table 3), while areas of pasture and agroforestry systems do not represent more than 2500 km^2 (~5 % of the total novel suitable area).

3.3 Country-level analysis

Analyses at country level reveal distinct trends for the northern and southern areas of the cork oak distribution (Fig. 2). Most southern areas where the species is currently present will decrease in environmental suitability, particularly in Portugal, Spain and Morocco. In Portugal, large areas currently occupied by the species will change from high to low environmental

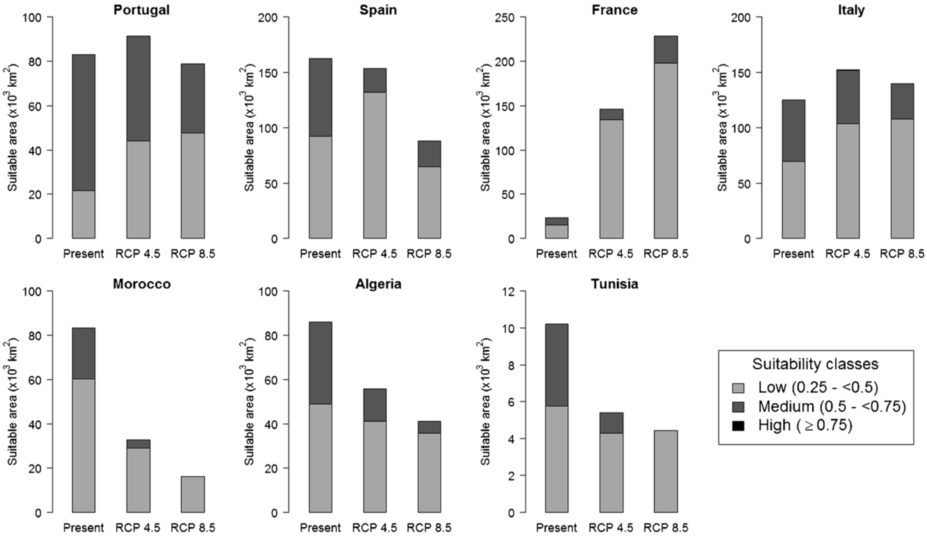

Fig. 3 Country-level analysis showing changes in environmental suitability for areas currently occupied by cork oak. Predictions are shown for the present (*left bars*) and future (year 2070) scenarios based on RCP 4.5 (*middle bars*) and RCP 8.5 (*right bars*)

Table 3 Percentage cover of the five most common land uses in areas likely to become environmentally suitable (medium and high suitability classes) for cork oak in the future (year 2070) under RCP 4.5 and RCP 8.5 scenarios

Rank	Representative concentration pathways			
	RCP 4.5		RCP 8.5	
	Land cover class	Area (%)	Land cover class	Area (%)
1	Transitional woodland-shrub	6633 (13.0 %)	Complex cultivation patterns	6780 (11.9 %)
2	Broad-leaved forest	6103 (11.9 %)	Transitional woodland-shrub	6582 (11.6 %)
3	Complex cultivation patterns	4720 (9.2 %)	Non-irrigated arable land	6010 (10.6 %)
4	Agriculture with natural vegetation	4437 (7.0 %)	Broad-leaved forest	5949 (10.5 %)
5	Non-irrigated arable land	3982 (4.8 %)	Agriculture with natural vegetation	3619 (5.5 %)
–	Other land uses	25,336 (49.5 %)	Other land uses	27,123 (47.7 %)

Land cover classes according to Corine Land Cover 2006 Label 3 (version 16) classification. Area values are shown in square kilometres and percentage values relate to total novel area of medium and high suitability where the species is currently absent

suitability. These areas total between ~5000 and 6000 km^2 under RCP 4.5 and RCP 8.5 scenarios, respectively (Fig. 3), which corresponds to approximately 55–66 % of high suitability areas in the country. In Spain and Morocco, many areas are also likely to become unsuitable for the species. The total extent of these areas ranges up to ~6000 km^2 in Spain and ~3500 km^2 in Morocco under RCP 8.5 (corresponding to approximately 60 and 70 % of currently suitable areas in Spain and Morocco, respectively; Fig. 3). In Italy, Algeria and Tunisia, climate change will mostly convert areas of high suitability into areas of low suitability. This change may range up to ~2000, 3000 and 800 km^2 for each country respectively under the RCP 8.5 scenario. France is the only country where the cork oak environmental suitability is likely to improve in presently occupied areas, with up to 1000 km^2 becoming highly suitable.

3.4 Assessment of the climatic suitability of recent afforestations

Many of the areas where cork oak stands were recently established in Portugal are likely change in suitability due to climate change (Fig. 4). Our results suggest that the most (~99.5 %) recent stands were established in areas that presently show high environmental suitability. Under the RCP 4.5 scenario, all stands are likely to remain in suitable areas, although approximately 30 % of them will decrease in suitability. However, under the RCP 8.5 scenario, up to 90 % of the new stands will have low climatic suitability and approximately 10 % will become unsuitable.

4 Discussion

4.1 Model assessment and predicted scenarios

Our results show that climate change is likely to affect the global distribution of cork oak woodlands. Up to 40 % of the current global distribution of these woodlands is expected to

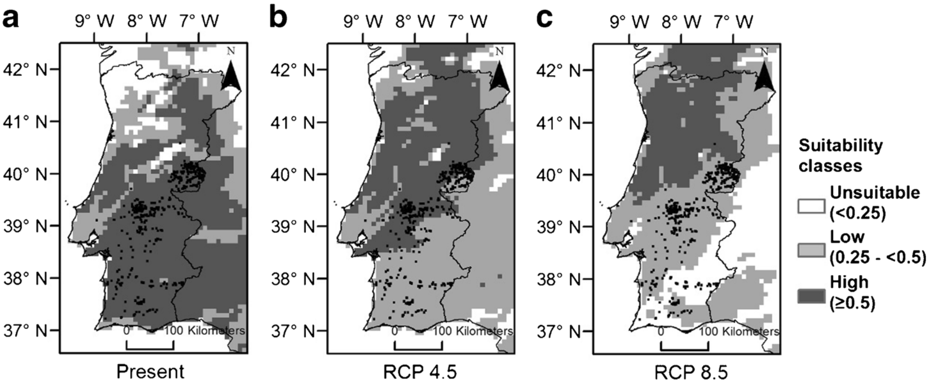

Fig. 4 Location of recently established cork oak stands in Portugal in relation to cork oak environmental suitability as predicted by MaxEnt models for present (**a**) and future (year 2070) environmental conditions based on RCP 4.5 (**b**) and RCP 8.5 (**c**) climate change scenarios. Cork oak stands are represented by *black dots*

become environmentally unsuitable, under the more extreme climate change scenario (3.7 °C by the end of the century). An additional 40 % of the current range is likely to suffer a decline in suitability. Presently, Portugal and Spain are the countries with the largest area of cork oak woodlands (Pausas et al. 2009), but approximately 60 % of this will lose suitability under the more extreme climate change scenarios (RCP 8.5). Southern areas of the current distribution will be the most affected, including Alentejo and Algarve in Portugal, Extremadura and Andalucía in Spain and most of North Africa. Cork production has an important socio-economic role and supports rural livelihoods in these regions (Berrahmouni et al. 2007). Additionally, several cork oak woodlands in these regions have high conservation value (Correia et al. 2015a; Dias et al. 2013). To counter the negative impact of climate change on these natural and socio-economic values, it is crucial to implement climate change adaptation measures. Such measures can take advantage of the opportunities to compensate predicted losses using new suitable areas (e.g. northern Iberia Peninsula, France and Italy, Fig. 2).

This study uses a robust modelling procedure which considers data from the whole cork oak distribution to predict changes in environmental suitability across the natural range of the species. This procedure improves model performance and transferability and is likely to produce more plausible future scenarios (Barbet-Massin et al. 2010; Thuiller et al. 2004). Previous studies, based on other approaches and using limited distribution data, suggested potential losses of up to 96 % of environmentally suitable areas for cork oak in the Iberian Peninsula (Benito Garzon et al. 2008) and a potential expansion of up to 522 % in Italy (Attorre et al. 2011). While our results partially agree with these forecasts, they give more conservative estimates for area gains and losses due to changes in environmental suitability. We found that the inclusion of the global range of the species in the modelling procedure was particularly important; initial models were trained without data from North Africa, the driest part of the species' range, and yielded clearly inadequate predictions.

Our models showed a very good fit, both in terms of AUC scores and in the high correspondence between the model response to environmental variables and the known species environmental limits. The natural distribution of cork oak trees is restricted to areas with an average annual precipitation equal or above 600 mm and average annual temperatures above 15 °C (Pausas et al. 2009; Pereira 2007). In Europe, cork oak distribution is partly restricted to southern regions because of its low tolerance to frequent winter frost, an important determinant of the northern limit for the species (Cavender-Bares et al. 2005; Larcher 2000; Pausas et al. 2009). In North Africa, however, tolerance to drought is likely the main limitation for cork oak occurrence (Larcher 2000; Pausas et al. 2009). Our choice of environmental variables for modelling calibration considered these environmental constraints, as recommended to obtain more robust predictions (Buckley et al. 2010; Kearney and Porter 2009; Synes and Osborne 2011). The number of frost days (an indicator of the duration of cold spells) and precipitation seasonality (indicating the intensity of drought spells) accounted for approximately 60 % of the model's explanatory power (Table 1). Soil characteristics are also strong determinants of cork oak distribution as the species prefers acidic soils with granite, schist or sandy substrates (Serrasolses et al. 2009). Our models also reflected this constraint, with soil type and pH together accounting for half of the remaining explanatory power. As with any other correlative modelling procedure, our model predictions are based on the characterization of the current conditions supported by the species and therefore do not account for potential acclimatization and genetic adaptation of the species to future conditions or novel management practices (e.g. irrigation).

4.2 Climate change adaptation recommendations for cork oak woodlands

Climate change adaptation targeting cork oak woodlands requires development and implementation of global-, national- and regional-level policies. To be effective, such efforts must incorporate regional differences in predicted changes in environmental suitability. Strategies should be distinct (i) for the regions that are becoming mostly unsuitable for the cork oak, (ii) for those that will in the long term maintain adequate suitability and (iii) for those regions that will harbour new suitable areas. For example, under the scenario of RCP 8.5, extensive regions of northern Africa and southern Iberian Peninsula will lose their overall suitability; within these regions, only small areas with different microclimatic conditions may support cork oak populations. These potential refugia sites will likely be located in northern slopes of hilly areas, where impacts of climate change are buffered by local conditions such as higher moisture and lower temperatures (Correia et al. 2015b). These refugia should be prioritized for protection because they are valuable to preserve existing biodiversity and as potential regeneration islets (Benayas et al. 2008), acting as sources of propagules to colonize neighbouring areas, when conditions become adequate. The protection of these refugia could also complement the current network of protected areas, such as the Natura 2000 network, by increasing connectivity and effectiveness. Such an approach, taking advantage of refugia, has been suggested as an important adaptation strategy for the Mediterranean region (Araujo et al. 2011; Klausmeyer and Shaw 2009) and other parts of the world (Canadell and Raupach 2008; Heller and Zavaleta 2009).

Our models also show that large regions within the current distribution of the species will remain environmentally suitable, in spite of changing local conditions. This includes central Portugal, most of southern and western Italy and the islands of Sicily, Sardinia and Corsica. In the short to medium term, these regions will remain the stronghold of cork oak woodlands and will require efforts to minimize already existing threats, as well as those driven by climate change. Promoting sustainable forest management will be necessary to preserve cork oak woodlands and their associated biodiversity, the delivery of ecosystem services (Bugalho et al. 2011), and can generate synergies between forest adaptation and climate mitigation strategies (Ravindranath 2007). Emergent mechanisms of forest certification and payment for ecosystem services (Bugalho and Silva 2014; Bugalho et al. 2016; Dias et al. 2013) can be used to incentivize sustainable forest management. In areas losing some level of suitability, responsive management practices, such as stand irrigation, may be necessary, but that will require prior ecological and economic evaluation. The cork industry in Portugal is already anticipating the effects of climatic change and supporting research exploring how novel management practices such as irrigation may affect the productivity of cork oak stands (Schmitt 2016). It remains to be seen, however, whether irrigation is a cost-effective solution, particularly in drier regions, where limited water availability will be exacerbated by future climate change (Barkhordarian et al. 2013; Cook et al. 2016).

The predicted northward shift of environmentally suitable areas represents an opportunity for promoting the expansion, and thus compensate losses, of cork oak cover. However, such a compensation process implies considerable policy and environmental challenges. Concerted regional and national policy efforts would be needed to compensate losses in North Africa and Iberia with expansion of the species in France. Such efforts would probably require a Common European Forest policy framework that currently does not exist (Winkel and Sotirov 2016). Nevertheless, legal and financial mechanisms for sustainable forest management and afforestation, presently under the European Common Agricultural Policy, could be explored to support this potential northern expansion of cork oak (Bonfiglio et al. 2016). Some natural range expansion into new environmentally suitable areas may take place but is very limited by the current low rates of cork oak regeneration and establishment (Acácio et al. 2007; Caldeira et al. 2014; Pons and Pausas 2006). Hence, afforestation will be necessary to support a northward range expansion of the species (de Dios et al. 2007). This study identified areas where these measures are more likely to succeed and demonstrated how modelling approaches can inform such decisions (Hidalgo et al. 2008; Vessella and Schirone 2013). For example, our results show that several recently established cork oak stands in Portugal are located in areas that will lose environmental suitability and are thus unlikely to balance potential future losses of cork oak cover, particularly under RCP 8.5 (Fig. 4). Finally, afforestation in new areas must consider social, economic and ecologic dynamics of present and past land uses in these areas, including local people needs (Linares 2007; Nyong et al. 2007). Areas that are increasing in suitability for cork oak are currently occupied by a matrix of other land uses, such as productive agricultural lands, native vegetation or legally protected areas (Table 3). This competition among land uses highlights the need for further studies addressing the potential socio-economic consequences of land cover changes resulting from climate change (Oliver and Morecroft 2014).

5 Conclusions

Forest ecosystems are under increasing pressure from climate change worldwide, and integrative forest adaptation and mitigation frameworks are necessary to address this challenge (Millar et al. 2007). Spatially explicit modelling approaches can contribute with useful information for the design of these frameworks (Rowland et al. 2011), and the models we developed illustrate this usefulness in the case of cork oak woodlands. The most satisfactory models we obtained were made robust by the use of predictor variables known to be physiologically important for the cork oak and by training the models using the full range of climatic conditions presently occupied by the species. Future modelling efforts aiming to analyse climate change impacts on forest ecosystems should also incorporate economic and social criteria whenever possible (Aaheim et al. 2011; de Bremond and Engle 2014).

The results of these models indicate that climate change will cause major shifts in the global distribution of cork oak woodlands. It is urgent to start addressing such shifts with appropriate mitigation and adaptation measures, as this ecosystem is very important for the rural economy and conservation of biodiversity in much of the Western Mediterranean Basin (Bugalho et al. 2011). Early implementation of adaptation strategies is particularly important for ecosystems with slow growth and maturation rates, such as cork oak woodlands. Their early deployment can also be carried out in a manner that stimulates synergies with climate change mitigation actions (Millar et al. 2007; Ravindranath 2007). However, the identified shifts in potential distribution of cork oak occur at a scale requiring a supra national response strategy, spanning several countries in Europe and Africa with very different social and economic realities, which poses particular challenges.

The results of our spatial models reinforce the idea that forest adaptation strategies need to be regionally adjusted (Afreen et al. 2011). The expected changes show a gradual pattern across a latitudinal gradient, but it is possible to divide this gradient into three rough regions that require partially distinct actions. In the southernmost region, which includes North Africa and parts of Iberia, the expected decrease in suitability is so great that resources should be concentrated in the preservation of the few refuges where microclimatic conditions will keep long-term suitability for the species (Dobrowski 2011). The intermediate region corresponds to the parts of the current range of cork oak that are likely to maintain adequate levels of suitability in the long term. This will for many decades remain the core of the range of this type of woodland, and a major objective here should be to improve the economic and ecological sustainability of the system, so that it can resist the greater aridity and the increasing competition for space resulting from the expected northward migration of agriculture. Irrigation may be required in part of this region to counter aridity, but the viability of this measure is questionable due to the increasing scarcity of water resources (Barkhordarian et al. 2013; Cook et al. 2016). It has been shown that the ecological and economic viability of deploying irrigation in response to increasing aridity can show substantial variation across regions with Mediterranean climate (Salinas and Mendieta 2013a, 2013b). We strongly recommend a similar assessment be made before the large-scale implementation of irrigation in the case of cork oak. Finally, the northernmost region corresponds to the relatively vast areas that are now mostly outside the range of cork oak but will become suitable as a consequence of climate warming. Assisted colonization, mostly in the form of new afforestations, should be a key tool for adaptation in this region, even though greatly limited by the competition of the various land use types that presently dominate the area. Adaptation strategies should address these important land competition issues (Lunda and Iremonger 2000). New afforestations should be planned using robust models predicting future suitability, to increase their chances of long-term success.

In spite of the growth of forest research, it was evident to us during this study that further multidisciplinary research covering the various dimensions of forest adaptation and mitigation is necessary to provide sound recommendations for the conservation of forests under climate change. In the case of cork oak woodlands, it is particularly crucial to address existing knowledge gaps associated with ecological functioning, biocultural heritage and regionally specific threats in Europe and North Africa, as these may greatly constrain adaptation and mitigation strategies.

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