

1 **Title:** Contribution of spatially explicit models to climate change adaptation and  
2 mitigation plans for a priority forest habitat

3  
4 **Abstract**

5 Climate change will impact forest ecosystems, their biodiversity and the livelihoods they  
6 sustain. Several adaptation and mitigation strategies to counteract climate change impacts  
7 have been proposed for these ecosystems. However, effective implementation of such  
8 strategies requires a clear understanding of how climate change will influence the future  
9 distribution of forest ecosystems. This study uses maximum entropy modelling (MaxEnt)  
10 to predict environmentally suitable areas for cork oak (*Quercus suber*) woodlands, a  
11 socio-economically important forest ecosystem protected by the European Union  
12 Habitats Directive. Specifically, we use two climate change scenarios to predict changes  
13 in environmental suitability across the entire geographical range of the cork oak and in  
14 areas where stands were recently established. Up to 40% of current environmentally  
15 suitable areas for cork oak may be lost by 2070, mainly in northern Africa and southern  
16 Iberian Peninsula. Almost 90% of new cork oak stands are predicted to lose suitability by  
17 the end of the century, but future plantations can take advantage of increasing suitability  
18 in northern Iberian Peninsula and France. The predicted impacts cross country borders,  
19 showing that a multinational strategy will be required for cork oak woodland adaptation  
20 to climate change. Such a strategy must be regionally adjusted, featuring the protection  
21 of refugia sites in southern areas and stimulating sustainable forest management in areas  
22 that will keep long-term suitability. Afforestation efforts should also be promoted but  
23 must consider environmental suitability and land competition issues.

24  
25 **Keywords:**

26 Afforestation, climate change impacts, conservation planning, dehesa, environmental  
27 niche modelling, montado

## 35 **1 Introduction**

36 Global climate change is affecting ecosystems worldwide (Parmesan, 2006;  
37 Parmesan and Yohe, 2003). Forest ecosystems are particularly susceptible to shifts in  
38 natural disturbance regimes induced by climate change (Dale et al., 2001; Trumbore et  
39 al., 2015). For example, changes in the intensity, frequency and duration of wildfires or  
40 droughts can negatively affect tree growth and recruitment, increase tree defoliation and,  
41 ultimately, induce tree mortality (Allen et al., 2010; Caldeira et al., 2015; Lindner et al.,  
42 2010; Walck et al., 2011). Adaptation and mitigation strategies against climate change  
43 are crucial to counteract such effects. However, effective implementation of such  
44 strategies requires accurate identification of areas that may remain environmentally  
45 suitable for forest species and areas with potential for afforestation (Aitken et al., 2008;  
46 Millar et al., 2007; Settele et al., 2014). This is particularly important in climate change  
47 hotspots, such as the Mediterranean Basin (Giorgi, 2006), where the development of  
48 forest adaptation and mitigation strategies is a pressing challenge (Doblas-Miranda et al.,  
49 2015; Scarascia-Mugnozza et al., 2000).

50 Cork oak (*Quercus suber*) woodlands are agro-silvo-pastoral systems of high  
51 socio-economic and conservation value, typical of the Western Mediterranean Basin.  
52 They cover approximately 1.5 million ha across Portugal, Spain, Italy and France, and 1  
53 million ha in North Africa between Morocco, Algeria and Tunisia (Bugalho et al., 2011;  
54 Díaz et al., 1997). Cork oak woodlands have a relatively open, savannah-like tree  
55 structure (about 30 to 60 trees per ha) and a heterogeneous shrub-grassland matrix  
56 understory (Bugalho et al., 2009). These woodlands host plant and animal species of high  
57 conservation value (Correia et al., 2015a; Díaz et al., 1997), including endemic or  
58 threatened species such as Iberian imperial eagle *Aquila adalberti*, Black stork *Ciconia*  
59 *nigra* or Iberian lynx *Lynx pardinus*. Cork oak woodlands are classified under the  
60 European Union Habitats Directive (92/43/CEE) and are included in the Natura 2000  
61 network of protected areas (Berrahmouni et al., 2009). Cork oak woodlands also have a  
62 very high socio-economic value, mostly derived from cork and livestock production  
63 (Bugalho et al., 2009; Pereira and Tomé, 2004). Cork can be harvested every 9 to 12 years  
64 without significant damage to the tree or affecting the biodiversity of these woodlands  
65 (Leal et al., 2011). Cork is mainly used for wine bottle stoppers (over 70% of production),  
66 although there has been a recent increase in other applications such as insulation materials  
67 and pavements (Bugalho et al., 2009; Bugalho et al., 2011). Approximately 300 thousand  
68 tons of cork are harvested across the western Mediterranean Basin annually (Berrahmouni

69 et al., 2007). Cork is the sixth most important non-timber forest product worldwide, with  
70 an estimated export value of US\$329 million, and processed cork products generate an  
71 annual revenue of US\$ 2 billion (Berrahmouni et al., 2007).

72 Current threats to cork oak woodlands include a lack of natural oak regeneration  
73 and high adult oak mortality, eventually leading to declines in tree density and area loss  
74 (Plieninger et al., 2010; Santos and Thorne, 2010). Climate change will exacerbate these  
75 threats through an increase in temperatures and frequency of droughts (Acácio et al.,  
76 2016; Besson et al., 2014; Caldeira et al., 2015), both of which will contribute to an  
77 increase in the frequency and severity of wildfires (Acácio et al., 2007; Godinho et al.,  
78 2016), especially in areas with inadequate management (Bugalho et al., 2011; Godinho  
79 et al., 2016).

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

88

## 89 **2 Methods**

### 90 **2.1 Cork oak distribution data**

91 Cork oak distribution was obtained by geo-referencing or collecting geo-  
92 referenced data in national forestry and biodiversity inventories. Data were collected for  
93 all the countries where the species occurs naturally (Fig. 1): Portugal (Autoridade  
94 Florestal Nacional, 2009), Spain (Dirección General de Medio Natural y Política Forestal,  
95 2009), France (Institut National de l'Information Géographique et Forestière, 2010), Italy  
96 (Vessella and Schirone, 2013), Morocco (Haut Commissariat aux Eaux et Forêts et à la  
97 Lutte Contre la Désertification, 2005), Algeria (Barry et al., 1974), and Tunisia (Khaldi,  
98 2004). The spatial resolution of the data differed among countries, so the complete  
99 distribution dataset was up-scaled to a 5 arc-minute resolution grid. This process served  
100 to homogenise the spatial resolution of the distribution data and match it to the resolution  
101 of the climate data used (see below).

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

106

## 107 **2.2 Environmental data**

108 Climate data representing current (1950-2000) and future (2061-2080) conditions  
109 were downloaded from the WorldClim database (<http://www.worldclim.org/>) at 5 arc-  
110 minute resolution. Future climatic conditions were derived from four Global Circulation  
111 Models (GCMs – ACCESS1-0, CCSM4, HadGEM2-ES and MPI-ESM-LR) and two  
112 Representative Concentration Pathways scenarios (RCP 4.5 and 8.5). These scenarios  
113 were chosen to represent moderate (RCP 4.5, average increase of 1.8°C by 2100) and  
114 extreme (RCP 8.5, average increase of 3.7°C by 2100) warming trends (Stocker et al.,  
115 2013). We collected data from the standard set of 19 bioclimatic variables (Hutchinson et  
116 al., 2009) available in the WorldClim database. Furthermore, we calculated additional  
117 variables potentially relevant for cork oak: number of frost days (New et al., 2000) and  
118 indices of annual and seasonal aridity (Zomer et al., 2008). Two soil related variables,  
119 Soil type and Soil pH, were collected from the Harmonized World Soil Database, also at  
120 5 arc-minute resolution (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

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

134

## 135 **2.3 Modelling framework**

136 Cork oak suitable areas were identified using a maximum entropy (MaxEnt)  
137 modelling framework and implemented in library *dismo* (Hijmans et al., 2015) for R  
138 software package v3.2 (R Core Team, 2016). MaxEnt modelling is a widely-used method  
139 for modelling species distributions (Merow et al., 2013) and has often been recommended  
140 over other available methods (Elith et al., 2006). Furthermore, it has recently been shown  
141 that the MaxEnt approach is analogous to a Poisson regression and thus mathematically  
142 equivalent to a Generalized Linear Modelling (GLM) approach (Renner and Warton,  
143 2013).

144 Models were fitted using only Linear and Quadratic features to make model  
145 responses more interpretable (Merow et al., 2014; Merow et al., 2013). This approach has  
146 also been recommended to obtain more realistic estimates of current and future potential  
147 distributions (Jimenez-Valverde et al., 2008; Thuiller et al., 2004), which are important  
148 for conservation purposes. Background points were selected from the whole study region,  
149 but excluded areas where the cork oak is known to be present. Models were replicated  
150 100 times by selecting 75% of data records for calibration and 25% for validation, using  
151 a sub-sampling approach. Each model run returned a prediction of current suitable areas  
152 for cork oak on a logistic scale varying from 0 to 1. Response curves for each  
153 environmental variable are available in Fig. S1 (Online Resource 1). Future predictions  
154 were also obtained on a logistic scale based on model response curves by applying  
155 environmental data representing future conditions to each model run.

156 Consensus maps were then calculated for present and future climate scenarios  
157 using an unweighted average of the logistic predictions obtained from model replicates  
158 using the *raster* library (Hijmans, 2015) for R software package v3.2 (R Core Team,  
159 2016). Areas with a suitability score under 0.25 were considered as potentially unsuitable  
160 for the cork oak based on the average value of the ‘Equal training sensitivity plus  
161 specificity’ threshold, which has been recommended as a good threshold selection  
162 approach (Jimenez-Valverde and Lobo, 2007). Suitable areas were then assigned to one  
163 of two suitability classes based on logistic prediction scores: low (0.25 to <0.5) and high  
164 ( $\geq 0.5$ ). These maps were used to estimate range-wide and country-level changes in the  
165 extent of suitable areas between present and future scenarios as well as the percentage of  
166 new stands likely to remain suitable in the future. The estimates of change in the extent  
167 of suitable area correspond to the environmental predictions of suitable area loss  
168 (measured in total grid cell area) and not observed cork oak range extent lost. Finally,  
169 Corine Land Cover 2006 raster maps (Version 16) were used to determine the current

170 land use in areas of high future suitability for the cork oak and explore the viability of  
171 different scenarios for the establishment of cork oak plantations. All map visualization,  
172 analysis and plotting was done using ArcGIS v10.0 (ESRI, 2011).

173

### 174 **3 Results**

#### 175 **3.1 Model assessment**

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

183

#### 184 **3.2 Global range analysis**

185 Current predictions indicate that the large majority of cork oak woodlands (~75%)  
186 are in areas of high suitability across their range (Fig. 2). Future predictions indicate an  
187 overall decrease in environmental suitability for the cork oak across its current range  
188 (average suitability decrease of 0.1 for RCP 4.5 and 0.3 for RCP 8.5, Fig. S2 in Online  
189 Resource 1). Our results suggest that suitability will decline in most countries where the  
190 species occurs (except in France) due to a northward shift of suitable environmental  
191 conditions (Fig. 2). Such changes will lead to a potential loss of suitable areas that varies  
192 between ~2 000 (RCP 4.5) and 13 000 km<sup>2</sup> (RCP 8.5), corresponding to ~5-40% of  
193 currently occupied areas (Fig. 3). Moreover, only ~5 000 (RCP 8.5) to 11 000 km<sup>2</sup> (RCP  
194 4.5), which account for ~20 to 35% of currently occupied areas, are likely to remain  
195 highly suitable. Thus in the future a large proportion of the area currently occupied  
196 (between ~65 and 80%) is likely to have a low suitability for the species.

197 Area losses resulting from decreasing environmental suitability may be  
198 compensated with afforestation in novel suitable areas (Fig. 2). The models predict that  
199 these new suitable areas correspond to ~51 000 km<sup>2</sup> under the RCP 4.5 scenario, and to  
200 ~58 000 km<sup>2</sup> under the RCP 8.5 scenario. This represents approximately twice the area  
201 currently occupied by cork oak woodlands. However, the conversion of most of these  
202 areas to cork oak woodland faces considerable policy and socio-economic challenges  
203 including competition with current land uses and alternative management options. Most

204 of the potential new suitable areas are currently occupied by native forests and agricultural  
205 land (~25 000 to 30 000 km<sup>2</sup>, Table 3) while areas of pasture and agro-forestry systems  
206 do not represent more than 2 500 km<sup>2</sup> (~5% of the total novel suitable area).

207

### 208 **3.3 Country-level analysis**

209 Analyses at country level reveal distinct trends for the northern and southern areas  
210 of the cork oak distribution (Fig 2). Most southern areas where the species is currently  
211 present will decrease in environmental suitability, particularly in Portugal, Spain and  
212 Morocco. In Portugal, large areas currently occupied by the species will change from high  
213 to low environmental suitability. These areas total between ~5 000 and 6 000 km<sup>2</sup> under  
214 RCP 4.5 and RCP 8.5 scenarios respectively (Fig. 3), which corresponds to approximately  
215 55-66% of high suitability areas in the country. In Spain and Morocco many areas are  
216 also likely to become unsuitable for the species. The total extent of these areas range up  
217 to ~6 000 km<sup>2</sup> in Spain and ~3 500 km<sup>2</sup> in Morocco under RCP 8.5 (corresponding to  
218 approximately 60 and 70% of currently suitable areas in Spain and Morocco respectively;  
219 Fig. 3). In Italy, Algeria and Tunisia, climate change will mostly convert areas of high  
220 suitability into areas of low suitability. This change may range up to ~2 000, 3 000 and  
221 800 km<sup>2</sup> for each country respectively under the RCP 8.5 scenario. France is the only  
222 country where the cork oak environmental suitability is likely to improve in presently  
223 occupied areas, with up to 1 000 km<sup>2</sup> becoming highly suitable.

224

### 225 **3.4 Assessment of the climatic suitability of recent afforestations**

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

233

## 234 **4 Discussion**

### 235 **4.1 Model assessment and predicted scenarios**

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

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

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

265         Our models showed a very good fit, both in terms of AUC scores and in the high  
266 correspondence between the model response to environmental variables and the known  
267 species environmental limits. The natural distribution of cork oak trees is restricted to  
268 areas with an average annual precipitation equal or above 600 millimetres and average  
269 annual temperatures above 15°C (Pausas et al., 2009; Pereira, 2007). In Europe, cork oak  
270 distribution is partly restricted to southern regions because of its low tolerance to frequent  
271 winter frost, an important determinant of the northern limit for the species (Cavender-



272 Bares et al., 2005; Larcher, 2000; Pausas et al., 2009). In North Africa, however, tolerance  
273 to drought is likely the main limitation for cork oak occurrence (Larcher, 2000; Pausas et  
274 al., 2009). Our choice of environmental variables for modelling calibration considered  
275 these environmental constraints, as recommended to obtain more robust predictions  
276 (Buckley et al., 2010; Kearney and Porter, 2009; Synes and Osborne, 2011). The number  
277 of frost days (an indicator of the duration of cold spells) and precipitation seasonality  
278 (indicating the intensity of drought spells) accounted for approximately 60% of the  
279 model's explanatory power (Table 1). Soil characteristics are also strong determinants of  
280 cork oak distribution as the species prefers acidic soils with granite, schist, or sandy  
281 substrates (Serrasolses et al., 2009). Our models also reflected this constraint, with soil  
282 type and pH together accounting for half of the remaining explanatory power. As with  
283 any other correlative modelling procedure, our model predictions are based on the  
284 characterization of the current conditions supported by the species, and therefore do not  
285 account for potential acclimatization and genetic adaptation of the species to future  
286 conditions or novel management practices (e.g. irrigation).

287

#### 288 **4.2 Climate change adaptation recommendations for cork oak woodlands**

289 Climate change adaptation targeting cork oak woodlands require development and  
290 implementation of global, national and regional-level policies. To be effective, such  
291 efforts must incorporate regional differences in predicted changes in environmental  
292 suitability. Strategies should be distinct (i) for the regions that are becoming mostly  
293 unsuitable for the cork oak, (ii) for those that will in the long term maintain adequate  
294 suitability, and (iii) for those regions that will harbour new suitable areas. For example,  
295 under the scenario of RCP 8.5, extensive regions of northern Africa and southern Iberian  
296 Peninsula will lose their overall suitability; within these regions only small areas with  
297 different micro-climatic conditions may support cork oak populations. These potential  
298 refugia sites will likely be located in northern slopes of hilly areas, where impacts of  
299 climate change are buffered by local conditions such as higher moisture and lower  
300 temperatures (Correia et al., 2015b). These refugia should be prioritized for protection  
301 because they are valuable to preserve existing biodiversity and as potential regeneration  
302 islets (Benayas et al., 2008), acting as sources of propagules to colonize neighbouring  
303 areas, when conditions become adequate. The protection of these refugia could also  
304 complement the current network of protected areas, such as the Natura 2000 network, by  
305 increasing connectivity and effectiveness. Such an approach, taking advantage of refugia,

306 has been suggested as an important adaptation strategy for the Mediterranean region  
307 (Araujo et al., 2011; Klausmeyer and Shaw, 2009) and other parts of the world (Canadell  
308 and Raupach, 2008; Heller and Zavaleta, 2009).

309 Our models also show that large regions within the current distribution of the  
310 species will remain environmentally suitable, in spite of changing local conditions. This  
311 includes central Portugal, most of southern and western Italy, and the islands of Sicily,  
312 Sardinia and Corsica. In the short to medium term, these regions will remain the  
313 stronghold of cork oak woodlands and will require efforts to minimize already existing  
314 threats, as well as those driven by climate change. Promoting sustainable forest  
315 management will be necessary to preserve cork oak woodlands and their associated  
316 biodiversity, the delivery of ecosystems services (Bugalho et al., 2011), and can generate  
317 synergies between forest adaptation and climate mitigation strategies (Ravindranath,  
318 2007). Emergent mechanisms of forest certification and payment for ecosystem services  
319 (Bugalho and Silva, 2014; Bugalho et al., 2016; Dias et al., 2013) can be used to  
320 incentivize sustainable forest management. In areas losing some level of suitability,  
321 responsive management practices, such as stand irrigation, may be necessary, but that  
322 will require prior ecological and economic evaluation. The cork industry in Portugal is  
323 already anticipating the effects of climatic change and supporting research exploring how  
324 novel management practices such as irrigation may affect the productivity of cork oak  
325 stands (Schmitt, 2016). It remains to be seen, however, whether irrigation is a cost-  
326 effective solution, particularly in drier regions, where limited water availability will be  
327 exacerbated by future climate change (Barkhordarian et al., 2013; Cook et al., 2016).

328 The predicted northward shift of environmentally suitable areas represents an  
329 opportunity for promoting the expansion, and thus compensate losses, of cork oak cover.  
330 However, such a compensation process implies considerable policy and environmental  
331 challenges. Concerted regional and national policy efforts would be needed to  
332 compensate losses in North Africa and Iberia with expansion of the species in France.  
333 Such efforts would probably require a Common European Forest policy framework that  
334 currently does not exist (Winkel and Sotirov, 2016). Nevertheless, legal and financial  
335 mechanisms for sustainable forest management and afforestation, presently under the  
336 European Common Agricultural Policy, could be explored to support this potential  
337 northern expansion of cork oak (Bonfiglio et al., 2016). Some natural range expansion  
338 into new environmentally suitable areas may take place, but is very limited by the current  
339 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 demonstrates 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).

355

## 356 **5 Conclusions**

357 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).

368 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

374 cork oak woodlands. Their early deployment can also be carried out in a manner that  
375 stimulates synergies with climate change mitigation actions (Millar et al., 2007;  
376 Ravindranath, 2007). However, the identified shifts in potential distribution of cork oak  
377 occur at a scale requiring a supra national response strategy, spanning several countries  
378 in Europe and Africa with very different social and economic realities, which poses  
379 particular challenges.

380         The results of our spatial models reinforce the idea that forest adaptation strategies  
381 need to be regionally adjusted (Afreen et al., 2011). The expected changes show a gradual  
382 pattern across a latitudinal gradient, but it is possible to divide this gradient into three  
383 rough regions that require partially distinct actions. In the southernmost region, which  
384 includes North Africa and parts of Iberia, the expected decrease in suitability is so great  
385 that resources should be concentrated in the preservation of the few refuges where  
386 microclimatic conditions will keep long term suitability for the species (Dobrowski,  
387 2011). The intermediate region corresponds to the parts of the current range of cork oak  
388 that are likely to maintain adequate levels of suitability in the long term. This will for  
389 many decades remain the core of the range of this type of woodland, and a major objective  
390 here should be to improve the economic and ecological sustainability of the system, so  
391 that it can resist the greater aridity and the increasing competition for space resulting from  
392 the expected northward migration of agriculture. Irrigation may be required in part of this  
393 region to counter aridity, but the viability of this measure is questionable due to the  
394 increasing scarcity of water resources (Barkhordarian et al., 2013; Cook et al., 2016). It  
395 has been shown that the ecological and economic viability of deploying irrigation in  
396 response to increasing aridity can show substantial variation across regions with  
397 Mediterranean climate (Salinas and Mendieta, 2013a, b). We strongly recommend a  
398 similar assessment be made before the large-scale implementation of irrigation in the case  
399 of cork oak. Finally, the northernmost region corresponds to the relatively vast areas that  
400 are now mostly outside the range of cork oak but will become suitable as a consequence  
401 of climate warming. Assisted colonization, mostly in the form of new afforestations,  
402 should be a key tool for adaptation in this region, even though greatly limited by the  
403 competition of the various land use types that presently dominate the area. Adaptation  
404 strategies should address these important land competition issues (Lunda and Iremonger,  
405 2000). New afforestations should be planned using robust models predicting future  
406 suitability, to increase their chances of long term success.

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

414

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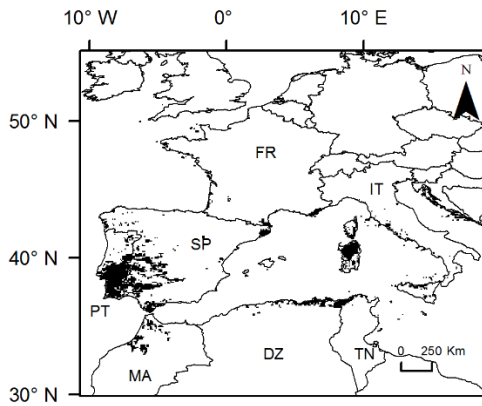
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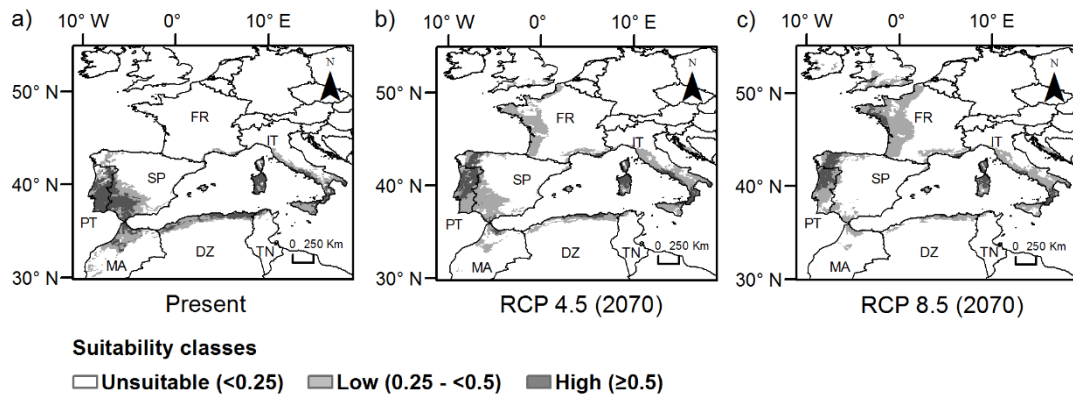
673 **Figures**

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



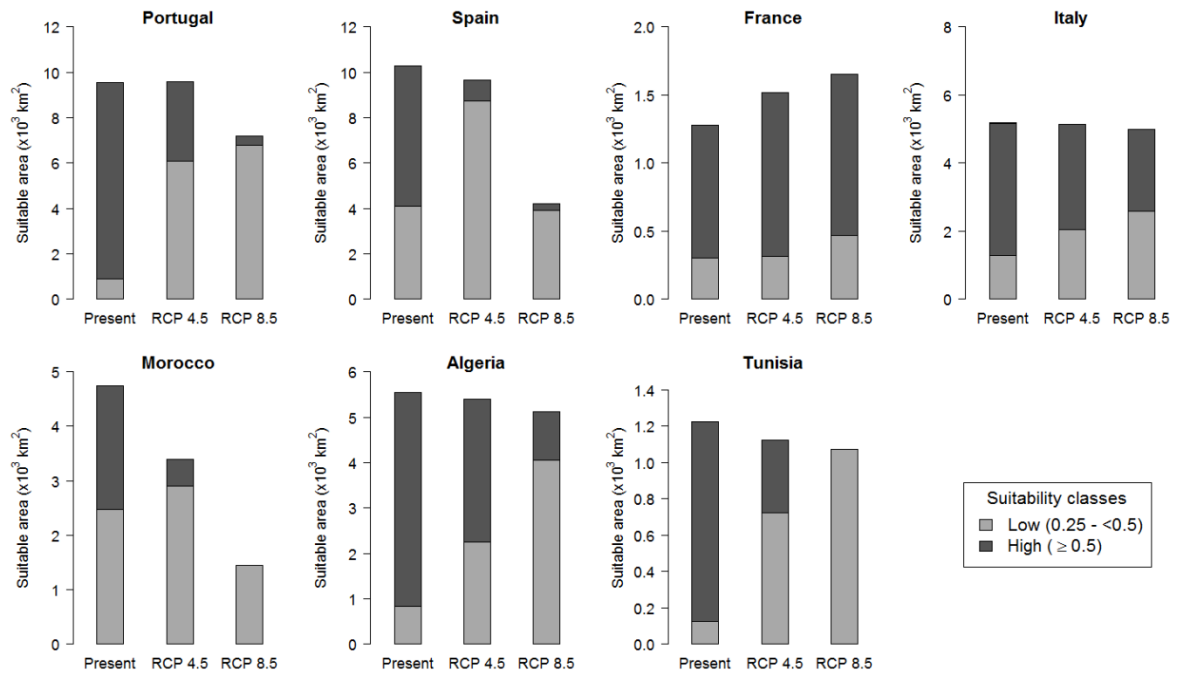
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700 Figure 2 – Cork oak environmentally suitable areas as predicted by MaxEnt models for  
 701 present (a) and future scenarios (year 2070), based on RCP 4.5 (b) and RCP 8.5 (c).  
 702 Country codes identify the nations where the species currently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



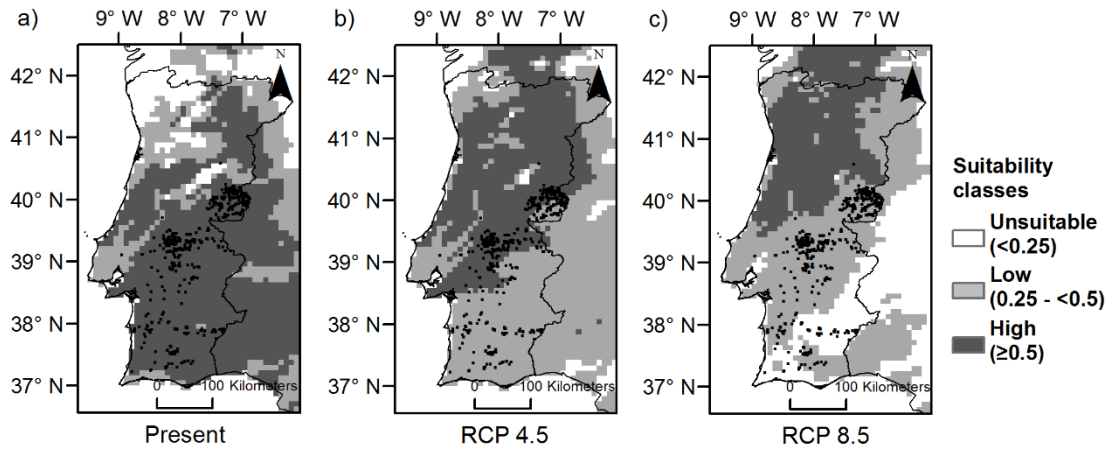
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726 Figure 3 – Country-level analysis showing changes in environmental suitability for areas  
 727 currently occupied by cork oak. Predictions are shown for the present (left bars) and future  
 728 (year 2070) scenarios based on RCP 4.5 (middle bars)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



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



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773 Table 1 – List of environmental variables tested for modelling the cork oak distribution. This set  
 774 of environmental variables was selected based on biological knowledge of the species (Pausas et  
 775 al. 2009). Variables included in the final model are highlighted in bold.

Environmental variable	Variable code	Description
<b>Number of frost days</b>	<b>Frost</b>	<b>Number of frost days in a year, calculated following New et al. (2000).</b>
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).
<b>Spring aridity index</b>	<b>Arid_spr</b>	<b>Aridity index calculated for the months of March, April and May.</b>
Winter aridity index	Arid_win	Aridity index calculated for the months of December, January and February.
<b>Temperature seasonality</b>	<b>T_seas</b>	<b>Calculated as the standard deviation of mean daily temperatures * 100, obtained from Worldclim database.</b>
<b>Precipitation seasonality</b>	<b>P_seas</b>	<b>Calculated as the coefficient of variation of weekly precipitation estimates. Obtained from Worldclim database.</b>
<b>Soil type class</b>	<b>Soil_class</b>	<b>Major soil grouping classes, obtained from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009).</b>
<b>Soil pH class</b>	<b>Soil_ph</b>	<b>Soil pH classes, obtained from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2009).</b>

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778 Table 2 –Environmental variables included in the final MaxEnt model and their contributions to  
779 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

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805 Table 3 – Percentage cover of the five most common land uses in areas likely to become  
 806 environmentally suitable (medium and high suitability classes) for cork oak in the future  
 807 (year 2070) under RCP 4.5 and RCP 8.5 scenarios. Land cover classes according to  
 808 Corine Land Cover 2006 Label 3 (Version 16) classification. Area values are shown in  
 809 square kilometers and percentage values relate to total novel area of medium and high  
 810 suitability where the species is currently absent.

Rank	Representative Concentration Pathways			
	RCP 4.5		RCP 8.5	
	Land cover class	Area (%)	Land cover class	Area (%)
1	Transitional woodland-shrub	6 633 (13.0%)	Complex cultivation patterns	6 780 (11.9%)
2	Broad-leaved forest	6 103 (11.9%)	Transitional woodland-shrub	6 582 (11.6%)
3	Complex cultivation patterns	4 720 (9.2%)	Non-irrigated arable land	6 010 (10.6%)
4	Agriculture with natural vegetation	4 437 (7.0%)	Broad-leaved forest	5 949 (10.5%)
5	Non-irrigated arable land	3 982 (4.8%)	Agriculture with natural vegetation	3 619 (5.5%)
-	Other land uses	25 336 (49.5%)	Other land uses	27 123 (47.7%)

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