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The success of *Quercus ilex* plantations in agricultural fields in eastern Spain

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Abstract

Twenty-five years after planting, we measured the survival, growth and reproduction of 153 *Quercus ilex* plantations promoted by the afforestation programme of the European Union's Common Agricultural Policy in agricultural fields in the east of the Iberian Peninsula, as a function of climatic aridity and stand characteristics related to water supply and competition among trees for water. Using field sampling, we found that, on average, 80% of the trees in plantations survived, more than 55% had already produced acorns and the tallest tree in each field exceeded 4 m, which are all higher values than those reported for forest plantations of this species in the same area and which represent the overcoming of the limitations imposed by climatic aridity on the natural regeneration of the species. A small proportion of the variation in all success variables was explained by water-related plantation characteristics, such as planting density, drought intensity in the year after planting, and soil permeability. However, climatic aridity only influenced the proportion of reproductive trees, but not the other variables of plantation success. However, most of the variation in planting success variables was linked to who owned the field, which nursery produced the seedlings, and the year of planting. Our results support the idea that the deep soils of agricultural fields counteract the negative effect of climatic aridity on plant performance, but that it is necessary to standardise nursery and planting practices, adapt planting density to the environmental characteristics of the site and provide irrigation supply in the early years to ensure the success of future plantations.

Keywords Afforestation · Aridity · Soil hydraulic conductivity · Planting density · Survival · Reproduction

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Introduction

Near three decades after the start of the afforestation programme for agricultural land under the Common Agricultural Policy (CAP) of the European Community, and given the need to reform it to bring it into line with the UN's Sustainable Development Goals (Pe'er et al. 2020) and the UN Decade on Ecosystem Restoration 2021–2030 (https://www.decadeonrestoration.org/about-un-decade), it is necessary to have an evaluation of the forestry plantations promoted by this programme and to know the factors that have contributed most to their success.

So far, evaluations of the CAP plantations and other worldwide plantations programs have usually consisted of either quantifying the area that has been reforested in the different regions or the number of fields or landowners that have been participating in the programs (Santiago-Freijanes et al. 2018; Vadell et al. 2019; Trac et al. 2007), or studying the effects that plantations have had on biodiversity (Santos et al. 2006; Derhé et al. 2016; Sánchez-Oliver et al. 2014; Vasconcelos et al. 2019). However, fewer studies have evaluated the success of plantations in terms of survival of the planted trees, the subsequent development of the trees and the ability of maintaining or expanding the populations over time by means of sexual reproduction, and what are the most influential factors on success. A similar gap had also occurred in relation to the evaluation of non-agricultural forestry plantations. Initially, the number of reforested hectares and the consequences for soil and water protection, biodiversity and ecosystem services were considered the main measures of success worldwide (Jiao et al. 2012; Schwärzel et al. 2020), and only in recent decades has the evaluation of success in terms of tree survival and development become more widespread (Palacios et al. 2009; Valbuena-Carabaña et al. 2010; Grossnickle 2012; Dumroese et al. 2016).

When tree survival and development were considered in evaluating success of forestry plantation, it was found that success depended not only on factors related to the environmental conditions of the stands during and after planting, but also on several technical aspects of the projects and management practices, such as the origin and vigour of the seedlings, the preparation of the planting site, and when and how planting was executed (Villar-Salvador et al. 2004; Jovellar et al. 2012; Lawson and Michler 2014; Grossnickle and MacDonald 2018; del Campo et al. 2010).

In this paper, we evaluated, 25 years after planting, the success of plantations of holm oaks (*Quercus ilex*) in agricultural fields in the east of the Iberian Peninsula within the Reforestation of Agricultural Land programme (CAP) of the European Union, along a climate gradient. In a previous work, we showed that climate aridity limits the natural regeneration of *Q. ilex* in wild populations on shallow calcareous soils in the same area (García-Fayos et al. 2020). Therefore, we expect that planting *Q. ilex* individuals in agricultural fields, which have deeper soils and better hydrological properties than those of wild populations, would totally or partially compensate the negative effect of climate aridity on plant establishment. We quantified the success of plantations by field sampling, measuring survival, height and sexual reproduction of the planted trees. To account for other variables that could influence the success of plantations because they interact with climatic aridity, we also measured environmental and intrinsic plantation characteristics of the plots with the potential to influence water availability for trees. In order to eliminate the consequences of soil nature variations on the success of plantations, such as the effect of soil nature on growth and reproduction of the trees, we restricted the study to plantations developed only on calcareous soils.

The data used in this study came from the planting forms signed by the owners and sent to the administration, as well as from field sampling.

Materials and methods

Site selection

During the autumn of 2019, we reviewed all the planting forms of the CAP reforestation programme for agricultural land in the Spanish provinces of Teruel, Castelló and València, in compliance with the commitments undertaken and declaring that the species planted was *Quercus ilex*. In total, we reviewed 517 forms from Castelló, 297 from València and 124 from Teruel.

Data collection

From these forms, we obtained information on the owner, the nursery where the planted seedlings were grown, the year in which they committed to do the plantations and the cartographic reference of the planted plots. We assumed that each plantation that we sampled was an independent measurement, even if they were plantations belonging to the same landowner, the seedlings came from the same nursery and they were planted in the same year. However, in the case where two or more contiguous plantations belonged to the same owner and were planted in the same year and with plants from the same nursery, only one of them was sampled.

We used the cartographic reference of the plots to locate the plantations, to verify that the soil was calcareous and to obtain the climate aridity values of the plots and the drought intensity values during the planting year and the following year. The bedrock lithology of plots was checked using the geological maps of the Spanish Geological and Mining Institute (IGME) (https://www.igme.es/).

We used the UNEP Aridity Index (UNEP 1992), the ratio of Mean Annual Precipitation (MAP) to Potential Evapotranspiration (PET), to characterize the climate aridity of the plots where the trees were planted. We obtained MAP data from the Digital Climate Atlas of the Iberian Peninsula (Ninyerola et al. 2005) and PET data from the Global Potential Evapotranspiration dataset developed by the Consortium of International Agricultural Research Centers (Trabucco and Zomer 2009) with 200 and 1000 m resolution, respectively. The Aridity Index takes higher values the lower the aridity is.

We also calculated the drought intensity of the planting year (drought intensity year 0) and the year after (drought intensity year 1) since in their first years of life, plants are very sensitive to drought conditions (Rey-Benayas 1998). Drought intensity was estimated using the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), which relates precipitation with atmospheric evaporative demand (potential ET) making it possible to compare drought intensity of different sites independently of their climate characteristics. The SPEI index takes negative values in drought conditions, while positive values indicate wet conditions. We used July SPEI values with a 10-month timescale, after previous research found a high sensitivity of *Q. ilex* tree growth and production to summer SPEI values with a 10-month timescale (Peña-Gallardo et al. 2018; Vicente-

Serrano et al. 2019; Moreno de las Heras et al. 2023). We obtained the SPEI data from the Historical Database of Meteorological Drought Indices for Spain (https://monitordesequia.csic.es/).

Field data survey

During the autumn-winter of 2019–2020, we visited the selected plantations to verify that (i) the plantations still existed, (ii) the planted species was *Q. ilex* and no other species was planted in mixture with it, (iii) they developed on a calcareous bedrock lithology, and (iv) the plants had not been inoculated with truffle. The exclusion of plantations with truffle-inoculated plants was intended to eliminate the source of variation that mycorrhization could introduce into the success of the plantations. Since owners did not always report the use of inoculated seedlings, we had to rely on a variety of evidence, such as the presence of permanent irrigation systems, fencing preventing access by animals and people, tillage between tree lines and even witnessing the truffle harvest itself.

We found 153 plantations executed from 1993 to 1998 that met all these requirements (see Fig. 1 for their geographical distribution and characteristics). These plantations cover an area of 283.5 ha, with an average size (±SE) of 1.8±0.2 ha per plantation and in all of them at least two trees were clearly recognized. These plantations represent approximately 30% of the initially selected plantations, which is a huge reduction. The most common cause for discarding a plantation was that the species planted was not *Q. ilex* or that the plantation had a mixture of species. Sometimes, it was impossible for us to locate the plantations or, when we did locate them, the trees had been felled (the owners had a commitment to maintain the plantations for only 25 years) or the soil was not calcareous. And in some other cases, several plantations were planted with truffle-inoculated trees.

Between the springs of 2020 and 2021, we sampled all the plantations to estimate the survival, growth and reproduction of trees in the plantations, and measure some covariables. In the central part of each plantation, we measured the distance between trees to estimate the planting density (trees ha^{-1}), which provides information on tree competition for resources

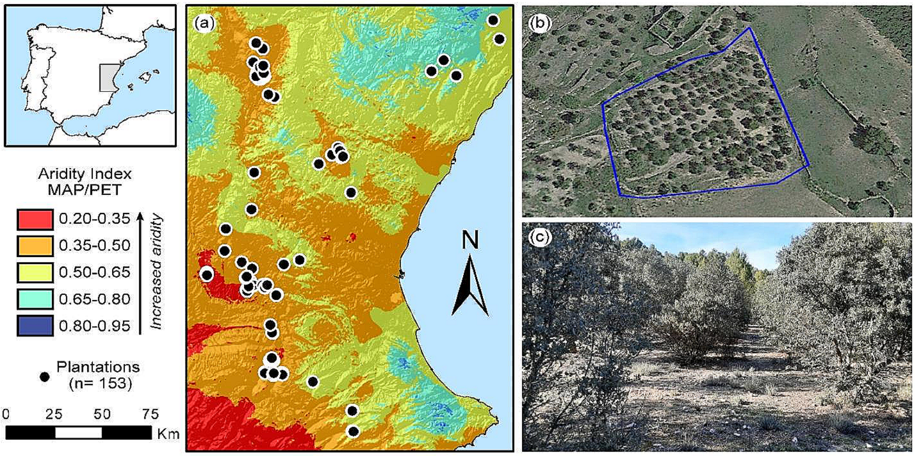

Fig. 1 Location of the study area: **a** geographical distribution of plantations in relation to the UNEP Aridity Index; **b** aerial view of a plantation; and **c** detail of a plantation

(e.g., water). In the same central part, we selected 30 contiguous planting points distributed in three rows of ten points each. Planting points could be easily identified even if the tree was no longer there by checking the planting pattern and other evidences, such as remains of planting holes, piles of stones or the presence of stakes. To avoid edge effects, we never sampled trees located in the outermost rows and columns of the plantations. Since the size and shape of eighteen of the studied plantations did not allow sampling three contiguous rows of 10 planting points in the central part without violating the edge effect condition, we used a different frame until reaching 30 contiguous planting points in the central part of the plot.

At each of the 30 sampling points, we noted whether there was a tree and whether it was alive. After visually inspecting the 30 trees, we measured the three tallest trees with a calibrated pole and retained the height of the tallest one. We also examined the trees for the presence of acorns and cupules on branches or the ground under the canopy. We considered that a tree had reproduced when we found at least one acorn or cupule attached in a branch or more than one acorn or cupule on the ground under its canopy. We precluded the presence of only one fruit on the ground under the canopy of a tree as a sign that the tree had reproduced because the impossibility of ruling out that its presence was accidental. Similarly, we precluded the presence of predated acorns under the canopy as a sign of reproduction, because they may be the result of the behaviour of animals that store and eat them away from the parent plant.

Soil sampling and analysis

At each end of the sampling frame, we took a 10×10×10 cm block of soil after removing loose surface rock fragments. Each block was then transferred to the laboratory and air-dried for one week and then, using the Soil Water Characteristics module of the SPAW model (Saxton and Rawls 2006), we obtained the value of saturated hydraulic conductivity (Ks) for each sample. This parameter is equivalent to the constant infiltration rate when the soil is saturated, and it informs about the permeability of the soil surface layer, which has a great influence on determining the water supply for seedlings and trees (van Lier et al. 2022). The Soil Water Characteristics module of the SPAW model uses information about the textural class of the soil, the proportion of gravels in the sample, the organic matter content and the bulk density. Following the FAO methodology (FAO 2009), we first measured the bulk density of each sample, then sieved it to obtain the proportion of gravel (>2 mm) and fine soil (fraction <2 mm) and determined the textural class of the fine soil fraction to the touch. Using the MUNSELL colour chart (Munsell Color, 2000. Munsell Soil Color Charts. GretagMacbeth) under laboratory light conditions, we determined the MUNSELL notation (VALUE) of this fine fraction. With the textural class and the VALUE, we obtained the mean value of the range of organic matter content of the soil.

Statistical analysis

We used the proportion of trees that survived and had produced acorns, as well as the height of the tallest tree in each plantation as continuous variables that measure the success of the plantations and were used as response variables in the models. We fitted generalized linear mixed models to analyse the relationship of the response variables with the covariates. For survival and reproduction, we used the *glmer* command of the lme4 package of R (R version 4.2.3) with binomial error distribution and the logit link function. For the tallest tree height model, since it fits a normal distribution, we used instead the *lme* command from the nlme package.

We assumed that each landowner manages his fields and carries out planting in a characteristic way that is different from the way other landowners do it, and also that plants obtained in the same nursery are more similar and perform more similarly to each other than do plants produced in other nurseries. However, since seventeen owners reported producing their own plants instead of buying them to a commercial nursery, we assumed that the quality of the plants produced by the owners would be more similar to that of the other owners and that the quality of these plants would be very different than to that of plants produced in commercial nurseries with production standards. Thus, we decided to group all plantations whose owners reported using plants produced by themselves into a single category. Similarly, we assume that plantations made in a year share the weather pattern (i.e., temperature fluctuations, cold and heat waves, rainy periods, etc.), and this weather pattern may differ from that of other years. Therefore, we considered that the interaction among owner, nursery and planting year structures several characteristics of the plantations and, accordingly, we included this interaction as a random effect factor in all models.

The covariates climatic aridity, the SPEI value of the planting year and that of the following year, tree planting density, saturated hydraulic conductivity of the soil and their interactions were included in the fixed term of the models. We first checked for multicollinearity among the covariates included in the fixed term using the *vif* command of the car package of R, the value of VIF in all cases being less than 1.5.

Before running the analyses, we applied logarithms to those covariates that showed strong left skewness (planting density and soil saturated hydraulic conductivity) and then we standardized all the covariates in the models to have mean 0 and variance 1.

We started by fitting the models with the more complex fixed term and, after eliminating sequentially the terms, we selected the simplest model that resulted in the lowest AIC value. We checked for the normality of the residuals distribution and calculated the conditional and marginal R^2 values of the model using the *r.squaredGLMM* command of the R package MuMin.

Results

The 153 plantations we sampled belonged to 48 owners, the plants came from 17 nurseries, and most of them were planted in 1994 and 1995 (84%).

The aridity index was 0.448 on average (95%CI = 0.438 to 0.458) (Fig. 2). SPEI values were more negative during the planting year, -1.347 (95%CI = -1.446 to -1.248) than during the following year, -0.642 (95%CI = -0.757 to -0.527). Mean hydraulic conductivity of the soils at saturation was 11.7 mm h^{-1} (95%CI = 9.2 to 14.3) and the initial planting density of the holm oaks was 616.9 trees ha^{-1} on average (95%CI = 586.1 to 647.7).

Twenty-five years after planting, an average of 80% of the trees in each plantation had survived (95%CI = 76.5 to −83.0) (Fig. 3), the mean maximum height of trees in the plantations exceeded 420 cm (95%CI = 404 to 437) and an average of 56.7% of the trees in each plantation had already reproduced (95%CI = 51.4 to 59.9).

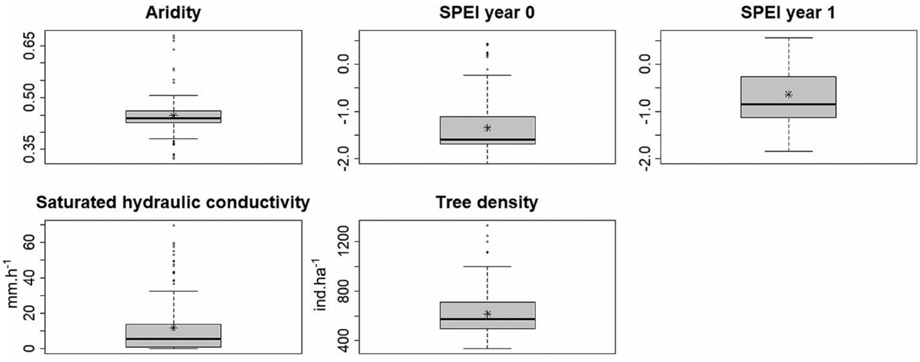

Fig. 2 Box plots for the covariates aridity (UNEP aridity index), SPEI for the planting year and that of the following year (the July values of the Standardized Precipitation-Evapotranspiration Index with a 10-month timescale), saturated hydraulic conductivity of the soil (from the Soil Water Characteristics module of the SPAW model fed with soil characteristics measured in the field and laboratory) and planting tree density (measured in the field). * denotes mean value. Note that the aridity and SPEI indexes are unit less

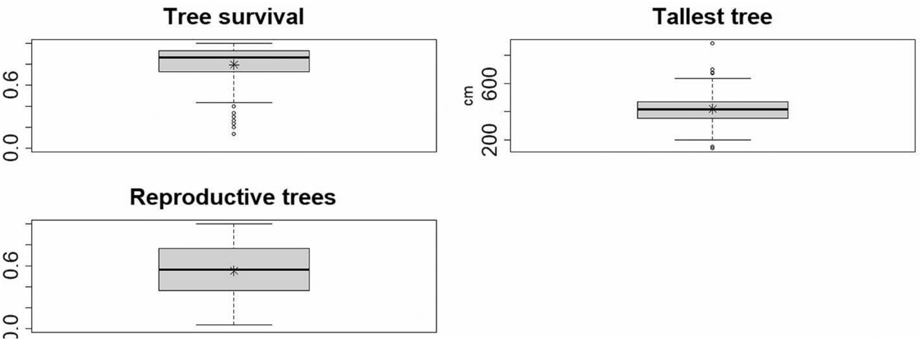

Fig. 3 Box plots for the variables of plantation success measured in the field. Survival (proportion of trees that survived measured in 30 sampled contiguous trees in the central part of the plantation), reproductive trees (proportion of the sampled trees that had reproduced), and tallest tree (the height of the tallest of the 30 sampled trees) * denotes mean value. The variables are proportions, except in the case of the tallest tree, whose values are centimetres

The models explained between 50 and 93% of the variation in the success variables measured (Table 1) and, in all models, more than 75% of this variation was explained by the random term, which included ownership, nursery where plants were produced and year of planting. However, the contribution of the fixed term covariates to this success was smaller (Table 1).

The model of tree survival included the covariates SPEI of the year after planting, which negatively affected survival, and the interaction between planting density and soil hydraulic conductivity. The interaction between planting density and soil hydraulic conductivity indicates that soil permeability modulated the negative effect that density had on tree survival. Thus, an increase in planting density caused a decrease in tree survival in plantations performed on permeable soils ($Ks \geq 2.5$ mm h^{-1}) (Figure S1), whereas in plantations on low permeable soils planting density had no effect and, even, in plantations on impermeable

Table 1 Conditional R^2 (whole model) and marginal R^2 (fixed term) for the best models of the variables of success of the *Quercus ilex*'s plantations

	TREE SURVIVAL	REPRODUCTION	TALLEST TREE
R^2c	0.8588	0.9249	0.4946
R^2m	0.1809	0.1844	0.0407
Intercept	**1.892±0.169**	**0.362±0.176**	**430.77±14.41**
Aridity	---	0.079±0.126	---
Planting tree density	**-0.246±0.083**	**-0.342±0.074**	-9.35±11.01
Saturated hydraulic conductivity (K_s)	**0.202±0.057**	0.018±0.053	3.98±7.89
SPEI year 0	---	---	---
SPEI year 1	**0.331±0.143**	0.220±0.142	---
SPEI year 0 * year 1	---	---	---
Aridity * Planting tree density	---	0.074±0.080	---
Aridity * K_s	---	**-0.245±0.107**	---
Ks * Planting tree density	**-0.285±0.058**	**-0.342±0.051**	**-19.34±7.73**
Aridity * Planting tree density * K_s	---	0.030±0.084	---

Response variables are proportions of surviving trees, proportion of trees that had reproduced, and the height of the tallest tree, obtained from 30 sampled trees in the central part of the plantations. Values for the covariates are estimates±SE of the standardized variables: aridity (UNEP aridity index), SPEI for the planting year and the following year (Standardized Precipitation-Evapotranspiration Index), saturated hydraulic conductivity of the soil (from the Soil Water Characteristics module of the SPAW model), and planting tree density. Bold values indicate significance at $p<0.05$. --- denotes that the covariate was not included in the final model.

soils (Ks < 1 mm h^{-1}) planting density slightly increased survival. In no case did the survival models include climate aridity or SPEI in the year of planting.

The model for the height of the tallest tree explained 50% of the variation, which has the lowest explanatory value of all the measured success variables (Table 1). Again, the random term (owner, nursery and planting year) contributed the most of the variation and, to a much lesser extent, did the environmental characteristics of the plots. Among the latter, only the interaction between planting density and soil permeability was included in the fixed term of the model, and its interpretation is the same as in the survival models (Figure S2).

The model for the proportion of trees that had reproduced after 25 years explained most of the variation (93%), indicating that, again, the proportion of trees that had reproduced depended mainly on the random term, that is, the ownership, the nursery and the planting year (75%) and, to a lesser extent, on the environmental covariates included in the fixed term (Table 1). Regarding the latter, the model included the interactions between hydraulic soil conductivity with planting density and with climate aridity. The first of these interactions indicates that the proportion of trees that had reproduced 25 years decreased because the increase of planting density in plots with moderate to highly permeable soils, while it had no effect in plantations with low permeable soils, or even, it slightly increased the proportion of trees that reproduced in plantations with impermeable soils (Figure S3A). The interaction between climate aridity and soil hydraulic conductivity indicates that, as the climate becomes less arid, the proportion of trees that had reproduced increased, but only if soil permeability of the plot was very high (Ks ≥ 2.5 mm h^{-1}) (Figure S3B). When soil permeability was low (Ks < 2.5 mm h^{-1}), the decrease in aridity reduced the proportion of trees that had reproduced.

Discussion and conclusions

Our results indicate that, after 25 years, *Quercus ilex* plantations in agricultural fields have resulted, in average, in a tree density of 500 ind.ha^{-1}, more than 50% of the trees in plantations have already produced acorns and the highest tree is more than 145 cm. These figures indicate a significant success compared to the natural regeneration of wild populations of *Q. ilex* in the same area and level of aridity, which, in average, recruited less than 51 trees ha^{-1} between 1965 and 2015 (García-Fayos et al. 2020), none of the recruits had reproduced, and only 3 out of 1700 recruits exceeded 145 cm (García-Fayos et al. unpublished results). Our results also indicate that climate aridity had only a slight effect on the measured plantation success variables and most of their variation was not the consequence of water related plot and stand characteristics but a consequence of intrinsic plantation attributes.

Tree survival in the studied plantations was higher than that reported in 9-year-old plantations in old fields in central Spain (55%, Rey-Benayas and Camacho 2004) and much higher than in 10-year-old forest plantations in our study area (10–20%, del Campo et al. 2021, 2022). The average height of the tallest trees in the studied plantations was considerable, 180 and 75 cm higher, respectively, than that of dominants trees in 10 and 15-year-old plantations (Jovellar et al. 2012; Olarieta et al. 2012). Relative to reproduction, we did not find any other study, except Rey-Benayas and Camacho (2004), reporting the proportion of reproductive trees in plantations. Age of first reproduction in this species typically occurs between 10 and 40 years (Ruiz de la Torre 1979; Barbéro et al. 1990) and, although Rey-Benayas and Camacho (2004) found 2% of the trees reproducing in 9 years-old plantations in old fields in central Spain, the 56% of reproductive individuals per plantation after 25 that that we found in our study may be considered a sign of success.

The studied variables explained most of the variation in tree survival and the proportion of reproductive trees in plantations but it explained less of the variation in the size of the tallest tree. Notwithstanding the differences in the variance explained, the effect of the explanatory variables on the success variables was consistent across all them.

Our results also indicate that climate aridity had very little influence on variation of the variables of plantation success, as did other plot and stand characteristics related to water availability and competition. However, we found that most of the variation was due to variables included in the random term of models, which were related to the origin of the plants and who the owner is, strongly suggesting that the decisions and choices made by owners and managers during the planning and execution of the plantations are of the most importance in determining their success.

The decisions and actions of the owners and who performed the plantations include how they managed the agricultural fields before they decided to join the CAP program, how they prepared the soil before planting the trees, whether they tilled or treated the fields after planting to eliminate weeds, the quality of the plants produced by each nursery, how and when they were planted, and the planting density. And these decisions are comparable to those taken by technicians when afforestation plans have to be executed and, on this regard, numerous studies have been highlighted that these technical aspects and management practices influence the success of plantations (Bocio et al. 2004; Navarro-Cerrillo et al. 2005; Sánchez-Andrés et al. 2006; Jiménez et al. 2007; Palacios et al. 2009; Jovellar et al. 2012; Villar-Salvador et al. 2014; del Campo et al. 2010, 2022).

In the present study, we were unable to measure or qualify most of the decisions and previous actions that the owners took, except the density at which trees were planted, and we found that increasing planting density not only reduced tree survival, but also reduced the height of the tallest tree and the proportion of reproductive trees after 25 years. However, this reduction in success occurred only in plantations on permeable soils, but not on impermeable or nearly impermeable soils. Since seedlings, both from commercial and home nurseries, are grown in containers for one to two years before planting in the field, the growth of tap root length is limited while the proliferation of shallower lateral roots is favoured (Tsakaldimi et al. 2009; Gonzalez-Rodríguez et al. 2011). If these seedlings are planted in permeable soils, where water percolates rapidly to deep horizons, competition between plants for water increases. However, if they are planted in less permeable soils, where water remains longer in the shallower horizons, competition may be relaxed.

Environmental variables such as climate and soil water balance in the first years of planting have been reported to strongly influence plantation success (Pascual et al. 2012; Andivia et al. 2021; del Campo et al. 2021). However, in our study, the effect on planting success of environmental variables with the potential to affect tree water availability was much smaller than the effect of the technical decisions and actions that owners and those who performed the plantations did take. Climate aridity did not affect most of the success variables of plantations, having only a negative effect on the proportion of reproductive trees when plantations develop on permeable soils. This can be explained because the differences between agricultural and forest soils derive, in part, from the fact that most of the time “best quality” were selected for agricultural land use, whereas native vegetation, such as forest, develop on the remainder “low quality” soils (Vanmechelen et al. 1997). Consequently, forest soils are usually characterized by certain limitations as regard agricultural standards that may be physical or chemical, whereas cultivated fields tend to be placed in valleys or slopes with gentle angle where soils are deeper, offer a higher soil volume per surface unit and have better physical characteristics than forest soils in the vicinity (Osman 2013). On those soil conditions, is possible to buffer the limitations that aridity imposes to the natural plant recruitment of *Q. ilex*.

Unexpectedly too, SPEI of the planting year did not affect the variables of planting success, and SPEI of the year after planting only decreased tree survival but did not affect the other success variables. Despite *Q. ilex* is a well-adapted species to dry habitats, their seedlings are very sensitive to drought in their first stages (Retana et al. 1999; Pérez-Ramos et al. 2013). Perhaps, the lack of influence of SPEI during the planting year could be a consequence of the widespread practice among farmers in dry and semi-arid climates of watering trees just after planting. Although *Q. ilex* plantations are not a crop, the familiarity of many farmers with fruit trees (walnut, almond, olive, etc.), makes them aware of the high sensitivity to drought during the first year of tree life. In fact, in fifteen of the plantations the owners stated that they planned to water the plants, although we had no way of verifying this.

Among the variables of planting success that we have studied, tree survival and reproduction have been shown to better predict success than the size of the tallest tree. Possibly this is because other variables, such as the genetic origin of the plant, soil fertility, etc. that we did not measure, are also important in determining the size of the tallest tree (del Campo et al. 2022). Likewise, we are aware of the limitations of our measurements to determine whether a tree has reproduced, since *Q. ilex* is a reputed mast seeding species (Siscart et al. 1999). This could mean that at the time of sampling we found no evidence of reproduction in trees that perhaps had reproduced in previous years and also, that a tree could have reproduced but with a too low acorn production the current season to be detected at the time of sampling or that acorns could have been consumed by animals or blown away by wind or runoff (Siscart et al. 1999).

Unlike most reforestations in tropical or temperate climatic conditions, where plant origin, site preparation and their interaction tend to determine plantation survival and development (South et al. 2001; Grossnickle 2012; Grossnickle and Mc Donald 2018; Andivia et al. 2021), in environments with water limitations due to climate or lack of soil, it is the climate itself and the weather during and after planting that tend to determine success (del Campo et al. 2021). However, the results of the present study suggest that in agricultural soils such as those that have benefited from the reforestation program promoted by the CAP, even under water limited climatic conditions, the unmeasured consequences of the decisions taken by owners and managers (i.e. origin of the plant, execution of the planting, watering after planting, etc.) are of the most importance in determining plantation success.

In conclusion, *Q. ilex* plantations in agricultural fields promoted by the CAP (UE) can be considered a success even under climate aridity conditions where the natural regeneration of the species was strongly limited. The variation in success was weakly influenced by plot and stand characteristics related to water availability, possibly because the water holding capacity of agricultural soils buffers the limitations imposed by climate. Our results strongly suggest that, for plantations of *Q. ilex* in semi-arid Mediterranean climate on calcareous soils, the technical and management decisions made by plantation owners and managers are important in determining the success, and we recommend standardizing not only seedling production, but also the way in which planting is carried out, including the recommendation to water the trees just after planting and the following year.

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Declarations

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