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More than trees: Stand management can be used to improve ecosystem diversity, structure and functioning 20 years after forest restoration in drylands

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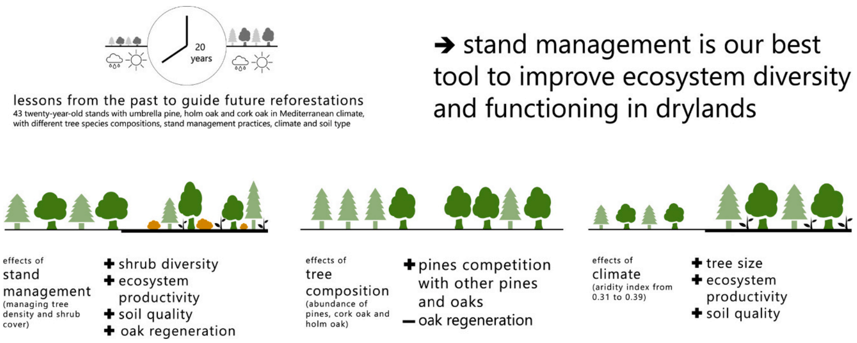
HIGHLIGHTS

- We can learn from past reforestations to improve current and future forest restoration.
- We evaluated 20-year-old reforestations with pines and oaks in Mediterranean drylands.
- Indicators of plant diversity, structure, and ecosystem functioning were assessed.
- Tree density and shrub cover were, overall, more relevant than tree composition.
- Stand management is critical to improve diversity and functioning of reforestations.

GRAPHICAL ABSTRACT



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ABSTRACT

In Mediterranean drylands, extensive areas have been restored by reforestation over the past decades to improve diversity, soil fertility, and tree natural regeneration, contributing to halting desertification and land degradation. However, evaluating reforestation success usually relies on tree survival, while holistic and long-term evaluations of reforestation success based on ecosystem diversity, structure and functioning are scarce. In this work, we provide the first assessment that combines the evaluation of planted trees and indicators of ecosystem diversity, structure, and functioning in established reforestations with three native Mediterranean species along a climatic gradient. We sampled 43 20-year-old stands with umbrella pine, holm oak and cork oak in Portugal, and tested the effects of tree species composition, stand management (i.e., differences in tree density and shrub cover), and edaphoclimatic conditions, on the size of planted trees, species diversity, structural complexity and indicators of ecosystem functioning related to productivity, soil nutrients and tree natural regeneration.

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Our results show that, after 20 years of reforestation, stand management was an essential driver of plant diversity and ecosystem functioning. Higher tree density, particularly of oaks, and higher shrub cover improved plant diversity, ecosystem productivity, and oak regeneration. The latter was also improved by structural complexity. Tree composition effects highlighted the importance of pine management to avoid competition. Since we evaluated these reforestations along a climatic gradient, we also conclude that climate influenced pine and holm oak size, ecosystem productivity, and soil C/N. Our research, by being based on assessing the long-term reforestation success in a more holistic way, highlighted the importance of stand management for improving ecosystem diversity and functioning in these restored systems. Practices such as increasing tree density up to ~800 trees/ha and allowing a shrub cover of ca. 30 %, may improve the ecological condition of future and currently reforested areas across the Mediterranean region.

1. Introduction

In the midst of the UN Decade on Ecosystem Restoration (UN General Assembly, 2021), an unprecedented amount of area and investment is being allocated to forest restoration worldwide (Castro et al., 2021; e.g. The Bonn Challenge [IUCN, 2011]). However, to obtain the much-needed return of this global effort of ecosystem restoration, i.e., to increase tree cover and promote carbon sequestration, biodiversity and sustainable livelihoods (Di Sacco et al., 2021), it is increasingly clear that long-term monitoring and adaptive management should be considered as important as initial planting (Castro et al., 2021; Ockendon et al., 2018). Long-term monitoring and assessing past reforestations offer an opportunity to learn which are the most important drivers influencing the restored ecosystem and its different components, such as ecosystem diversity and functioning, and which stand management practices are most useful to improve the ecological condition of these systems (del Campo et al., 2021; Nunes et al., 2016). Nevertheless, the evaluation of reforestation success usually relies on assessing tree survival in the first years after plantation but not on how or if other components of the ecosystem benefit on the medium- and long-term time scales (Tomaz et al., 2013). To evaluate the effects of reforestation on the ecosystem, it is important to measure indicators of the three ecosystem attributes—diversity, structure and functioning—together with the assessment of the survival and growth of the planted species (Cruz-Alonso et al., 2019; Gatica-Saavedra et al., 2017).

In the Mediterranean Basin, restoration measures based on reforestations made with pines and oaks are ubiquitous and have been installed over the past decades as measures to prevent desertification and land degradation (Jones et al., 2011; Sheffer, 2012). These reforestations aim at increasing the value of marginal, low-productive areas, promoting soil quality, species diversity and tree natural regeneration, particularly of oaks (Estratégia Nacional para as Florestas, 2015), which are key aspects for the maintenance of Mediterranean woodlands and forests with high natural and cultural value (Bugalho et al., 2009; Ferraz-de-Oliveira et al., 2016). Increasing tree cover in these systems can improve natural regeneration by alleviating summer drought at the microclimatic scale (González-Moreno et al., 2011; Pons and Pausas, 2006). Soil fertility may also be improved with tree cover, which offers protection from erosion and promotes an increase in soil organic matter content (Fernández-Ondoño et al., 2010). This, in turn, is crucial for the soil nutrient supply and water retention (Costantini et al., 2016). Nevertheless, Mediterranean ecosystems are profoundly shaped by edaphoclimatic conditions (Cruz-Alonso et al., 2021; Nunes et al., 2019). On the other hand, stand characteristics such as tree composition, tree density or shrub cover (controlled mainly by periodic clearings) can also influence the restored ecosystem in terms of ecosystem diversity, structure and functioning (Ruiz-Benito et al., 2012).

Here, we assessed pure and mixed stands of pines and oaks, with ca. 20 years in a Mediterranean dryland region to evaluate the effects of tree species composition and management options on the ecosystem along a climatic gradient. Our main aim was to identify the drivers influencing the reforested ecosystem and to assess the relevance of different tree species compositions and different management practices, considering the potential effects imposed by climate and soil type. More specifically, we evaluated the effects of pine and oak abundance (tree composition), tree density and shrub cover (stand management practices), climate and soil type on tree size, plant diversity, vegetation structural complexity and indicators of ecosystem functioning namely ecosystem productivity, soil organic matter and soil C/N, and tree natural regeneration. Because pines are typically faster-growing species than oaks (Gómez-Aparicio et al., 2011), we hypothesized that pine abundance would have a negative effect on oak size but that sites with higher pine abundance would have higher ecosystem productivity and tree biomass. We also expected tree density to have a positive effect on soil organic matter, while climate, particularly aridity, would limit ecosystem productivity, species diversity and oak regeneration.

2. Methods

2.1. Study area and sampling design

This work was conducted in reforested areas throughout the *Alentejo* region, a dryland area in southern Portugal (Fig. 1). The climate is Mediterranean, with mildly cold and wet winters and hot dry summers with mean annual precipitation and temperature of 551 mm/year and 16 °C (average 1970–2000, Fick and Hijmans, 2017). Elevation ranges between 110 and 480 m a.s.l., and soils vary between lithosols and luvisols (APA, 1982).

The study area is mainly occupied by seminatural open woodlands called *montados*, dominated by cork oak or holm oak in low stand densities, between 20 and 80 trees/ha (Pinto-Correia and Mascarenhas, 1999). It is common, however, to find reforested properties with these two species and with umbrella pine, either in pure or mixed stands (ICNF, 2022). Pine species, although presumably native to the area, are mostly found in planted populations, as their heliophilous behavior and ability to establish under dry climates and poor soil conditions have made them a common choice for reforestation in Mediterranean climates (Gómez-Aparicio et al., 2009; Tomaz et al., 2013), and they allegedly facilitate the establishment of slower-growing oaks in the long term (Pausas et al., 2004). The aim of these reforestations is, in general, to increase tree cover and, with it, halt soil erosion in degraded *montado* areas and marginal old fields, promoting biodiversity, soil quality, tree regeneration and the economic value of properties (ICNF, 2019). Reforestations are subsidized for 20 years after the plantation. For this period landowners are not allowed to change the land use or use the area for cattle grazing, and they are advised to conduct periodical shrub clearings to decrease the fire risk. Shrubs develop naturally in these systems, as secondary succession tends to lead these sites to Mediterranean forests with a well-developed shrub layer (Bugalho et al., 2009; Dias et al., 2016). While landowners typically clear shrubs every 5–6 years, in some properties this management is less frequent and shrubs dominate the understory (Mendes et al., 2011; Suess et al., 2018).

In 2015, using the records from the *Instituto de Conservação da Natureza e Florestas, I.P.* (the national forest authority), reforested sites with an age of approx. 20 years were stratified to the aridity index to focus the sampling on established reforestations. From this pool, 43 sites with umbrella pine, holm oak and/or cork oak were chosen randomly. At each site, a rectangular 0.1 ha plot was established for vegetation and soil sampling. The location of the sampling plot was chosen avoiding potential confounding effects operating at the local scale. Therefore, first we controlled variations in topography and aspect by excluding places with either very high or very low solar exposition, assessed using the potential solar radiation (PSR). This variable is computed using digital terrain models and corresponds to the potential amount of solar radiation arriving at a surface on the ground (Fu and Rich, 2002). Second, areas with high relative tree density and height within the reforestation were chosen by visual inspection, thus focusing on assessing the best potential outcome of each reforestation site. This was done to control as much as possible the variability at the local scale, allowing the analysis of the effects of interest.

2.2. *Field assessment of vegetation and soil*

Information on initial tree density and tree survival in each site was not available, but plants that die in the initial stages after planting, when mortality is also higher, are usually replaced to reach the planting density defined initially by the landowner. Additionally, tree density did not correlate with any climatic or soil type (data not shown), thus, we could assume that tree density was mainly a result of stand management. Tree density was measured by counting the trees in the plot, including any tree stump from recent thinning activities.

To measure tree size, all trees in the sampling plot were identified to the species level, and their height was measured with a hypsometer. Perimeter at breast height, i.e., the perimeter of the trunk at 1.30 m height from the ground, was measured using a tape measure in a third of the trees in the plot. For the remaining trees the perimeter was estimated based on the relationship with tree height to optimize the cost-effectiveness of field measurements (see the functions used for estimation in Sup. Fig. 1). The diameter at breast height (DBH) was then calculated by dividing the perimeter by *Pi*. In young trees with a DBH $<$ 7.5 cm, the perimeter was not measured and a DBH of 3.25 cm (the mean value) was assumed.

Shrub cover and composition were assessed with the line intercept method (Elzinga et al., 1998) along three transects laid at regular intervals within the plot. The length of the transects varied between 25.55 and 37.20 m because it spanned two lines of plantation to ensure that a homogeneous stand structure was being sampled among sites. All shrubs intercepting the transect were identified, the height measured, and the length of interception with their canopy registered. Total shrub cover corresponds to the percentage of transect length intercepting shrubs. Species percentage cover, which was later used to calculate species diversity, was obtained as the sum of all canopy lengths of each species divided by the total length of the transect (Elzinga et al., 1998). Tree regeneration was assessed along the same transects by counting and identifying all tree seedlings found within an area of 1 m along the transect (50 cm on each side along the transect line) (Elzinga et al., 1998). Species richness corresponds to the number of species found in the three transects, considering shrubs and tree seedlings.

Finally, soil samples were collected to measure the organic matter content (SOM) and carbon and nitrogen ratio (C/N). At each site, a composite soil sample was collected with four subsamples of the first 15 cm of soil, excluding any litter, moss or lichen in the topsoil. Samples were sieved with a 2 mm mesh and dried at 60 °C for two days. SOM was quantified with a modified loss-on-ignition method (Ball, 1964) by burning 5 g of dry soil at 600 °C overnight. Total carbon and nitrogen contents were measured on ground soil samples (ball mill Retsh, Hann, Germany) by continuous flow isotope mass spectrometry, using an Isoprime stable isotope ratio mass spectrometer (GV, UK), coupled to a EuroEA elemental analyzer (EuroVector, Italy).

2.3. *Data retrieval and analysis*

From the data obtained in the field, we calculated shrub taxonomic diversity, structural complexity and tree biomass. Species diversity was calculated as Diversity of order one, ^{1}D (Hill, 1973), using the *R* package *vegan* (Oksanen et al., 2019), from the shrub percentage cover. ^{1}D quantifies the effective number of species in a community, i.e., how many species the given community would have if all the species had the same proportion as the actual community did on average (Tuomisto, 2010). Structural complexity was estimated by calculating the functional dispersion of height, FDis (Laliberté and Legendre, 2010), considering all individual trees and shrubs. FDis was calculated on the Euclidean distance matrix between individuals, using presence/absence data, corresponding, thus, to the mean absolute deviation of height; it

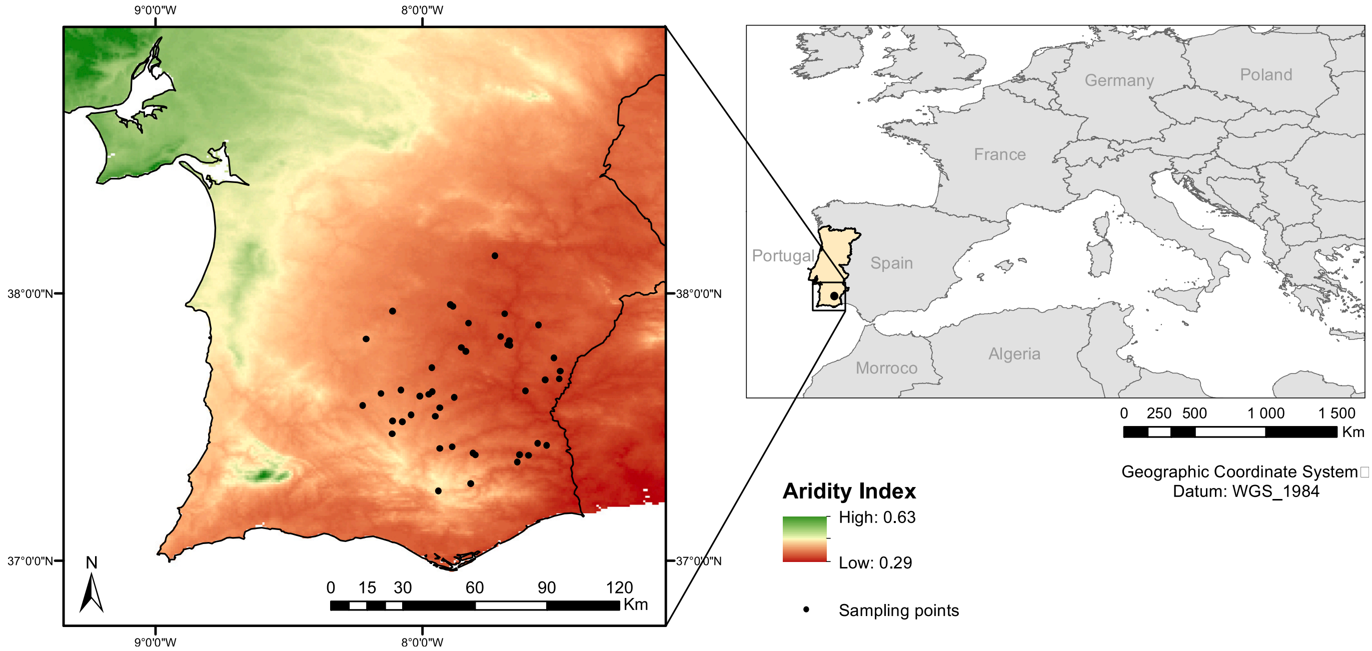

Fig. 1. Location of the study area in southern Portugal (right) and distribution of the sampling points along the aridity gradient (left). Aridity index from Trabucco and Zomer (2022).

was computed with *R* package *FD* (Laliberté et al., 2014). Tree biomass was calculated for each tree with allometric equations specific for *P. pinea* from Correia et al. (2008) and for *Q. ilex* and *Q. suber* from Paulo and Tomé (2006). Tree biomass per plot was then obtained by summing all individual biomass values.

NDVI was retrieved from Landsat 8 satellite imagery in the dry season of 2015, with a spatial resolution of 30 m^2. This index corresponds to the difference between the maximum absorption of radiation in the red spectral band and the maximum reflection of radiation in the near-infrared spectral bands (Rouse et al., 1974). An average NDVI value was calculated per plot with the NDVI values of the pixels covering the area of the plot, including all pixels that have more than half of their area within the plot, as implemented in ArcMap v10.3 (ESRI, 2015).

Climatic data correspond to the bioclimatic variables for WorldClim version 2 at 30 arc *sec* resolution (~1 km^2; Fick and Hijmans, 2017). This is the finest spatial resolution available for WorldClim data and is the most adequate for this dataset, since sites are, on average, 37.3 km apart (min. distance is 0.9 km and median is 37.8 km). A subset of low-correlated bioclimatic variables among them and with the aridity index (Pearson correlation below 0.70) was selected to integrate the data analyses. The effects of the tree species composition, stand management and edaphoclimatic context on the ecosystem were assessed by fitting linear models to each indicator of tree size, ecosystem composition, structure and function. The covariates were the stand's age, the number of trees of each species (which stands for tree species composition), tree density and shrub cover (proxies of stand management) and edaphoclimatic conditions (Table 1). All covariates were continuous variables, except for soil type, a factor with two levels. Structural complexity and SOM were primarily assessed as response variables, but for some indicators, their effect as predictors was also tested, namely, we tested whether structural complexity was a predictor of oak regeneration and whether SOM was a predictor of oak regeneration, tree size and NDVI.

Before the models were fit, exploratory analyses were performed following Zuur et al. (2010) to assess the correlation between covariates (see the correlation matrices in Sup. Fig. 2) to assess whether the relationship between a response variable and a predictor was likely to be simple linear or polynomial and if any interactions were to be expected. We then applied the model-averaging approach to select the predictors most likely to have significant effects on the indicators by averaging the bestfitting models based on the Bayesian Information Criterion (with a $\Delta\text{BIC} \leq 2$, using *R* package *MuMIn* [Bartoń, 2020]). BIC was used over the Aikaine Information Criterion because, while both indices selected models with the same significant predictors, BIC penalizes more the addition of parameters (Shmueli, 2010) and thus tended to select models with fewer nonsignificant parameters. A pseudo-R^2 was calculated for each averaged model, as the Pearson correlation between observed and predicted values.

Table 1
Covariates characterizing the sampling sites, presented as the average ± standard deviation and range.

Type of covariate	Variable (units)	Average ± SD	range
	Stand age (time in years)	19.36 ± 4.31	11–37
Tree composition	N° of *Pinus pinea* trees	12.43 ± 19.30	0–67
	N° of *Quercus ilex* trees	12.73 ± 14.90	0–43
	N° of *Quercus suber* trees	13.09 ± 16.30	0–51
Stand management	Tree density (trees/ha)	432.27 ± 178.45	70–790
	Shrub cover (%)	8.51 ± 13.03	0–56.75
Climate and soil	Potential Solar Radiation (KW/h)	$19.7 \times 10^4 \pm 9.17 \times 10^4$	9.12×10^4–48.2×10^4
	Mean diurnal temperature range (°C)	10.29 ± 0.44	9.6–11.2
	Isothermality (unitless)	0.41 ± 0.01	0.40–0.43
	Minimum temperature of the coldest month (°C)	6.10 ± 0.30	5.2–6.7
	Precipitation of the driest quarter (mm)	21.80 ± 1.53	18–26
	Precipitation of the warmest quarter (mm)	23.86 ± 1.05	22–27
	Aridity index (unitless)	0.35 ± 0.01	0.31–0.39
	Soil organic matter (%)	5.55 ± 1.72	2.17–12.07
	Soil type	luvisol: $n = 13$; lithosol: $n = 31$	

Covariates were centered and scaled prior to model fitting. The variance inflation factor (VIF) of the global model was tested with *R* package *performance* (Lüdecke et al., 2021), and any predictor with a VIF higher than 5 was excluded. Most indicators were fit with gamma GLMs with a logarithmic link function, but for soil C/N, a Gaussian model offered the best fit. Species richness was modeled with Poisson GLMs, also with a log. Link function. Oak regeneration, because of the high number of zeros, was modeled with zero-altered Poisson models (also called hurdle models) using the *R* package *pscl* (Jackman, 2020). Tree regeneration focused on oaks because pine regeneration was residual (data not shown). All analyses were performed in *R* software (R Core Team, 2021), assuming $\alpha = 0.05$. *P* values between 0.05 and 0.1 were considered marginally significant.

3. Results

3.1. Tree size

The size of the planted trees was influenced by different predictors among the three species (Fig. 2; see the exact coefficient values ± standard errors and significance levels in Table S1 and the smoothed conditional means for each pair of indicator vs. predictor in Fig. S3). The abundance of pine trees negatively influenced the size of pine, holm oak trees, and, although only marginally significant, of cork oak trees. Pines and holm oaks also decreased with mean diurnal temperature range, while holm oaks increased with tree density. The size of cork oak trees increased with precipitation of the driest quarter.

3.2. Ecosystem diversity, structure and functioning

Overall, the indicators of species diversity, structural complexity and ecosystem functioning, except for oak regeneration, were driven by stand management, climate and soil but not by the planted tree species composition (Fig. 2, coefficient values and significance in Tables S2 and S3, and smoothed conditional means plots in Fig. S3). Woody species richness varied between 0 and 10 species per site, was positively influenced by shrub cover and SOM. Species diversity varied between 0 and 7.5 effective species per site and increased with SOM. The stand's structural complexity increased with isothermality, i.e., increased with the ratio between the site's diurnal temperature range and the annual range.

Ecosystem productivity, measured by the NDVI, increased with tree density, shrub cover, diurnal temperature range, and aridity index (i.e., productivity was higher in more mesic conditions). Tree biomass increased with isothermality, SOM and depended on soil type, being higher in luvisols than in lithosols. Soil organic matter content, in turn, was solely influenced by shrub cover following a unimodal relationship. SOM increased until a shrub cover of ca. 30 % and decreased in sites with higher cover. Soil C/N ratio, varied between 6.54 and 22.55 and increased with shrub cover but decreased with the minimum temperature of the coldest month.

Oak regeneration was positively influenced by structural complexity, both in terms of the likelihood of its presence, as well as of seedling abundance (Table 2, and smoothed conditional means in Fig. S3). Additionally, the abundance of seedlings decreased with increasing abundance of pines in the stand, while the likelihood of seedling presence increased with the abundance of holm oak.

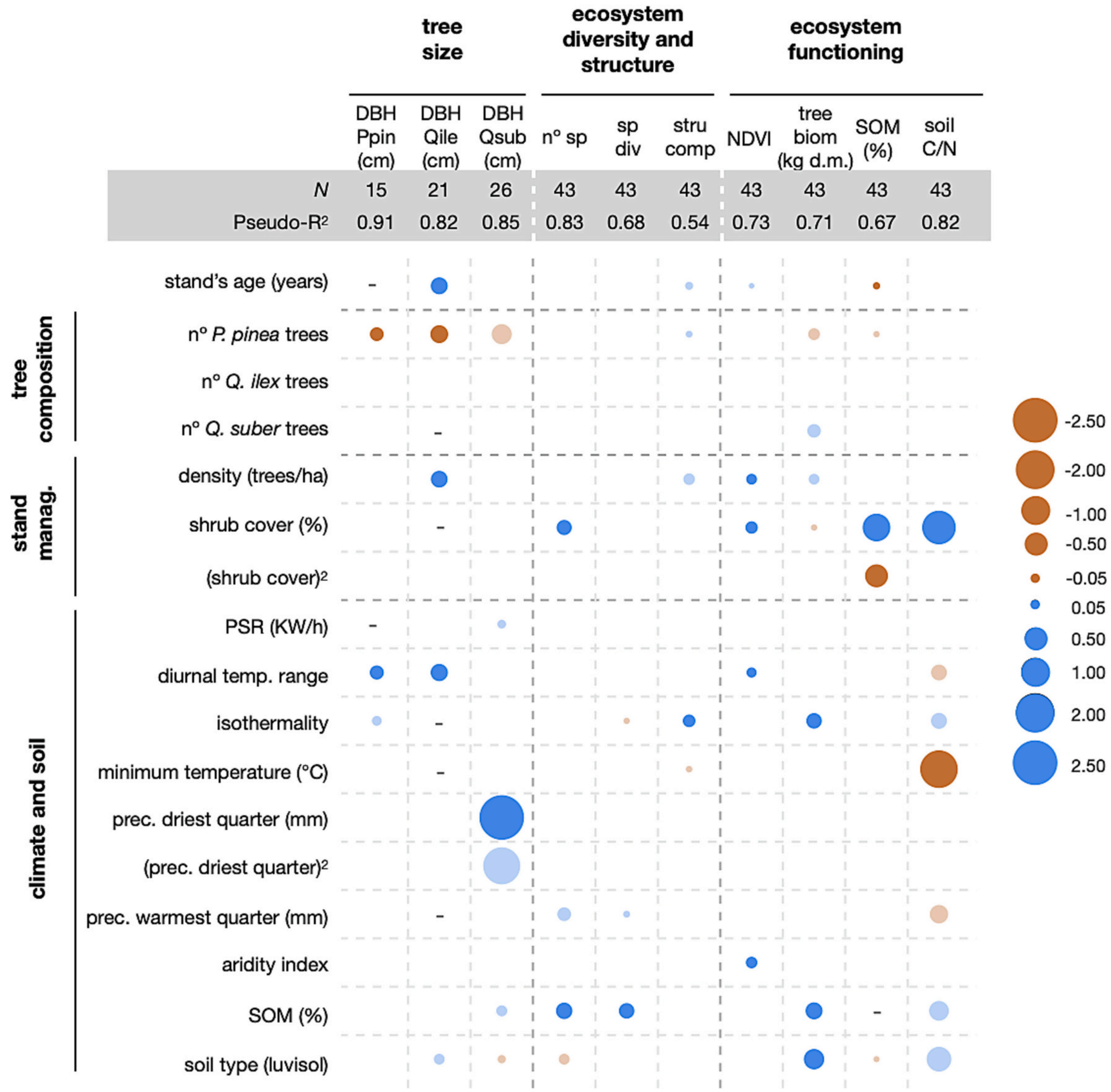

Fig. 2. Covariates selected as best predictors of the indicators of tree size, ecosystem diversity, structure and functioning. Column names represent, from left to right, the diameter at breast height of *Pinus pinea*, *Quercus ilex* and *Q. suber*, shrub species richness, shrub species diversity, structural complexity, NDVI, aboveground tree biomass, soil organic matter content and soil C/N ratio. Row names, from top to bottom, indicate the stand's age, abundance of *Pinus pinea*, *Quercus ilex* and *Q. suber* trees, tree density, shrub cover, potential solar radiation, mean diurnal temperature range, isothermality, minimum temperature of the coldest month, precipitation of the driest quarter, precipitation of the warmest quarter, aridity index, soil organic matter content and soil type (where the coefficient for luvisols is presented). "(predictor)^2" indicates a polynomial relationship of second order. Circles represent the estimated averaged coefficients (red for negative, and blue for positive). Semitransparency indicates covariates kept in the averaged model but with no significant effects. A blank space indicates that the covariate was not kept during model selection, and the symbol "-" indicates the covariate was not tested for that particular indicator due to a high variance inflation value. On top, the *N* and the Pseudo-R^2 of each model are indicated.

Table 2
Estimated standardized coefficients ± standard errors, z values and *P* values for the oak regeneration hurdle model. The pseudo-R^2 is 0.96, with $N = 42$.

	Estimate ± SE	z value	*P*-value
Count model (truncated Poisson with log. link)			
(intercept)	1.210 ± 0.149	8.110	5.06×10^{-16}
n° *Pinus pinea* trees	−0.948 ± 0.179	−5.303	1.14×10^{-07}
Structural complexity	0.848 ± 0.111	7.635	2.26×10^{-14}
Zero hurdle model (binomial with log. link)			
(intercept)	0.056 ± 0.427	0.131	0.895
n° *Quercus ilex* trees	1.954 ± 0.698	2.799	0.005
Structural complexity	1.573 ± 0.527	2.986	0.003

4. Discussion

In this study, we assessed reforestation success in different tree species composition stands (umbrella pine, holm oak or cork oak) and different stand management practices along a climatic gradient in drylands. To the best of our knowledge, our study is the first to assess reforestation success involving established plantations with these three typical Mediterranean tree species on the three main ecosystem components—diversity, structure and functioning. Overall, our results suggest that the ecological outcome of reforestations, after ca. 20 years, was more influenced by stand management than by the tree species composition per se. Management-related variables were important predictors of tree size, species richness, ecosystem productivity and soil quality, while tree composition influenced mostly tree size and regeneration. As expected, the edaphoclimatic context also played an important role in these drylands, particularly for productivity and soil nutrients. These results highlight the importance of monitoring these different ecosystem components in reforestations and that stand-management is a key aspect of these systems.

4.1. Effects of stand management

Tree density in these reforestations is largely the result of initial tree planting density and occasional thinning set by the landowner. In our study, increasing tree density improved holm oak tree size and ecosystem productivity, in accordance with previous studies conducted in pine and holm oak stands in Spanish drylands, (González-Moreno et al., 2011; Morcillo et al., 2022; Ogaya et al., 2020). Also in plantations across the Mediterranean climate and dry woodlands in Australia, productivity was driven by tree density and local environmental conditions, and not by tree diversity (Staples et al., 2019).

Our results show that increasing tree density (but not with pines) increases holm oak size, suggesting an intraspecific facilitative effect of oaks. Although increasing tree density may promote competition for groundwater resources, holm oak may to be particularly resistant to competition in comparison with other species (Gómez-Aparicio et al., 2011). Higher tree density in holm oak stands may ameliorate microclimatic conditions, resulting in the trees being less affected by drought and heat extremes (Gea-Izquierdo et al., 2009). However, it is important to underline that the positive effects of tree density may vary along the density range: other studies have shown that tree density above 1000 trees/ha, in Mediterranean climate, may decrease diversity and oak regeneration (Gómez-Aparicio et al., 2009; Ruiz-Benito et al., 2012). Thus, our results suggest that at lower tree densities, namely, within the studied range of 70–790 trees/ha, increasing tree density up to 790 trees/ha improves holm oak growth and ecosystem productivity.

Another aspect controlled by stand management is shrub cover, with periodic clearings aiming at, mainly, decreasing fire risk. While shrub clearing every 5–6 years is a common practice (Mendes et al., 2011), less frequent clearings are also common resulting in sites where shrubs dominate in the understory (Suess et al., 2018). Hence, despite likely influence of other factors, shrub cover in these stands is first and foremost a result of management. Our results show that sites with higher shrub cover had also higher species richness, ecosystem productivity and soil C/N ratio, in accordance with results found for open oak woodlands in this region (Köbel et al., 2021; Nunes et al., 2019). Shrub cover was also related to soil organic matter, following a unimodal relationship. We, thus, suggest that shrub management should take these effects into account for improving ecosystem functioning in reforestations. Namely, a shrub cover of ca. 30 % may be ideal for having a positive effect of species diversity and productivity while maximizing soil organic matter content.

The fact that we observed more relevant effects of stand management than tree species composition in 20-year-old plantations, does not mean, however, that longer time periods cannot display different outcomes. The presence of pines among holm oak forests has been associated with a more acidic soil pH in 60-year-old stands (Iovieno et al., 2010), and this acidity may further promote changes in understory diversity and composition (Selvi et al., 2016), and decrease organic matter decomposition rate in the soil (Joly et al., 2017). Additionally, pine and oak abundance in 40- to 70-year-old Mediterranean reforested areas influenced soil nutrient pools and greenhouse gas fluxes (Mazza et al., 2021), showing the tree species matters for the ecological outcome, particularly of introducing pines in oak-dominated systems. In our work, climate (temperature) and shrub cover were the most important factors determining soil characteristics, in accordance with a recent global assessment in drylands (Sardans and Peñuelas, 2013; Valencia et al., 2015). Thus, while we should not discard the hypothesis of tree composition having a more prominent effect on the ecosystem over longer periods, we show that, at least within 20 years after plantation with native species, stand management may be more important for the ecosystem outcome than tree composition. Therefore, we suggest that stand management should be considered a key tool to improve tree size and species richness and ecosystem functioning in future reforestated areas and currently reforested areas.

4.2. Effects of tree species composition

In the studied reforestations, tree species composition influenced mainly tree size and oak regeneration. The abundance of pines limited the tree size of pines, holm oaks, and, marginally, of cork oak. Pine abundance was also associated with lower oak regeneration. Our results highlight the importance of managing umbrella pine in these reforestations to prevent intraspecific competition and competition toward planted and naturally regenerating oaks. Pine management in both pure and mixed plantations is important to prevent detrimental effects on pine growth, particularly under dry climates (Cattaneo et al., 2018; Gómez-Aparicio et al., 2011) and to prevent this faster-growing species to outcompete slower-growing cork- and holm oak (Gómez-Aparicio et al., 2011), especially in the first decades after plantation. Pine management (i.e. pine thinning or cutting), is not done in most of these reforestations over time. As a result, high-density stands are commonly found across the Mediterranean Basin, with impacts negative on vegetation diversity and regeneration (Morcillo et al., 2022; Ruiz-Benito et al., 2012) and on faunal communities (e.g. Azor et al., 2015) and increasing the risk of fire. The provision of financial and technical resources specific to improving the ecological condition of reforestated areas could be beneficial in these cases.

We found a negative relationship between oak regeneration and pine abundance in the stand. Previous research has shown that pine-dominated stands can harbor significant oak regeneration under the right circumstances, namely, a balanced pine density (between 300 and 1000 pines/ha, depending on climate), structural complexity to promote the coexistence of closed canopy areas with open canopy areas, and low distance to oak forest patches as sources of acorns (González-Moreno et al., 2011; Morcillo et al., 2022; Ruiz-Benito et al., 2012). Oak seedlings benefit from canopy protection from drought in the first stages after germination, yet competition increases with time as saplings grow (Morcillo et al., 2022). Our study, while confirming the beneficial role of structural complexity for oak regeneration, indicates that pine abundance does not favor regeneration, having, in fact, a negative effect in 20-year-old reforestations. Thus, our results suggest that planting pines with oaks does not favor oak regeneration, being preferable to plant oaks for this purpose.

In our study, high oak abundance was generally associated with positive effects on the ecosystem indicators. Higher holm oak abundance was positively related to more oak regeneration, and cork oak abundance was marginally associated with higher tree biomass at the stand level. While the typical resprouting ability of holm oaks may have influenced the observation of seedlings, this effect is likely limited in our study, since i) there was no relationship with seedling abundance, but only with the probability of finding regeneration, and ii) these stands were relatively young and were not coppiced, which promotes recruitment from seedlings rather than from resprouting (Espelta et al., 1995).

4.3. Effects of climate and soil

Our study shows that climate exerts an important influence on the reforested ecosystem, confirming its central role in shaping dryland ecosystems (Berdugo et al., 2020; Durán et al., 2018). We found a negative effect of aridity on ecosystem productivity, while summer drought in particular limited cork oak size. Temperature-related variables had important effects on the ecosystem structure and functioning, influencing pine and holm oak size, structural complexity, ecosystem productivity, tree biomass and soil C/N ratio.

Climatic conditions in Mediterranean ecosystems, namely, low water availability combined with high temperatures in summer, are known to limit ecosystem productivity (Astigarraga et al., 2020; Ramos et al., 2015), oak regeneration (Arosa et al., 2015; Garcia-Fayos et al., 2020) and tree growth, although some species are more sensitive than others (de-Dios-García et al., 2018; Gómez-Aparicio et al., 2011). Our results suggest that among the three species assessed, cork oak is the most sensitive to water scarcity in summer. Previous studies suggested that, in the studied area, umbrella pine and cork oak may be at the driest edge of their climatic envelope, and their population stability within the next decades is at risk due to the forecasted aridity increase (Duque-Lazo et al., 2018; Stephan et al., 2020; Vessella and Schirone, 2022). Thus, we suggest that future reforestations, especially in semiarid areas with an aridity index below 0.39, should prioritize holm oak, as this species may better cope with current and future climatic conditions, and may be more resilient to wildfires compared to umbrella pine (Dias et al., 2008; Mayoral et al., 2015; Pausas et al., 2008). Moreover, our study suggests that temperature, namely, minimum temperature, is an important driver of soil C/N ratio, together with shrub cover. In Mediterranean ecosystems, microbial activity is typically limited in winter due to low temperatures and in summer due to low water availability (Reichstein et al., 2002). Our results show that sites with warmer winter temperatures have a lower proportion of carbon to nitrogen compared to cooler sites, and this probably results from higher soil respiration rates that consume C stocks in this season (Cookson et al., 2007; Mazza et al., 2021).

5. Conclusions

Our work shows that, if we want reforested areas to be more effective as ecological restoration measures, we should evaluate reforestation success focusing not only on the planted species, but also on ecosystem diversity, structure and functioning. Our results highlight the prominent role of stand management in improving ecosystem diversity and functioning in Mediterranean reforestations, at least in the first 20 years after plantation. Thus, we suggest increasing tree density, particularly of oaks, up to ~800 trees/ha, increasing structural complexity by promoting the coexistence of shrubs and trees with different heights, and the maintenance of a shrub cover of ca. 30 % to promote species richness, ecosystem productivity, soil organic matter and oak regeneration. Tree species composition effects suggest that pines should also be carefully managed by decreasing their density to prevent intra- and interspecific competition. Holm oak, on the other hand, should be promoted, as this species may better cope with current and future aridity conditions in semiarid areas. Finally, climate had an important influence on the ecosystem, particularly on tree size and ecosystem functioning.

Acknowledging the effects of reforestation on ecosystem diversity and functioning found in this study, may help us to fine-tune future restoration projects in drylands, to more effectively improve ecosystem diversity, productivity, soil quality and tree regeneration. Finally, incorporating our practical recommendations in the stand management of currently reforested areas across the Mediterranean Basin, similar to those studied, may provide an opportunity to improve ecosystem diversity and functioning, contributing significantly to the delivery of provisioning and regulating ecosystem services across the Mediterranean region.

CRediT authorship contribution statement

Melanie Köbel: Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Adriana Príncipe:** Methodology, Investigation, Writing – review & editing. **Cristina Soares:** Investigation, Writing – review & editing. **Pedro Pinho:** Conceptualization, Methodology, Writing – review & editing. **Alice Nunes:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Cristina Branquinho:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The dataset is published on figshare (10.6084/m9.figshare.23896563).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166107.

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