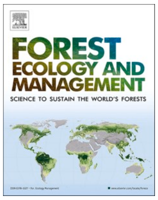
Forest Ecology and Management 568 (2024) 122105

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco



# Is forest certification mitigating oak decline in Mediterranean open woodlands?

Teresa Mexia[a,b,*], Maria Conceição Caldeira[a], Xavier Lecomte[b], Filipe S. Dias[c,d,e], Margarida Tomé[a], Leónia Nunes[b], Miguel Nuno Bugalho[b,**]

[a] Forest Research Centre (CEF), Associate Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda, Lisboa 1349-017, Portugal
[b] Centre for Applied Ecology "Prof. Baeta Neves" (CEABN-InBIO), School of Agriculture, University of Lisbon, Tapada da Ajuda, Lisboa 1349-017, Portugal
[c] BIOPOLIS Program in Genomics, Biodiversity and Land Planning, CIBIO, Vairão, Portugal
[d] CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Laboratório Associado, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, Lisbon 1349-017, Portugal
[e] CIBIO/InBIO, Centro de Investigação em Biodiversidade e Recursos Genéticos, Laboratório Associado, Universidade do Porto, Campus Agrário de Vairão, Vairão 4485-661, Portugal

## ARTICLE INFO

*Keywords:*
Quercus suber
Silvopastoral systems
Sustainable forest management
Tree mortality
Tree cover loss

## ABSTRACT

Forest certification is a voluntary conservation tool that aims to promote sustainable forest management. While research on forest certification has increased recently, there remains a significant gap in understanding how and to what extent certification can promote forest conservation.

Mediterranean cork oak open woodlands are ecosystems of high conservation and socio-economic value. However, these ecosystems are threatened by increased adult oak mortality and regeneration failure, often due to inadequate management and the rise of pests and diseases, aggravated by climate change.

Forest certification prescribes management practices intended to enhance tree regeneration and maintain stand health conditions. Therefore, it is anticipated that forest certification could mitigate the observed decline of oak trees in Mediterranean regions. Here, we investigate whether forest certification contributes to the ecological sustainability of Mediterranean cork oak open woodlands in Portugal. We compare the stand biometrics of non-certified and certified cork oak stands before and after certification implementation, using both National Forest Inventory data and field sampling from 2005 and 2020.

Our findings indicate that the density of adult oak trees decreased by 16 % in certified estates and 28 % in non-certified estates between 2005 and 2020. Similarly, cork oak cover declined by 6 % tree cover in certified plots and 19 % in non-certified plots during the same period. Consequently, by 2020, tree density was 20 % higher in certified stands than in the non-certified ones, and tree cover was 36 % higher in certified stands. Tree diameter and height increased at similar rates in both certified and non-certified stands from 2005 to 2020.The age structure of the stands also remained consistent, showing a bell-shaped distribution of tree diameters in both years. However, results on oak regeneration were inconclusive.

Our results suggest that cork oak decline, measured by the changes in density and cover of adult trees from 2005 to 2020, is slower in certified cork oak woodlands. Nonetheless, the increase in tree diameter and the age structure shape indicate potential regeneration issues in both certified and non-certified stands, needing further measures to address the aging of cork oak open woodlands.

---

* Corresponding author at: Forest Research Centre (CEF), Associate Laboratory TERRA, School of Agriculture, University of Lisbon, Tapada da Ajuda, Lisboa 1349-017, Portugal.

** Corresponding author.

*E-mail addresses:* teresa.mexia@gmail.com (T. Mexia), caldmaria@edu.ulisboa.pt (M.C. Caldeira), xlecomte@isa.ulisboa.pt (X. Lecomte), fsdias@cibio.up.pt (F.S. Dias), magatome@isa.ulisboa.pt (M. Tomé), lnunes@isa.ulisboa.pt (L. Nunes), migbugalho@isa.ulisboa.pt (M.N. Bugalho).

https://doi.org/10.1016/j.foreco.2024.122105
Received 29 February 2024; Received in revised form 22 May 2024; Accepted 19 June 2024

## 1. Introduction

Forests, which cover approximately one-third of the terrestrial surface, are among the most biodiverse ecosystems, also generating essential ecosystem services for humankind (FAO and UNEP, 2020; Brockerhof et al., 2017). However, forest degradation threatens these benefits, emphasizing the increasing need for conservation efforts (FAO and UNEP, 2020). Alongside preserving species and habitats, the sustainable management of forests is essential for maintaining these ecosystems and the benefits they generate (FAO and UNEP, 2020; United Nations, 2008).

Forest certification, a voluntary third-party audited tool, aims to promote sustainable management in exchange for the added economic value of services and products generated by certified forests (Girolami and Arts, 2018; Auld et al., 2008). The Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC) are the dominant global forest certification schemes, covering 162 and 296 million hectares of productive forests worldwide, respectively (FSC Internacional, 2024; PEFC International, 2024). Forest certification schemes are being implemented in different forest ecosystems, including the biodiversity-rich and socio-economically relevant Mediterranean cork oak (*Quercus suber* L.) woodlands.

Cork oak is endemic to the Mediterranean Basin, covering approximately 1.5 million hectares in Europe and 1 million hectares in North Africa (Bugalho et al., 2011). Cork oak formations, ranging from dense forests to open woodlands, have high environmental, social, and economic value, and are classified under the "Natura 2000" Pan-European network of protected areas. Cork oak open woodlands are predominantly silvopastoral systems dominated by cork oak, with tree density varying between 20 and 80 trees per hectare and an understory of crops, grassland patches and shrubs (Bugalho et al., 2009; Pinto-Correia and Mascarenhas, 1999). The most valuable product generated by these systems is cork, a non-timber forest product, but livestock production is also an important source of income (Bugalho et al., 2009, 2011). Cork, the oak tree bark, is harvested every 9–12 years without felling the tree and is mainly used as wine bottle stoppers, although other applications are common (Bugalho et al., 2011).

Cork oak is declining in different regions of the Iberian Peninsula because of adult oak mortality and regeneration failure (e.g., Plieninger et al., 2021; Acácio et al., 2017). In Portugal, which displays the largest area of cork oak globally, the coverage area decreased from 746,800 ha to 719,900 ha between 1995 and 2015 (ICNF, 2019), along with losses of canopy cover (Acácio et al., 2021; Aubard et al., 2019). The causes of cork oak decline are complex and linked to factors such as increased drought, changes in land use, and inadequate or lack of management, coupled with pests and diseases like *Phytophthora cinnamomi* Rand (Acácio et al., 2021; Matías et al., 2018). Certification of cork oak open woodlands by FSC started in Portugal in 2007, covering an area of 150, 000 ha by 2023, approximately 21 % of the total cover in the country (Portugal, 2024).

Under FSC certification, cork oak managers must comply with standardized socio-economic and environmental management practices (FSC Internacional, 2015; Supplementary material, Table S1). Such practices include promoting oak regeneration, favoring a heterogeneous oak stand age structure, and maintaining and ameliorating oak stand health, to promote the ecological sustainability of these ecosystems, as well as creating areas targeting biodiversity conservation (Mexia et al., 2022; Dias et al., 2016). Social practices, including improving working conditions and capacitating workers, can also contribute to healthier ecosystems through, for example, promoting training to cork harvesters, a highly skilled activity which if not properly conducted will damage the tree (Table S2).

Certified management practices also address factors like overgrazing, livestock trampling, and soil compaction, which can hinder successful oak regeneration (Pausas et al., 2009). Persistent grazing pressure over the long term may result in even-aged park-like oak stands, characterized by the dominance of large trees with no recruitment of juvenile trees, endangering the long-term sustainability of the system (Plieninger et al., 2010). However, under low grazing pressures, the subsequent accumulation of competitive herb biomass or shrubs may also negatively affect the survival of oak seedlings through competition (e.g., Caldeira et al., 2014, Pulido et al., 2010; Acácio et al., 2007). While nurse shrub species (e.g., *Retama sphaerocarpa* (L.) Boiss) may facilitate oak regeneration (e.g., Gómez-Aparicio et al., 2004), other competitive shrubs (e.g., *Cistus ladanifer* L.) may prevent the establishment and recruitment of seedlings (e.g., Acácio et al., 2024, 2007; Pulido et al., 2010). Shrub encroachment may also intensify competition between adult oak trees and shrubs, increase the risk of wildfire and reduce ecosystem resilience to drought, pests, and diseases (Lecomte et al., 2024, 2019; Caldeira et al., 2015; Jactel et al., 2009). Management strategies, under certification, aim to maintain the shrub-grassland matrix through temporally and spatially controlled shrub clearing (e.g., Simões et al., 2016) and the creation of low grazing pressure or grazing exclusion areas (e.g., Mexia et al., 2022; Köbel et al., 2021). These strategies not only promote biodiversity but also support oak natural regeneration. Practices such as soil tillage or shrub clearing with heavy machinery are limited under certification, as such practices may cause seedling mortality (Arosa et al., 2015), damage the superficial roots and weaken the health of mature oaks (Branco and Ramos, 2009). Implementing good cork harvesting practices, namely cork stripping by capacitated and skilled workers, is essential to prevent permanent damage to the trees. Similarly, adopting proper silvicultural works, such as sanitary pruning, can further help to avoid weakening the trees and, ultimately, tree death (Oliveira and Costa, 2012; Branco and Ramos, 2009). Consequently, certification, by promoting practices such as those described (see also Table S2), may contribute to the ecological sustainability of cork oak open woodlands and eventually minimize oak decline.

With the present work, we aim to assess the effect of FSC forest certification on the ecological sustainability of cork oak open woodlands. We compare the tree and stand biometrics of certified and non-certified cork oak stands over a period of 15 years. We expect that after this time, certified stands will show (1) an increase in the abundance and cover of adult trees, and (2) a decrease in the mean diameter and height of trees, due to (3) an age structure characterized by a higher abundance of smaller trees and greater diversity of tree sizes compared to non-certified stands. To test these hypotheses, we used data from both the National Forest Inventory and field data.

## 2. Materials and methods

### 2.1. Study area and site selection

Our study area is located in the region of Coruche in Portugal, spanning from 38° 47'N, 8° 50'W to 39° 09'N, 8° 10'W. Cork oak is the dominant tree cover in this region. The climate is sub-humid Mediterranean, with mild, rainy winters and hot, dry summers. The mean annual temperature is 16.0 °C, and the mean annual precipitation is 697 mm (1971–2000; IPMA, 2020). The predominant soil type is haplic podzols (Panagos et al., 2011).

To assess the changes induced by forest certification, we used the 2005 Portuguese National Forest Inventory (2005 NFI) plots as our baseline, considering that cork oak certification in Portugal started in 2007 (Portugal, 2024). Additionally, we conducted a resampling of the 2005 NFI plots in 2020. Consequently, we have information collected in 2005 (pre-certification) in areas that either became certified or remained non-certified by 2020. This dual time-point approach allows for a comprehensive analysis of changes over time associated with cork oak certification.

To select the sampling plots, we overlaid the Geographical Information System (GIS) layers of the study area with (1) the locations of the 2005 NFI open cork oak woodland plots, (2) areas not yet certified in

2020, and (3) areas certified in 2020. To ensure certification effects, we excluded areas with less than five years of certification by 2020 (Dias et al., 2015). Additionally, plots located in oak stand margins or those undergoing significant alterations in land use between 2005 and 2020 (e.g., due to urban expansion) were excluded.

This process resulted in the selection of 24 sampling plots located in 14 certified estates (hereafter referred to as “certified plots”) and 27 sampling plots located in 20 non-certified estates (hereafter referred to as “non-certified plots”; Fig. 1; Table S3), all of which are managed (i.e., not abandoned).

### 2.2. *Data derived from the 2005 National Forest Inventory*

NFI sampling plots in cork oak open woodlands consist of 2000 $m^2$ circular plots (with 25.23 m radii), systematically distributed along a 2×2 $km^2$ grid (AFN - Autoridade Florestal Nacional, 2009). To characterize the stand structure at each of the 2000 $m^2$ circular plots, we extracted information from the 2005 NFI on the number of adult oak trees, and the respective diameter at breast height (DBH) and tree height. Additionally, the cork oak basal area was used as a proxy for oak cover. The frequency distribution of diameter classes of adult oak trees was used to visualize the age structure of the oak woodlands. Moreover, we calculated the Gini coefficient index based on individual tree basal area using the formula

$$Gini = 2\left(\left(\sum\nolimits_{i=1}^{n} ig_i\right)/(nG)\right) - ((n+1)/n),$$

where $g_i$ is the basal area of tree $i$, $G$ is the total basal area and $n$ is the number of trees (trees are sorted in ascending order; Cordonnier and Kunstler, 2015). The Gini index, which was originally used to measure the distribution and inequality of economic income among individuals, has been used for assessing tree size inequality (e.g., Cordonnier and Kunstler, 2015; Damgaard and Weiner, 2000). The Gini coefficient ranges from 0, which indicates no difference between tree basal areas, to 1, which represents maximum theoretical inequality among basal areas.

### 2.3. *Data collected during the 2020 field survey*

From January to April 2020, we conducted a re-sampling of the 2005 NFI plots. During this period, we assessed adult oak abundance, as well as tree DBH and height. To estimate oak natural regeneration, we counted the number of juvenile trees (height $\geq$ 50 cm and DBH $<$ 7.5 cm) in each 2000 $m^2$ plot.

### 2.4. *Data analysis*

We analyzed the effect of FSC certification and time on tree density, tree basal area, tree diameter, and tree height as well as on the Gini coefficient index of basal areas using a hierarchical Bayesian approach to account for the unbalanced design and estate effects. This model can be thought of as a linear mixed model with two categorical variables: one that considers the individual contribution and heterogeneity from each individual estate (i.e., an estate-level varying effect) and another that considers the effects of “certification” and “year”. We attempted to model the abundance of juvenile trees, but none of the resulting models met the necessary assumptions, preventing us from drawing formal conclusions.

#### 2.4.1. *Tree density, tree basal area, diameter, and height*

To analyze the effects of year and certification on tree density, basal area, diameter and height, the model was as follows:

$$Tree\ density, Basal\ area, Height\ and\ Diameter \sim Log-normal(\mu, \sigma)$$

$$\mu = \alpha_{estate} + \beta_{Certification, Year}$$

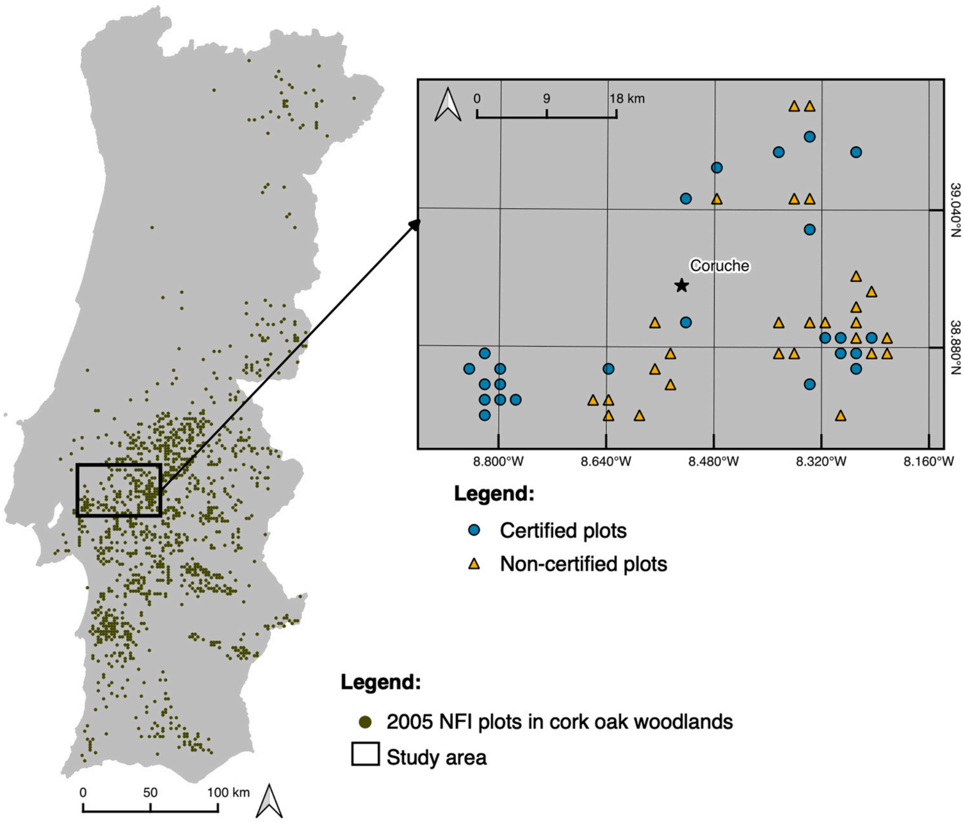


**Fig. 1.** Location of the study area in Portugal, showing the cork oak woodlands distribution (2005 NFI – Portuguese National Forest Inventory), and the location of the sampling plots in non-certified and certified areas in the region of Coruche in 2020.

$$a_{estate} \sim \log Normal(\mu_{estate}, \sigma_{estate})$$

$$\mu_{estate} \sim Normal(1, \quad 1)$$

$$\sigma_{estate} \sim Exponential(3)$$

$$\beta \sim Normal(1, \quad 1)$$

$$\sigma \sim Exponential(3)$$

As the data values were right-skewed, we opted to use a log-normal distribution. This distribution is parameterized by a location parameter μ, which represents the mean on the log-scale, and a scale parameter σ, which indicates the standard deviation on the log-scale. To derive the expected median values, we exponentiated the location parameter μ ($e^{\mu}$). We then bound the linear model of the covariates to the location parameter μ.

The term $a_{estate}$ represents a varying effect that accounts for the independent contribution from each estate, with. a unique value assigned to each estate. The prior for $a_{estate}$ is a function of two hyperparameters, $\mu_{estate}$ and $\sigma_{estate}$. This regularizing prior prevents overfitting by learning the appropriate amount of regularization from the data itself (McElreath, 2020). This approach helps ensure that the model is not excessively influenced by the results from estates with a higher number of sampling points. For reference, it is worth noting that frequentist methods employ a similar approach known as "penalized likelihood". The term $\beta_{Certification,Year}$ represents the combined effect of "certification" and "year". This parameter can assume four possible values, corresponding to the four possible combinations between the certification treatment (certified and non-certified) and the survey years (2005 and 2020). We assigned a weakly informative prior to this parameter that accommodates both positive and negative effects on the dependent variables. We assessed the effects of "certification" and "year" on the dependent variables by calculating the difference (i.e., contrast) between the posterior distribution of the parameters representing specific combinations of the two variables. To assess if there is a difference in tree density between certified and non-certified plots in 2005, for instance, we calculated $e^{\beta Certified,2005 - \beta Non\text{-}Certified,2005}$ and examined the distribution of this difference. To formally assess the credibility of this difference, we calculated the probability of the difference being greater than 0. This approach allows us to quantify the likelihood of observing a positive effect, providing valuable insights into the impact of certification and survey year on the studied variables.

### 2.4.2. Gini coefficient index

To analyze the effects on the Gini coefficient index we wrote the following model:

$$Gini\ index \sim Normal(\mu, \sigma)$$

$$\mu = a_{estate} + \beta_{Certification,Year}$$

$$a_{estate} \sim Normal(\mu_{estate}, \sigma_{estate})$$

$$\mu_{estate} \sim Normal(1, \quad 1)$$

$$\sigma_{estate} \sim Exponential(3)$$

$$\beta \sim Normal(1, \quad 1)$$

$$\sigma \sim Exponential(3)$$

We modeled the Gini index with a normal distribution and bound the linear model of the covariates to the mean of the distribution μ. As in the previous model, the term $a_{estate}$ denotes a variable effect capturing independent contributions from individual estates. Again, the prior for $a_{estate}$ is a function of two hyperparameters, $\mu_{estate}$ and $\sigma_{estate}$, designed to prevent overfitting by learning the appropriate amount of regularization directly from the data. We assigned weakly informative priors compatible with both positive and negative effects. To assess the effects of "certification" and "year" on the dependent variables, we calculated the differences (i.e., contrasts) in the posterior distribution of parameters for specific combinations of these two variables. For instance, to determine the difference in the Gini coefficient between certified and non-certified plots in 2005, we calculated $\beta_{Certified,2005} - \beta_{Non\text{-}Certified,2005}$ and examined the distribution of this difference. To formally evaluate the credibility of this difference, we calculated the probability of the difference being greater than 0.

### 2.4.3. Prior predictive checks and model validation

We validated our prior choices by simulating 1000 distributions from the prior model and visually analyzed the results. To validate the model, we conducted the following checks: 1) examined whether the Markov chains were stationary and allowed for reasonable estimation of posterior expectation values, 2) ensured that the Rhat values for all functions of interest were consistent with 1, and 3) looked for any divergent transitions or chains that reached the maximum tree depth. To assess if the model captures the data's relevant structure, we generated 1000 predicted distributions and compared them against the observed data through visual analysis.

Since most of the studied variables did not folow a normal distribution, the median and interquartile range were used for results description. All statistical analyses were performed in R version 4.3.1 (R Core Team, 2023), using the package rethinking (McElreath, 2023).

## 3. Results

In our baseline year of 2005, the median density of adult oak trees in plots to be certified (from now on certified plots) was 73 trees ha$^{-1}$ (interquartile range (IQR) 54–105), slightly higher than in plots remaining non-certified (hereafter non-certified plots), which had a median density of 70 trees ha$^{-1}$ (IQR 55–85). The median basal area was 7.91 m$^{2}$ ha$^{-1}$ (IQR 6.02–9.86) in certified and 7.49 m$^{2}$ ha$^{-1}$ (IQR 4.25–9.48) in non-certified plots.

The trees in certified plots had a median diameter of 35.4 cm (IQR 28.8–39.9), compared to 31.7 cm (IQR 28.4–39.8) in non-certified plots. Additionally, the median tree height in 2005 was 8.1 m (IQR 7.5–9.4) for certified plots and 8.1 m (IQR 6.6–9.1) for non-certified plots.

The Gini coefficient index reflected differences in tree basal area distribution, with a median value of 0.31 (IQR 0.23–0.37) in certified plots and 0.28 (IQR 0.22–0.32) in non-certified plots, meaning that the plots were slightly more heterogeneous in the certified plots. The distribution of tree diameters was bell-shaped, with higher abundances of trees in the middle classes in both certified and non-certified woodlands in 2005 and remained so in 2020 (Fig. 2).

The median abundance of juvenile trees was 2.5 trees ha$^{-1}$ (IQR 0.0–10.0) in certified stands and 0.0 trees ha$^{-1}$ (IQR 0.0–2.5) in non-certified stands in 2020 (Supplementary material, Fig. S1).

### 3.1. Tree population density

In 2005, the difference between median tree population densities in certified and non-certified plots was approximately 3 % (Fig. 3; Fig. S2 and Table S4). There is a 54 % probability that the difference was positive and a 46 % probability that it was negative. This result suggests that the difference is likely to be small, but the model could not resolve whether it was positive or negative. In 2020, the median tree population density of certified plots was 20 % higher than that of non-certified plots (Fig. 3, Fig. S2, and Table S4). The probability of this difference being positive was 81 %, suggesting that certification contributes to higher tree population densities.

Between 2005 and 2020, the median tree density decreased in both certified and non-certified plots, but such decrease was higher in the non-certified plots (Fig. 3, Fig. S2, and Table S4). While in the certified plots the median tree population density declined by 16 %, in non-certified plots it declined by 28 %. In both cases, the probability of the

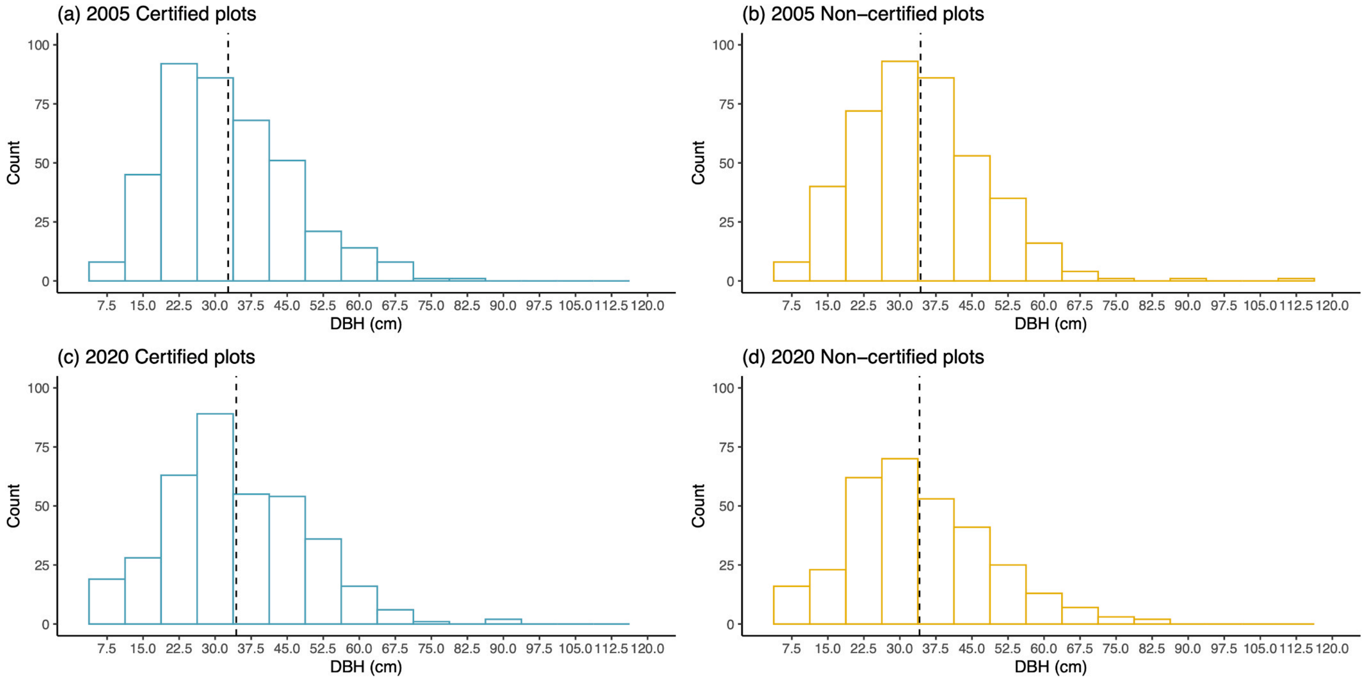


**Fig. 2.** The frequency distribution of diameter (DBH) classes of adult oak trees is presented for: (a) 2005 certified plots (n = 395), (b) 2005 non-certified plots (n = 410), (c) 2020 certified plots (n = 369), and (d) 2020 non-certified plots (n = 315). Dashed lines indicate the mean value.

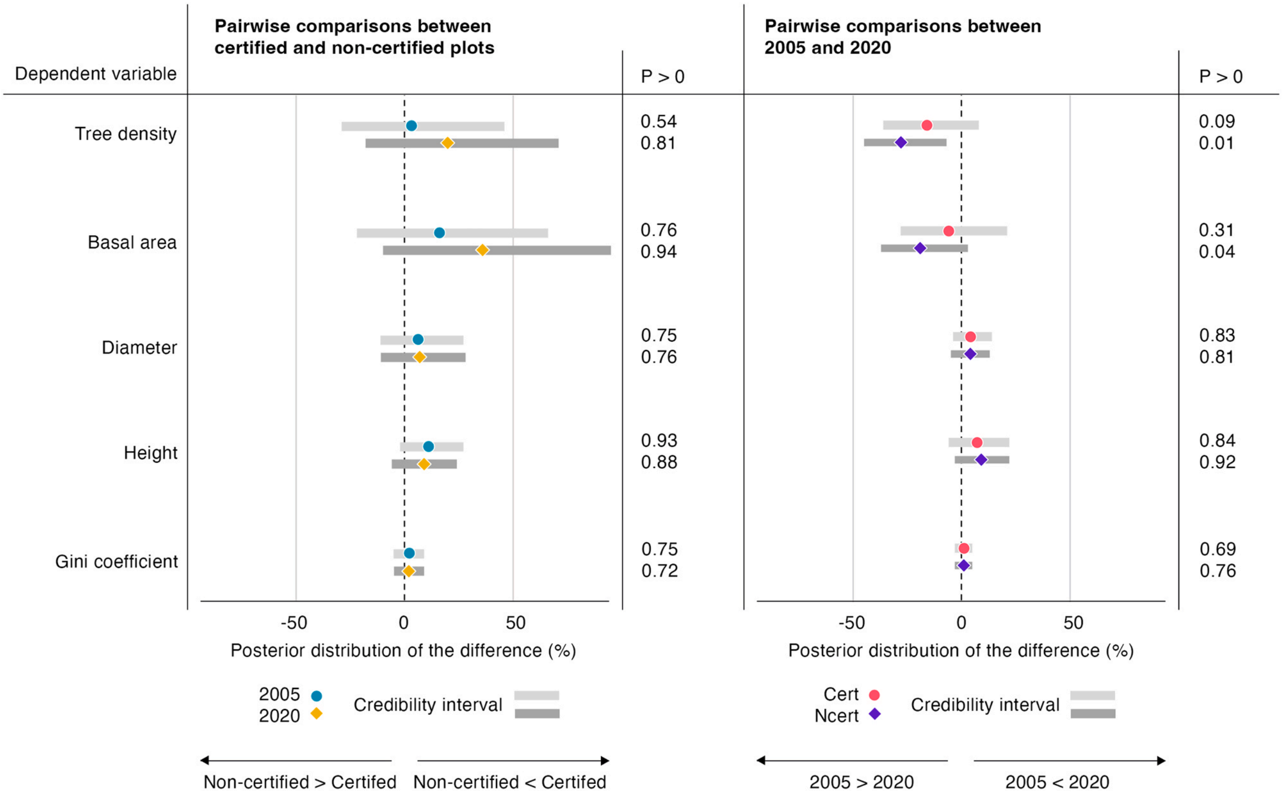


**Fig. 3.** Pairwise comparisons between treatment groups expressed as the probability of the posterior difference between $\beta_{\text{Certification,Year}}$ parameters being positive. The grey bars represent the 95 % credibility interval. In the left plot, positive values mean higher values in certified areas than in non-certified areas, while negative values indicate the opposite. In the right plot, positive values indicate higher values in the 2020 survey compared to the 2005 survey, while negative values indicate the opposite.

difference being positive was less than 10 %, indicating a high likelihood that the difference is negative, confirming a more accentuated decline in the non-certified plots.

### 3.2. *Basal area*

In 2005, the median basal area of surveyed trees in certified plots was 16 % higher than in non-certified plots, with a 76 % probability of this difference being positive (Fig. 3, Fig. S2, and Table S4). By 2020, this difference increased to 36 %, with a 94 % probability of a positive effect, suggesting that basal area is higher in certified plots.

Over the period from 2005 and 2020, median basal areas decreased by 6 % in certified plots and by 19 % in non-certified plots (Fig. 3, Fig. S2, and Table S4). For certified plots, there was a 31 % probability that the change was positive and a 69 % probability that it was negative. Conversely, for non-certified plots, the model estimated a 4 % probability that the change was positive and a 96 % probability that it was negative. These findings strongly show that basal area loss was much lower in certified areas.

### 3.3. *Tree diameter*

In 2005, the median diameter of trees in certified plots was 6 % higher than in non-certified plots. The probability of this difference being positive was 75 % (Fig. 3, Fig. S2 and Table S4). By 2020, the difference was 7 %, with a 76 % probability of being positive. These results suggest that tree diameters increased at approximately the same rate in both certified and non-certified plots.

The median tree diameters in both certified and non-certified plots increased by approximately 4 % between 2005 and 2020 (Fig. 3, Fig. S2, and Table S4). The probabilities of these differences being positive were 83 % for certified plots and 81 % for non-certified plots.

### 3.4. *Tree height*

In 2005, the median height of the trees in certified plots was 11 % higher than in non-certified plots (Fig. 3, Fig. S2, and Table S4), with a 93 % probability of this difference being positive. By 2020, the difference was 9 %, with an 88 % chance of it being positive. These results suggest that trees in certified plots grew slightly less in height as in non-certified plots, but the difference between the medians was relatively small, less than 2 %.

Finally, between 2005 and 2020, the median tree height increased by 7 % in certified plots and by 9 % in non-certified plots (Fig. 3, Fig. S2 and Table S4). The probabilities of these differences being positive were 84 % and 92 %, respectively.

### 3.5. *Gini coefficient index of basal areas*

In 2005, the median tree size inequality (i.e., stand heterogeneity), measured using the Gini coefficient of basal areas, was 2 % higher in certified plots compared to non-certified ones (Fig. 3, Fig. S2, and Table S4). The probability of this difference being positive was 75 %. By 2020, the median difference remained at 2 %, with a 72 % probability of being positive, suggesting slightly higher heterogeneity in certified stands.

Between 2005 and 2020, the Gini coefficient increased by 1 % in both certified and non-certified plots, with probabilities of being positive at 69 and 76 %, respectively. These findings suggest no major changes in stand heterogeneity of tree sizes.

## 4. Discussion

Our results indicate that certification contributes positively to mitigating the decline in the abundance and cover of cork oak trees. Unlike most studies on certification effects, which focus on wood production forests where stand structure is highly influenced by logging practices (e.g., selective logging, clear-felling; e.g., Kalonga et al., 2016; Medjibe et al., 2013), our research examines a multiple-use system, where cork, a non-wood forest product, is the primary harvest and does not involve tree felling. Previous studies in wood production forests found either similar tree abundances in certified and non-certified forests (e.g., Medjibe et al., 2013; Foster et al., 2008) or higher tree abundances in certified forests (e.g., Kalonga et al., 2016). In contrast, the cork harvesting process in our study does not result in a reduction in the abundance or cover of oak trees. Furthermore, national laws prohibit the cutting of live cork oak trees (Decree-law no. 169/2001, of 25 May, modified by Decree-law no. 155/2004, of 30 June), ensuring that tree cork harvesting practices do not diminish tree populations. Any observed decrease in adult tree density is likely due to tree mortality, insufficient recruitment or both. The decline in cork oak density between 2005 and 2020 in both certified and non-certified plots aligns with the concerning trend of decline observed in other studies of cork oak and other oak species (e.g., Acácio et al., 2017; Thomas et al., 2002).

Broad and local environmental conditions, such as precipitation, temperature, aspect and soil type, can impact cork oak cover (Príncipe et al., 2022; Matías et al., 2018). By limiting the study area to the Coruche region, we narrowed the range and variation of the environmental factors considered. Additionally, an exploratory analysis showed no significant relationship between environmental variables and the response variables (e.g., tree density, tree DBH; Supplementary material, Table S3 and Fig. S3), ensuring that the observed effects were primarly due to certification rather than environmental differences. The high probability that tree density and cover were higher in certified stands than in non-certified stands in 2020, compared to 2005, likely reflects a lower impact of mortality in certified stands due to the implementation of best management practices prescribed under certification. These practices include the use of lighter woodcutters, proper pruning of trees, cork extraction by skilled harvesters, and removal of unhealthy trees from the stands. Interestingly, in the baseline year of 2005, the plots that would later be certified, already had slightly higher median tree density and basal area compared to non-certified plots. This could be attributed to a greater awareness among cork oak producers who were committed to certification and had already begun implementing good management practices in their estates. Indeed, Dias et al. (2013) found that certification in cork oak open woodlands in Portugal began in better cork production regions, where producers were more organized and better capacited to implement good management practices. However, certified and non-certified estates were located in the primary cork production region of Portugal, and most of the studied estates belong to one of the country's largest forest producer associations. More importantly, this context reinforces our findings, as the differences in tree density and basal area increased between certified and non-certified plots over time. This suggests that certification has a positive impact on these forest attributes, building on the initial advantages observed in the baseline year.

The age structure of the woodlands highlights recruitment challenges in both certified and non-certified areas, as evidenced by a bell-shaped distribution of adult tree sizes and low tree age heterogeneity (e.g., Plieninger et al., 2010). This persistent pattern suggests more managed and aging stands rather than the naturally expected reverse J-shaped age structure (Matías et al., 2018; Plieninger et al., 2010), characterized by a higher abundance of smaller trees. The high probability of an increase in median tree diameter and height in both certified and non-certified stands between 2005 and 2020 further suggests a growing proportion of larger trees.

While we observed a tendency towards a greater abundance of juvenile trees in certified stands compared to non-certified stands in 2020 (Fig. S1), we were unable to assess this statistically. Studies in other forest types, such as timber logging forests, have suggested a positive effect of certification on tree seedling abundances (e.g., Kalonga et al., 2015; Rivett et al., 2016). However, in our study, the low abundance of smaller adult trees raises the possibility that, even in certified stands, the transition from juvenile to adult trees might be compromised. In cork oak open woodlands, regeneration success might be affected by various management practices, including the presence of livestock (e.g., Leal et al., 2022) or the extent, diversity and identity of shrub cover (e.g., Acácio et al., 2024; Dias et al., 2016; Gómez-Aparicio et al., 2004). Although grazing pressure was not assessed in our study area, the plant understorey layer was mostly composed of herbs, and the shrub cover was likely too sparse (personal observation) to effectively protect seedlings and juvenile trees from grazing. The implementation of conservation zones, covering a minimum area of 10 % of certified estates for biodiversity conservation, is a requirement of forest certification and might positively affect regeneration in certified estates (Mexia et al., 2022; Dias et al., 2016). However, our findings suggest that forest managers may need to undertake further additional measures beyond conservation zones to facilitate successful regeneration. Strategies such as temporary grazing exclusion areas and the use of individual tree shelters to protect juvenile trees from livestock and foster regeneration, may be necessary to ensure the long-term sustainability of cork oak open woodlands. This is particularly crucial in the current context of climate change, where increasing droughts pose a significant challenge to cork oak regeneration success (Acácio et al., 2024; Caldeira et al., 2014).

## 5. Conclusions

Our work shows that forest certification contributes to mitigating cork oak decline, supporting previous studies that recommend using appropriate management practices in cork oak open woodlands (e.g., Acácio et al., 2021; Branco and Ramos, 2009). Our results demonstrated a smaller decline in tree density and cover in cork oak open woodlands FSC certified for less than 12 years compared to non-certified woodlands in the same region. Consequently, managers should consider complying with forest certification schemes to help mitigate cork oak decline.

However, we did not obtain definitive results concerning oak regeneration. The similar increase in median tree diameter and the bell-shaped age structure observed in both certified and non-certified stands indicate potential risks to regeneration. While certification helps mitigating cork oak decline, more emphasis on addressing regeneration failure and stand aging within certification guidelines could be crucial. By highlighting these aspects among other indicators, certification can become a powerful tool for the conservation of cork oak open woodlands in the Mediterranean Basin.

## CRediT authorship contribution statement

**Teresa Mexia:** Methodology, Writing – original draft, Methodology, Investigation, Formal analysis. **Maria Conceição Caldeira:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Xavier Lecomte:** Writing – review & editing, Supervision, Methodology, Investigation. **Filipe Dias:** Writing – review & editing, Formal analysis. **Margarida Tomé:** Writing – review & editing. **Leónia Nunes:** Writing – review & editing. **Miguel Nuno Bugalho:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Member of the Editorial Board, Margarida Tomé. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data Availability

Data will be made available on request.

## Acknowledgments

We are grateful to José Uva from ICNF – Instituto da Conservação da Natureza e das Florestas for the initial meetings and discussion on the early stages of this work. We are grateful to Conceição Silva from UNAC – União da Floresta Mediterrânica, Rui Alves from Companhia das Lezírias SA, APFC - Associação de Produtores Florestais de Coruche, and the landowners for granting access to the study areas. This research was funded by CEF, a research unit funded by Fundação para a Ciência e a Tecnologia I.P. (FCT) (UIDB/00239/2020), and by CEABN-InBIO, a research unit funded by FEDER funds (Operational Programme for Competitiveness Factors—COMPETE; POCI-01–0145-FEDER-006821) and by FCT (UID/BIA/50027/2020). The authors also acknowledge the financial support of FCT and European Union through the project BIOJUST/BIODIVERSA (DivProtect/0001/2021) and FCT DRESIL (2022.09115.PTDC), Ph.D. Programme SUSFOR (PD.00157.2012), and SUSFOR Ph.D. Programme grant to TM (PD/BD/128256/2016).

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122105.

## References

Acácio, V., Dias, F.S., Catry, F.X., Rocha, M., Moreira, F., 2017. Landscape dynamics in Mediterranean oak forests under global change: understanding the role of anthropogenic and environmental drivers across forest types. Glob. Chang. Biol. 23, 1199–1217. https://doi.org/10.1111/gcb.13487.

Acácio, V., Dias, F.S., Catry, F.X., Bugalho, M.N., Moreira, F., 2021. Canopy cover loss of Mediterranean Oak woodlands: long-term effects of management and climate. Ecosystems. https://doi.org/10.1007/s10021-021-00617-9.

Acácio, V., Dias, F.S., Ferreira, M., Rodríguez-González, P., Matias, H., Caldeira, M.C., 2024. Effects of shrub species dominance and diversity on oak seedling survival in Mediterranean woodlands: the interplay of abiotic conditions and plant traits. . Ecol. Manag. 555, 121713 https://doi.org/10.1016/j.foreco.2024.121713.

Acácio, V., Holmgren, M., Jansen, P.A., Schrotter, O., 2007. Multiple recruitment limitations causes arrested succession in Mediterranean cork oak systems. Ecosystems 10, 1220–1230. https://doi.org/10.1007/s10021-007-9089-9.

AFN - Autoridade Florestal Nacional, 2009. Instruções para o trabalho de campo do inventário florestal nacional – IFN 2005/2006.

Arosa, M.L., Ceia, R.S., Costa, S.R., Freitas, H., 2015. Factors affecting cork oak (Quercus suber) regeneration: acorn sowing success and seedling survival under field conditions. Plant Ecol. Divers. 8 (4), 519–528 https://doi.org/10.1080/17550874.2015.1051154.

Aubard, V., Paulo, J.A., Silva, J.M.N., 2019. Long-Term monitoring of Cork and Holm Oak stands productivity in Portugal with landsat imagery. Remote Sens 11, 525. https://doi.org/10.3390/rs11050525.

Auld, G., Gulbrandsen, L.H., McDermott, C.L., 2008. Certification schemes and the impacts on forests and forestry. Annu. Rev. Environ. Resour. 33, 187–211. https://doi.org/10.1146/annurev.environ.33.013007.103754.

Branco, M., Ramos, A.P., 2009. Coping with Pests and Diseases, in: Aronson, J., Pereira, J.S., Pausas, J.G. (Eds.), Cork Oak Woodlands on the Edge. Society for Ecological Restoration International, Washington, DC, p. 352.

Brockerhof, E.G., Barbaro, L., Castagneyrol, B., Forrester, D.I., Gardiner, B., González-Olabarria, J.R., Lyver, P.O.B., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I.D., van der Plas, F., Jactel, H., 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers. Conserv. 26, 3005–3035. https://doi.org/10.1007/s10531-017-1453-2.

Bugalho, M.N., Caldeira, M.C., Pereira, J.S., Aronson, J., Pausas, J.G., 2011. Mediterranean cork oak savannas require human use to sustain biodiversity and ecosystem services. Front. Ecol. Environ. 9, 278–286. https://doi.org/10.1890/100084.

Bugalho, M.N., Plieninger, T., Aronson, J., Ellatifi, M., Crespo, D.G., 2009. Open Woodlands: A Diversity of Uses (and Overuses), in: Aronson, J., Pereira, J.S., Pausas, J.G. (Eds.), Cork Oak Woodlands on the Edge. Society for Ecological Restoration International, Washington, DC, p. 352.

Caldeira, M.C., Ibáñez, I., Nogueira, C., Bugalho, M.N., Lecomte, X., Moreira, A., Pereira, J.S., 2014. Direct and indirect effects of tree canopy facilitation in the recruitment of Mediterranean oaks. J. Appl. Ecol. 51, 349–358. https://doi.org/10.1111/1365-2664.12189.

Caldeira, M.C., Lecomte, X., David, T.S., Pinto, J.G., Bugalho, M.N., Werner, C., 2015. Synergy of extreme drought and shrub invasion reduce ecosystem functioning and resilience in water-limited climates. Nat. Sci. Rep. 5, 15110 https://doi.org/10.1038/srep15110.

Cordonnier, T., Kunstler, G., 2015. The Gini index brings asymmetric competition to light. Perspect. Plant Ecol. Evol. Syst. 17, 1–9. https://doi.org/10.1016/j.ppees.2015.01.001.

R. Core Team, 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

Damgaard, C., Weiner, J., 2000. Describing inequality in plant size or fecundity. Ecology 81, 1139–1142. https://doi.org/10.1890/0012-9658(2000)081[1139:DIIPSO]2.0.CO;2.

Dias, F.S., Bugalho, M.N., Orestes Cerdeira, J., João Martins, M., 2013. Is forest certification targeting areas of high biodiversity in cork oak savannas? Biodivers. Conserv. 22 (1), 93–112. https://doi.org/10.1007/s10531-012-0401-4.

Dias, F.S., Bugalho, M.N., Rodríguez-González, P.M., Albuquerque, A., Cerdeira, J.O., 2015. Effects of forest certification on the ecological condition of Mediterranean streams. J. Appl. Ecol. 52, 190–198. https://doi.org/10.1111/1365-2664.12358.

Dias, F.S., Miller, D.L., Marques, T.A., Marcelino, J., Caldeira, M.C., Orestes Cerdeira, J., Bugalho, M.N., 2016. Conservation zones promote oak regeneration and shrub diversity in certified Mediterranean oak woodlands. Biol. Conserv. 195, 226–234. https://doi.org/10.1016/j.biocon.2016.01.009.

FAO and UNEP, 2020. The State of the World's Forests 2020. Forests, biodiversity and people. Rome. https://doi:10.4060/ca8642en.

Foster, B.C., Wang, D., Keeton, W.S., 2008. An exploratory, post-harvest comparison of ecological and economic characteristics of forest stewardship council certified and uncertified Northern hardwood stands. J. Sustain. 26, 171–191. https://doi.org/10.1080/10549810701879701.

FSC Internacional, 2015. FSC Principles and Criteria for Forest Stewardship, FSC-STD-01. ed.

FSC Internacional, 2024. Forest Stewardship Council Facts and Figures. URL: https://connect.fsc.org/impact/facts-figures [Last accessed on 05/07/2024].

FSC Portugal, 2024. Forest Stewardship Council. URL: https://pt.fsc.org/pt-pt/cortica-fsc-uma-escolha-natural [Last accessed on 05/07/2024].

Girolami, E., Arts, B., 2018. Environmental Impacts of Forest Certification. . Nat. Conserv. Policy Group, Wagening. Univ. Res. 39.

Gómez-Aparicio, L., Zamora, R., Gómez, J.M., Hódar, J., Castro, J., 2004. Applying plant facilitation to forest restoration In Mediterranean ecosystems: a meta-analysis of the shrubs as nurse plants. Ecol. Appl. 14, 1118–1138. https://doi.org/10.1890/03-5084.

ICNF, 2019. 6º Inventário Florestal Nacional - Relatório Final. Coord. J. S. Uva. Instituto da Conservação da Natureza e das Florestas.

IPMA, 2020. Normais climatológicos 1971-2000. Instituto Português do Mar e da Atmosfera, I.P.

Jactel, H., Nicoll, B.C., Branco, M., Gonzalez-Olabarria, J.R., Grodzki, W., Langstrom, B., Moreira, F., Netherer, S., Orazio, C., Piou, D., Santos, H., Schelhaas, M.J., Tojic, K., Vodde, F., Karl, T., Floor, V., 2009. The influences of forest stand management on biotic and abiotic risks of damage. Annu. Sci. 66, 701. https://doi.org/10.1051/forest/2009054.

Kalonga, S.K., Midtgaard, F., Eid, T., 2015. Does forest certification enhance forest structure? Empirical evidence from certified community-based forest management in Kilwa District, Tanzania. Int. Rev. 17, 182–194. https://doi.org/10.1505/146554815815500570.

Kalonga, S.K., Midtgaard, F., Klanderud, K., 2016. Forest certification as a policy option in conserving biodiversity: an empirical study of forest management in Tanzania. Ecol. Manag. 361, 1–12. https://doi.org/10.1016/j.foreco.2015.10.034.

Köbel, M., Listopad, C.M.C.S., Príncipe, A., Nunes, A., Branquinho, C., 2021. Temporary grazing exclusion as a passive restoration strategy in a dryland woodland: effects over time on tree regeneration and on the shrub community. . Ecol. Manag. 483, 118732 https://doi.org/10.1016/j.foreco.2020.118732.

Leal, A.I., Bugalho, M.N., Palmeirim, J.M., 2022. Effects of ungulates on oak regeneration in Mediterranean woodlands: a meta-analysis. . Ecol. Manag. 509, 120077 https://doi.org/10.1016/j.foreco.2022.120077.

Lecomte, X., Bugalho, M.N., Catry, F.X., Fernandes, P.M., Cera, A., Caldeira, M.C., 2024. Ungulates mitigate the effects of drought and shrub encroachment on the fire hazard of Mediterranean oak woodlands. Ecol. Appl., e2971 https://doi.org/10.1002/eap.2971.

Lecomte, X., Caldeira, M.C., Catry, F.X., Fernandes, P.M., Jackson, R.B., Bugalho, M.N., 2019. Ungulates mediate trade-offs between carbon storage and wildfire hazard in Mediterranean oak woodlands. J. Appl. Ecol. 56, 699–710. https://doi.org/10.1111/1365-2664.13310.

Matías, L., Abdelaziz, M., Godoy, O., Gómez-Aparicio, L., 2018. Disentangling the climatic and biotic factors driving changes in the dynamics of *Quercus suber* populations across the species‘ latitudinal range. Divers. Distrib. 25, 524–535. https://doi.org/10.1111/ddi.12873.

McElreath, Richard. 2020. Statistical Rethinking: A Bayesian Course with Examples in R and Stan. 2nd edition. Chapman and Hall/CRC, Boca Raton.

McElreath, R., 2023. rethinking: statistical Rethinking book package. R. Package Version 2, 31.

Medjibe, V.P., Putz, F.E., Romero, C., 2013. Certified and uncertified logging concessions compared in Gabon: changes in stand structure, tree species, and biomass. Environ. Manag. 51, 524–540. https://doi.org/10.1007/s00267-012-0006-4.

Mexia, T., Lecomte, X., Caldeira, M.C., Bugalho, M.N., 2022. Conservation zones increase habitat heterogeneity of certified Mediterranean oak woodlands. Ecol. Manag. 504, 119811 https://doi.org/10.1016/j.foreco.2021.119811.

Oliveira, G., Costa, A., 2012. How resilient is Quercus suber L. to cork harvesting? A review and identification of knowledge gaps. Ecol. Manag. 270, 257–272. https://doi.org/10.1016/j.foreco.2012.01.025.

Panagos, P., Jones, A., Bosco, C., Senthil Kumar, P.S., 2011. European digital archive on soil maps (EuDASM): Preserving important soil data for public free access. Int. J. Digit. Earth 4, 434–443. https://doi.org/10.1080/17538947.2011.596580.

Pausas, J.G., Marañón, T., Caldeira, M., Pons, and J, 2009. Natural Regeneration, in: Aronson, J., Pereira, J.S., Pausas, J.G. (Eds.), Cork Oak Woodlands on the Edge. Society for Ecological Restoration International, Washington, DC, p. 352.

PEFC International, 2024. PEFC Global Statistics, March 2024. URL: http://www.pefc.org/discover-pefc/facts-and-figures [Last accessed on 05/07/2024].

Pinto-Correia, T., Mascarenhas, J., 1999. Contribution to the extensification/intensification debate: new trends in the Portuguese montado. Landsc. Urban Plan. 46, 125–131. https://doi.org/10.1016/S0169-2046(99)00036-5.

Plieninger, T., Flinzberger, L., Hetman, M., Horstmannshoff, I., Reinhard-Kolempas, M., Topp, E., Moreno, G., Huntsinger, L., 2021. Dehesas as high nature value farming systems: a social-ecological synthesis of drivers, pressures, state, impacts, and responses. Ecol. Soc. 26 (3), 23.

Plieninger, T., Rolo, V., Moreno, G., 2010. Large-scale patterns of Quercus ilex, Quercus suber, and Quercus pyrenaica regeneration in central-western Spain. Ecosystems 13, 644–660. https://doi.org/10.1007/s10021-010-9345-2.

Príncipe, A., Nunes, A., Pinho, P., Aleixo, C., Neves, N., Branquinho, C., 2022. Local-scale factors matter for tree cover modelling in Mediterranean drylands. Sci. Total Environ. 831, 154877 https://doi.org/10.1016/j.scitotenv.2022.154877.

Pulido, F., García, E., Obrador, J.J., Moreno, G., 2010. Multiple pathways for tree regeneration in anthropogenic savannas: Incorporating biotic and abiotic drivers into management schemes. J. Appl. Ecol. 47, 1272–1281. https://doi.org/10.1111/j.1365-2664.2010.01865.x.

Rivett, S.L., Bicknell, J.E., Davies, Z.G., 2016. Effect of reduced-impact logging on seedling recruitment in a neotropical forest. Ecol. Manag. 367, 71–79. https://doi.org/10.1016/j.foreco.2016.02.022.

Simões, M.P., Belo, A.F., Fernandes, M., Madeira, M., 2016. Regeneration patterns of *Quercus suber* according to montado management systems. Agrofor. Syst. 90, 107–115. https://doi.org/10.1007/s10457-015-9818-6.

Thomas, F.M., Blank, R., Hartmann, G., 2002. Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. For. Pathol. 32, 277–307. https://doi.org/10.1046/j.1439-0329.2002.00291.x.

United Nations, 2008. Non-legally binding instrument on all types of forests.