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Assessment of the future stability of cork oak (*Quercus suber* L.) afforestation under climate change scenarios in Southwest Spain

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ABSTRACT

Intensive afforestation programmes were developed in Spain during the end of the 20 th century and the beginning of the 21st, under the European Economic Community's (EEC) agricultural reforestation directives. However, these afforestations were performed without considering future climate change scenarios and now these areas have to cope with more-severe climatic conditions. We used ensemble Species Distribution Models (SDMs) to study the future stability of cork oak (*Quercus suber* L.) plantations established in Andalusia between 1993 and 2000. We used presence/absence data from the national forest inventory and RED SEDA Network, together with survival rate data from 2008 for cork oak afforestations planted between 1993 and 2000, to forecast the potential optimal distribution of cork oak and to model the distribution of the survival rate of cork oak afforestations. We evaluated the change over time of the volume overlap of the environmental space between the potential distribution and the afforestations. The ensemble modelling approach gave highly-accurate results for the current potential distribution of cork oak in Andalusia (AUC = 0.943, TSS = 0.718, Kappa = 0.718) and moderately-accurate estimations of the distribution of the survival rate of cork oak afforestations in Andalusia (RMSE = 0.290). We found that 10% of the cork oak afforestations planted between 1993 and 2000 were established in the optimal area of occurrence of cork oak (probability of presence above 70%) and presented an acceptable survival rate (> 50%); also, the volume of the environmental space defined by cork oak afforestation decreased over time. We have confirmed the potential of SDMs to predict the distribution of the survival rate of cork oak afforestations and to assess their future stability. In the worst scenario, 3% of the cork oak afforestations would withstand climate change.

1. Introduction

Historically, afforestation has been the main forest restoration tool of the Spanish forest administration. Afforestation activity started with the first national restauration plan in 1938 and continued until ours days (Vadell et al., 2016). The general objectives were to stop deforestation, soil degradation and flooding, and attend the market woody supply (Navarro Cerrillo et al., 2016; Vadell et al., 2016). Lately, at the end of the 20 th century and the beginning of the 21 st, intensive afforestation programmes were implemented in Spain. The area of land afforested in Spain during the period 1993–2006 reached 468,000 ha, of which 232,000 ha were in Andalusia (Navarro Cerrillo et al., 2016; Vadell et al., 2016). These reforestation initiatives were promoted by the European Economic Community's (EEC) directive 2080/92, and later the EEC 1698/2005, which established a Community aid scheme for forestry measures in agriculture, with the general aim of transforming agricultural lands into forested areas. The aid scheme of the afforestation programme funded the cost of planting, conservation and maintenance; this covered the initial planting of seedlings, and replanting, during the first five years and the maintenance of the afforested land for 20 years after planting (Vadell et al., 2016). Additionally, to ensure the establishment of these afforestations, elevated planting densities were recommended: 600 plants ha^{-1} for cork production (Aronson et al., 2009) and 300–400 plants ha^{-1} in Mediterranean oaks woodlands (Aronson et al., 2009; Campos et al., 2013). However, many of these afforestations took place on private, abandoned or highly-degraded lands (Tomaz et al., 2013) and did not follow the recommendations about: site preparation, protection against grazing, competing vegetation, seedling quality or planting date, which might affect seedling survival (Aronson et al., 2009; Palacios et al., 2009; Arosa et al., 2015). Also, there was no consideration of the optimal potential range of the planted species (Ovando et al., 2007) or the

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stability of the afforestation in the near future, in relation to climate change scenarios (Dirección General de Desarrollo Rural and Ministerio de Agricultura Pesca y Alimentación, 2006). Therefore, the future of many of these afforestations remains uncertain (Vadell et al., 2016).

Cork oak (*Quercus suber* L.), with 55,826 ha, and Holm oak (*Quercus ilex* L.) were the species planted most frequently from 1993 to 2006 in Andalusia, as a consequence of the above-mentioned programmes (Navarro Cerrillo et al., 2009). Cork oak is a typical Mediterranean evergreen tree, tolerant of cutting and grazing and well adapted to prolonged drought and fire but not extreme cold. It grows in areas with mean annual rainfall above 600 mm and mean annual temperature close to 15 °C, preferably over acid substrates (Aronson et al., 2009). At an optimal site it can grow up to 20 metres tall and live for several centuries (Pausas et al., 2009). Cork oak is distributed in the western part of the Mediterranean Basin, with the south-western Iberian Peninsula as the area of maximum representation (Aronson et al., 2009; Campos et al., 2013). Spain and Portugal are the most-representative countries, with 500,000 and 715,923 ha, respectively (Costa Tenorio et al., 1998; Aronson et al., 2009). Cork oaks are normally found in highly-anthropogenic, open woodlands with a savanna-like land cover pattern (Esselink and van Gils, 1994), but they also occur in semi-natural woodlands that are gradually becoming forests, as in the Los Alcornocales Natural Park in the south of Spain (Costa Tenorio et al., 1998; Aronson et al., 2009). The unique ecological importance of cork oak woodlands and forest is recognised by the 92/43/EEC Habitat Directive (habitat 6310, cork oak woodlands and habitat 9330, forests) and by their inclusion in the Natura 2000 network as a representative model of sustainability involving human activity and natural resources (Aronson et al., 2009; Campos et al., 2013). The products obtained from the cork oak woodlands contribute to the local economy and development, which gives extra value to this ecosystem. In addition to cork production, extensive livestock production and sheltering of hunting species; cork oak woodlands are especially valuable for their high degree of biodiversity (Costa et al., 2006; Campos et al., 2013).

However, the projected global climate change includes an increase in mean annual temperatures and a decrease in the total annual precipitation in the Mediterranean Basin, threatening cork oak woodland, forest and artificial regenerations (Carrasco et al., 2009; Fernández-Cancio et al., 2012). This expected change in the climate will lead to increased drought by the end of the 21 st century (Lindner et al., 2010). Such scenarios threaten the future stability of cork oak artificial regenerations and reveal uncertainties regarding the ecological conditions under which these plantations were established. Artificial regeneration should be carried out using species within their natural distribution or considering the potential future distribution of the species (Hidalgo et al., 2008; López-Tirado and Hidalgo, 2016b; Vessella et al., 2017). Therefore, afforestations established within their potential distribution might give higher survival rates, although adequate field techniques might improve cork oak establishment and survival rates (Aronson et al., 2009; Arosa et al., 2015). But, the afforestations completed since 1993 in Andalusia did not follow a regeneration programme in which the species most suitable for regeneration in a specific area were selected beforehand. Moreover, niche theory states that the relationship between the species probability of presence (POP) and the environmental gradient follows a hump-shaped curve, the POP being lower on the edges and higher in the centre of the curve (Peterson et al., 2011). Hence, after regeneration, survival rates should be higher in areas with higher POP and lower in areas with lower POP.

Species Distribution Models (SDMs) can help in the design of a proper afforestation programme, by identifying areas suitable for cork oak reforestation under climate change scenarios (Hidalgo et al., 2008; Vessella et al., 2015, 2017). The SDMs predict the probability of species occurrence based on the statistical relationships between species presence/absence or count data and environmental variables; these relationships are later projected across a specific region using gridded environmental layers, resulting in a map showing the potential distribution of the species (Vessella et al., 2015; López-Tirado and Hidalgo, 2016b; Vessella et al., 2017). Moreover, SDMs can predict the future potential distribution of the species using gridded environmental variables obtained from climate change scenarios (Navarro Cerrillo et al., 2016). The SDMs have been pointed out as a suitable tool for conservation and management (van Gils et al., 2008, 2012, 2014), including afforestation (Navarro Cerrillo et al., 2016), and have predicted the distribution of cork oak (Hidalgo et al., 2008; Vessella et al., 2015; López-Tirado and Hidalgo, 2016b). However, to the best of our knowledge, SDMs have not been used to assess the future prospects of past afforestations.

The probability of more-stressful conditions in the Mediterranean Basin in the coming decades together with the heterogeneous climate in Spain make Andalusia a suitable scenario for assessing the potential effects of climate change on terrestrial ecosystems (Duque-Lazo et al., 2016). Indeed, in the Sierra Morena—the mountain range stretching the length of northern Andalusia—close to 25% of all afforestation was carried out with cork oaks (Navarro Cerrillo et al., 2009). However, some of these afforestations might be displaced from the potential range of cork oak occurrence due to the climate change expected in Andalusia (Fernández-Cancio et al., 2012).

In this paper, we used survival rate data, measured in 2008, from cork oak afforestation sites planted between 1993 and 2000, to assess their present and future stability. We compared the survival rate of cork oak afforestations with the current potential distribution of cork oaks obtained with the ensemble SDMs and compared the forecasted survival rate with the future potential distribution of cork oaks, both obtained with ensemble models. The specific objectives were (i) to assess the average environmental conditions of the cork oak afforestations; (ii) to verify if higher survival rates of cork oak plantations match the areas with higher probability of presence; and (iii) to assess the displacement of the environmental niche of cork oak afforestation versus natural populations, in order to predict the future distribution of the survival rate of the afforestations. Our results are valuable for the adaptation of cork oak afforestation to future climate change scenarios.

2. Material and methods

2.1. Study area

Andalusia (southwestern Spain, 87,300 km^2) is located in the south of the Iberian Peninsula, between 36.06° and 40.11°N latitude and −8.09° and −1.47°W longitudes (Fig. 1). The region is characterised by a central valley with agricultural lands, surrounded by mountains; the “Sierra Morena” and “Sierras Sub-Béticas”. The former is distributed along the northern edge of Andalusia with a maximum elevation of 1300 m.a.s.l. and acid soil substrates. The latter occupies the east of the region, having a maximum altitude of 3800 m.a.s.l. and limestone soils. The climate of Andalusia has typical Mediterranean features, with long, hot and dry summers and irregular annual precipitations, due to the topography, concentrated in spring and autumn (Duque-Lazo et al., 2016; Duque-Lazo and Navarro-Cerrillo, 2017). Mediterranean oak woodlands and scrublands dominate this region, occupying 4.6 million hectares. Of this area, 1.4 million hectares are populated by Holm, Cork and Portuguese oaks which spread throughout Andalusia, although Cork and Portuguese oaks are mainly present in western Andalusia (Costa et al., 2006; Fig. 1).

2.2. Cork oak presence/absence datasets

Cork oak presence/absence data were obtained from the Andalusia Forest Monitoring Network, the Forest Phytosanitary Alert Network (RED SEDA; Junta de Andalucía, 2016) and the third National Forest Inventory (IFN3; MAGRAMA, 2007). The IFN3 dataset was used to train the SDMs and the RED SEDA dataset was used for evaluation purposes. In both datasets, the presence point locations of cork oaks were