

## Effect of Tree Shelters and Regeneration Method on Survival and Growth of Cork Oak Plantations in the Maamora Forest, Morocco

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### ABSTRACT

Forests are under intense human pressure, hindering their restoration. A potential solution to regeneration problems is the adoption of tree shelters, which have demonstrated protective benefits in the early establishment of forest plantations. A 9-year study was conducted in the Maamora forest (Morocco) to evaluate the effects of tube shelters and regeneration methods (direct seeding and seedling) on the growth and survival of cork oak (*Quercus suber*) plantations. A split-plot design was developed with three replicates of 36 plants for each of the four shelter treatments, including T0 (control), T1 (Tubex 1.20 m), T2 (Tubex 1.50 m), and T3 (Tubex 1.80 m) for a total of 964 plants, where periodic inventories were conducted to assess plant survival and growth. Our results show regeneration methods and shelters significantly influenced the survival of cork oak. Direct-seeded plants were more successful than those from seedlings, presenting survival rates of up to 97%. Despite a minimal shelter effect at the beginning, their positive influence was strong later on. Only plants installed with the 1.20 m shelter had an overall success rate of over 50%. Regeneration method had a strong influence on height and diameter growth, with seedling units showing taller plants initially, which shifted to direct-seeded plants in subsequent years. Conversely, the effect of shelters on growth parameters was generally non-significant. Nonetheless, sheltered trees exhibited greater height and diameter than unsheltered trees, particularly in the latter years. Sheltered plants showed an overall faster rate of vertical growth, while unsheltered plants showed faster radial growth.

**Keywords:** Adaptation to climate change, arid climate, cork oak, forest regeneration, Morocco, tree shelters.

### INTRODUCTION

Forests provide a variety of ecosystem services serving economic (food, timber), ecological (carbon storage, soil conservation), and social (recreational and aesthetic values) functions (Lal 2005; Barton et al. 2015; FAO 2020). However, the transformation of dynamic forest landscapes through deforestation for timber production as well as agriculture can have devastating effects on entire ecosystems. Indeed, effects include increased sediment runoff into streams, replacement of entire stands with monocultures that decrease

wildlife habitat and can render stands more susceptible to disease and pests, and increased stream flows and relentless flooding due to loss of vegetative cover that otherwise mitigates their impacts, diminish carbon sequestration, among others (Lee et al. 2011; Gatti et al. 2021; Lawrence et al. 2022). Therefore, forests must be regenerated after harvesting activities to sustainably fulfill their functions. To achieve this goal, forest managers often have a choice between artificial regeneration through plantations and natural regeneration, which relies on the natural reproductive cycle of existing stands (Shono et al. 2007).

Natural regeneration is generally preferred because it is less costly and less disruptive to the ecosystem. In addition, it allows the conservation of genetic diversity and ensures that the trees are well adapted to local conditions (Lohbeck et al. 2021). However, it is characterized by great uncertainty because it is highly dependent on the fruiting of stands before harvesting. In addition, climatic conditions such as reduced precipitation, particularly drought, may limit the regeneration potential and composition of plant species, given their high sensitivity to environmental factors at the seedling stage. An additional barrier to natural regeneration is herbivory, which is particularly detrimental to newly planted unprotected seedlings due to the accessibility of terminal buds and the potential for increased mortality during the early development phase (Leiva et al. 2014; Woolery and Jacobs 2014; Thyroff et al. 2022). To overcome the limitations of natural regeneration, forest managers rely on assisted natural regeneration and artificial regeneration approaches. Assisted regeneration combines active planting and passive restoration where humans intervene to help native vegetation recover naturally by removing obstacles and threats to its growth (Crouzeilles et al. 2020). In contrast, artificial regeneration is achieved through seedling planting or direct seed planting, the latter being reserved for remote or inaccessible areas where seedling planting is not cost-effective (Binkley 1997; Hallsby et al. 2015; Jonsson et al. 2022).

In Morocco, forests cover nearly 13.5% of the territory (HCEFLD 2022), of which one of the most prominent species is the cork oak (*Quercus suber*). Despite their importance, cork oak forests have experienced continuous degradation over the years, with the current extent not exceeding 350,000 ha. In addition, management strategies to protect and preserve these forests have had limited success, as cork oak stands are still subject to regeneration constraints. Indeed, the deterioration of climatic conditions manifested by periods of drought as well as the accentuation of anthropic pressures characterized by overgrazing, overexploitation, acorn collection by the local population have resulted in diminished natural regeneration of the species (Belghazi et al. 2001; El Boukhari et al. 2016; Gauquelin et al. 2016). Such is the case of the Maamora forest, whose cork oak forest is considered to be the largest continuous lowland

cork oak forest in the world. Despite continued attention to cork oak regeneration, results have been mixed. Efforts in recent years have produced encouraging results in some areas, but overall results remain unsatisfactory, requiring activities and strategies that promote both assisted and artificial regeneration (El Boukhari et al. 2016; Abdedelhamid et al. 2019).

Among the measures to promote artificial regeneration of forest species is the installation of tree shelters at the time of seedling plantation. Tree shelters create favorable microenvironment conditions that promote seedling growth (Tuley 1985; Bergez and Dupraz 2009; McCreary et al. 2011). In addition, they contribute to protection from herbivory as well as reduce herbicide contact with protected plants, thereby enhancing their survival (Thyroff et al. 2022). While tree shelters in most cases have a positive effect on height growth, their effect on diameter growth depends on the species and shelter type. Indeed, tree shelter design and characteristics can affect plant physiological and morphological responses both immediately after planting and during plant development. The height of the shelter needs to be above the herbivore browse line to provide protection from browsing (Sweeney et al. 2007). In addition, the type of shelter material can influence light, temperature and air flow, thus affecting the conditions inside the shelter (Oliet et al. 2018).

Studies on the effect of tree shelters are generally limited to one or two growing seasons, with little information available for longer periods (Taylor et al. 2009; Mechergui et al. 2012, 2017; Mariotti et al. 2015). Against this background, this work aims to examine their effect in parallel with the type of regeneration method adopted in cork oak plantations in the Maamora forest, Morocco, during eight years of study. Specifically, the study focused on comparing the influence of tube shelters of three different sizes (1.20 m, 1.50 m, and 1.80) on cork oak seedling survival and growth between 2010 and 2018. In addition, in conjunction with the influence of tree shelters, differences in species growth and development under the two main artificial regeneration strategies (direct seeding and seedling planting) were evaluated. The rationale was to assess survival ability and morphological traits at the early stage and short-term development of the species with the goal of developing effective regeneration strategies in a forest associated with a significant human-animal presence that hinders its restoration.

## MATERIALS AND METHODS

### Study site description

#### *General description*

The Maamora forest is located between 6° and 6° 45' West and 34° and 34° 20' North in Morocco, extending between the cities of Rabat and Kenitra over an area of approximately 132000 ha. The characteristic climate is sub-humid with warm winters in the west and semi-arid with temperate winters in the central and eastern regions of the forest. Mean annual precipitation ranges from 350 to 650 mm and is characterized by a decreasing gradient from west to east of up to 100 mm/year (Aafi 2007; Cherki 2013), with the wettest months being November and December while the driest are July and August. Mean monthly temperatures range from 12°C (January) to 25 °C (July–August), while the maximum and minimum of the coolest and warmest months are 3.5 °C and 37 °C respectively. Summer drought across the forest often lasts more than two months (Aafi 2007; Belghazi and Mounir, 2016). Geologically, the forest is composed of a layer of marl and clay from the Miocene, and sand and sandstone from the Pliocene over which lies deposits of the Maamora red clay (Lepoutre 1965). The characteristic of the soils is a sandy cover resting on an ancient sandy-clay layer (Lepoutre 1967) whose horizons are marked by traces of hydromorphy. The dominant plant cover is cork oak, which extends over more than 60,000 ha and is notable for the predominance of low density stands (Laarbiya et al. 2013; El Abidine et al. 2020). Significant areas of the forest are made up of forested stands that are mostly composed of eucalyptus, pine, acacia.

#### *Overview of climate during study period*

Forest plantations and their establishment are conditioned by climatic conditions. Species growth, productivity, and survival are dependent on the changing conditions of climatic variables. Supplementary Material 1 presents the weather parameters and climatic conditions of the study site measured throughout the study period between 2009 and 2018. Mean annual precipitation was highest at the beginning of the study, especially in 2010 when it was recorded as high as 950 mm. This was followed by a sharp decline

in subsequent years, where precipitation mostly fell below 450 mm, with the lowest value (243 mm) recorded in 2015. Except for 2010 when it was recorded at 18.1 °C, mean temperature fell below 18 °C during the study period, with the lowest value recorded at the beginning of the study at 16.6 °C.

### Plant material and tree shelters

The cork oak seeds (acorns) and 3-month-old seedlings used for plantation in this study were obtained from the Dayet Zerzour nursery in Sidi Yahya (Gharb, Morocco). The choice of species was based on its socio-economic and ecological importance, as well as on the state of degradation of current cork oak stands in the Maamora forest. The tree shelters used were Tubex tubes whose purpose is to provide plants with an improved microclimate, promoting their growth, while protecting them from animal browsing and herbicide spraying, thus increasing survival rates by up to 25%, especially in the early stages of growth (Tubex n.d.). They are designed to last at least 5 years, although the longevity of the shelters depends on the site and weather conditions.

### Methods

#### *Plot construction and experimental design*

The experimental site was chosen on a plot of 1.5 ha composed of cork oak stands with a density of 625 trees/ha. In view of the two study factors tested (tree shelters and regeneration method), a split-plot design (Figure 1) was implemented because it was not possible to assign either of these factors completely randomly to all units in the block. Each block was selected based on the regeneration mode (direct seeding and seedlings) and consisted of 432 plants, with three established replicates in which four treatments were used. The treatments consisted of a control (T0) where no shelter was installed and tube shelters of three different height dimensions, namely T1 (1.20 m), T2 (1.50 m) and T3 (1.80 m). Correspondingly, the 36 plants were planted manually (Figure 2) in each treatment unit: three to four acorns for the direct seeding block; one three-month-old seedling for the seedling block, in 50×50×50 cm pits which were spaced 4×3 m apart.

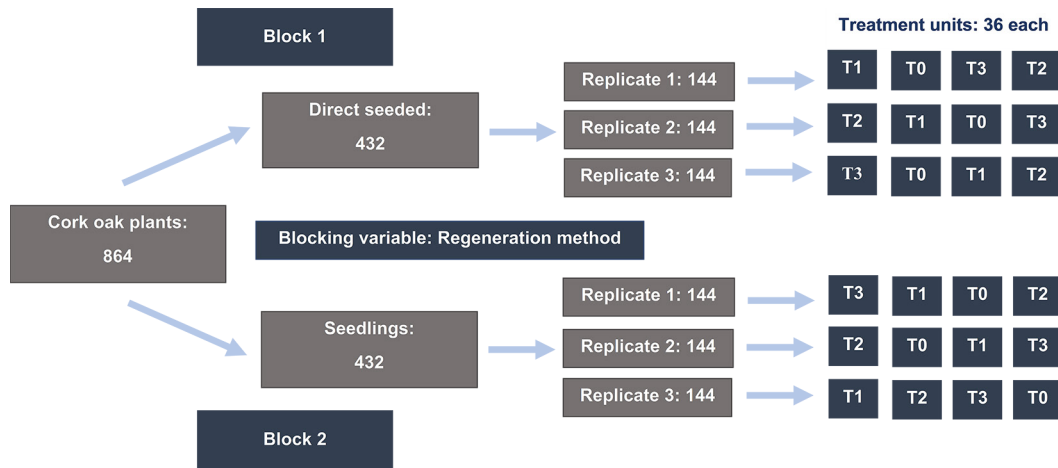


Figure 1. Study design outlining the different stages of the experiment

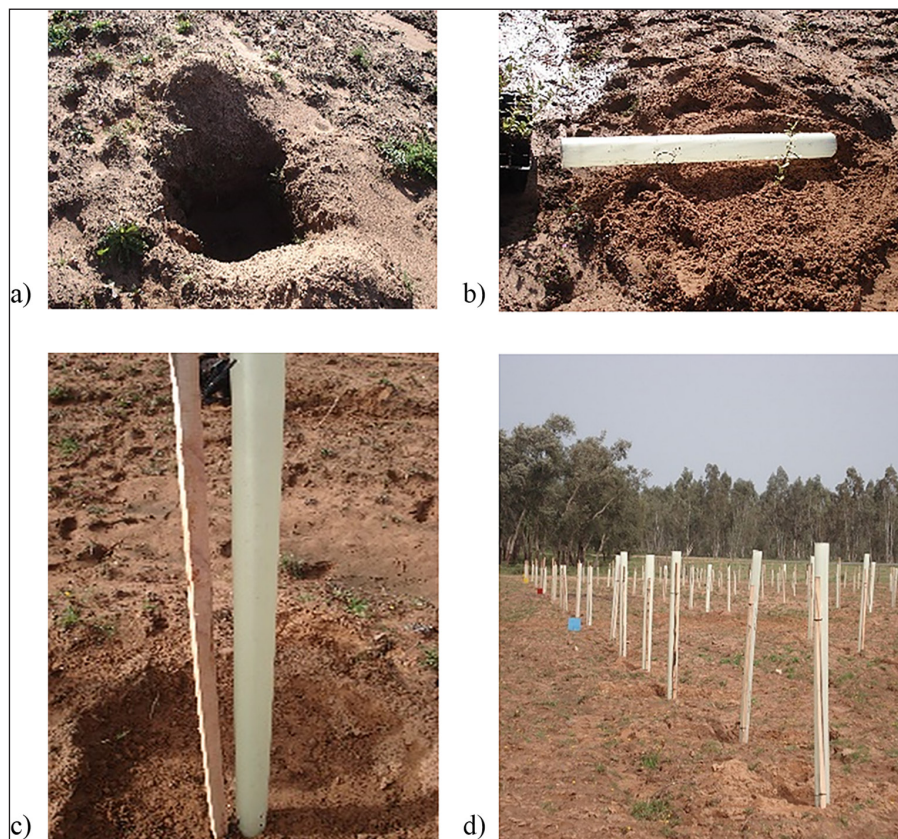


Figure 2. (a) Preparation of the planting pits; (b) planting of cork oak seedlings; (c) installation of tree shelters; (d) completed implementation of the experimental plot

### Data collection and measurements

Data were collected each year after the experiment was set up through 2015 at the time the tree shelters were opened after the laser line break, as well as in 2018 at the end of the study period. Measurements of seed germination success and plant survival, as well as growth parameters including height and diameter at breast height (DBH: in 2015 and 2018) were recorded

during the study period to determine the growth rate of cork oak under the different tree shelter treatments. The survival rate for each growing season was calculated based on the total number of successful plants from the previous period.

### Statistical analyses

The Chi-square test ( $\chi^2$  test) for independence was performed to assess the relationship

of predictor variables (regeneration method and shelter treatments) and therefore influence on cork oak survival. On the other hand, the analysis of variance (ANOVA) test was leveraged to examine the effect of the aforementioned predictor variables on the cork oak growth parameters (height and DBH), as well as on the overall growth rate between 2010 and 2018. To meet the assumptions of normality and homoscedasticity in the study, the Shapiro-Wilk test and Levene's test, respectively, were tested on the dependent variable (growth parameters). Accordingly, because of the variable nature of the data over the study period, the Welch's two-way ANOVA was used in the event that the normality assumption was satisfied but the equality of variances assumption was not, whereas the Kruskal-Wallis (K-W) test was used when the normality assumption was not met. Pairwise post hoc tests after identifying significant effects using Welch's ANOVA and Kruskal-Wallis tests were performed using the Games-Howell test and Dunn's test, respectively.

The Pearson correlation approach was adopted to evaluate the relationship between growth parameters of cork oak in 2015 and 2018 under both regeneration methods and tree shelter treatments. Multiple linear regression using the backward elimination technique was implemented to examine the relationship and thus the ability of height and the two predictor variables (regeneration method and tree shelter treatment) to predict plant height in subsequent years. The predictor variables were encoded into dummy variables to measure the effect of their respective classes on height growth between growing seasons of the trees. For this study, an a priori alpha level of  $\alpha = 0.05$  was used for statistical analyses, hence effects were considered significant when  $p < 0.05$ . All analyses were performed using the R software and the resulting graphical data produced using the ggstatsplot package.

## RESULTS

### Influence of tree shelters and regeneration method on plant survival

#### *Success rate by regeneration method*

After the first growing season, seedling emergence from seeded acorns was very high (97%). Survival rates generally remained high (>80%) in subsequent years as well as in the final growing season of the study. However, there was a

considerable decline in success rates in the 2014–2015 season in which mortality of previously successful seedlings was recorded at 32%. The conducted chi-square tests revealed highly significant ( $p < 0.001$ ) relationships between regeneration method and plant survival (Figure 3), with emerged plants generally exhibiting higher success rates than planted seedlings. Indeed, with the exception of the 2011–2012 and 2014–2015 growing seasons, cork oak survival was highest the direct seeded units. The greatest variation ( $\chi^2(1) = 47.20$ ,  $p < 0.001$ ) in the plantation success between the two regeneration units was observed in the final growing season of the study, where survival rates of trees from the direct seeding units were 48% higher than those from the seedling planting.

#### *Success rate by shelter treatment*

Consistent with observations of the influence of the regeneration method, tree shelter treatment had a generally strong influence on cork oak survival (Figure 4). Although weaker in the first growing season, the effect of shelters was still statistically significant ( $\chi^2(3) = 9.31$ ,  $p < 0.05$ ). During this period, seedling emergence from acorns as well as planted seedling establishment was higher (93%) in unsheltered units than in sheltered units. This trend continued throughout the 2013–2014 growing season, with unsheltered seedlings exhibiting success rates above 90%, with the exception of the 2012–2013 season. However, this changed in the 2014–2015 season, where survival was by far the lowest in unsheltered units at 53%, compared to the 75%+ seedling establishment rate recorded in sheltered units. Even higher mortality rates were recorded in the final growing season of the study, at 60%, while in sheltered seedlings it never exceeded 30%. Within the sheltered units, plants installed with the 1.20 m shelters were generally more successful in their establishment. In fact, with the exception of observations in the first and last years of the study, they had the highest survival rates. Moreover, they were the only plants that showed an overall survival rate at least 50%. It should be noted that mortality rates, although not statically significant ( $p > 0.05$ ), were highest in unsheltered plants in 2015 (47%) and 2018 (60%), whereas sheltered units during these growing seasons never exhibited failure rates above 30%.

#### *Follow-up assessment of cork oak survival in 2021*

A follow-up inventory was conducted in 2021 to assess the survival and performance of cork oak

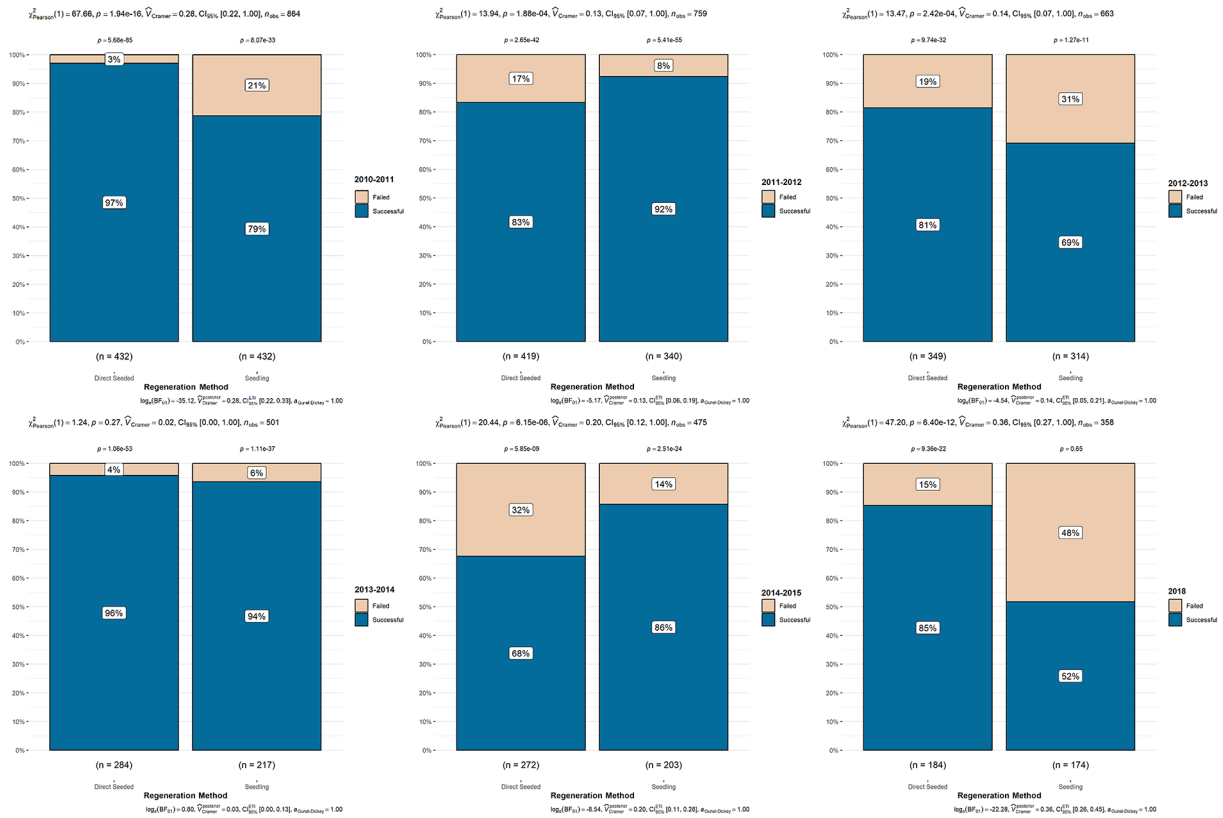


Figure 3. Chi-square test evaluating the relationship between plant survival and regeneration method over the course of the study period

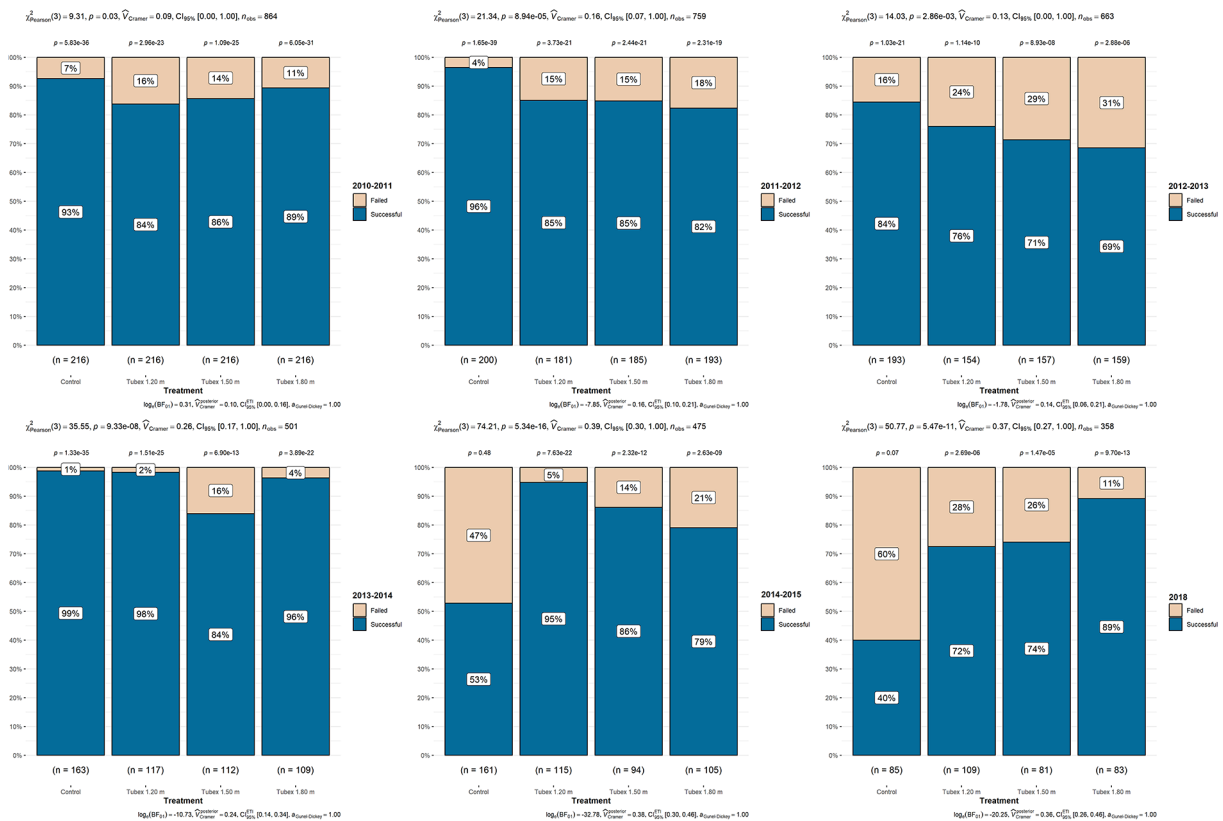


Figure 4. Chi-square test evaluating the relationship between plant survival and tree shelter treatment over the course of the study period

plantations. Results showing success rates for both regeneration units. Plantation success was generally higher in trees from acorn-emerged seedlings. Indeed, in this block, the highest survival rates were recorded under the plants installed with the 1.50 m high shelter, at about 64%, followed by the units with the 1.20 m high shelters, at 58%. Overall, the sheltered trees performed considerably better than the unsheltered trees, for which survival rates did not exceed 22%. Compared to the results observed in the direct seeding units, success rates were considerably lower in the trees from the seedling planting. Indeed, in this regeneration block, while the most successful plantings were recorded in the control treatment units, survival rates fell below 50%. Plantings installed with the 1.80 m high shelter units exhibited a survival rate of 33%, while those with the 1.20 m high shelter units exhibited a success rate of approximately 31%. The lowest survival rates were observed in trees installed with the 1.50 m high shelter units, at 14%.

### Influence of tree shelter and regeneration method on plant growth

#### Effect on height and diameter growth

Results of the evaluation of the influence of regeneration methods and tree shelter treatments on cork oak growth parameters between 2010 and 2018 are presented in Table 1. With the exception

of DBH measured in 2015, regeneration method was shown to significantly ( $p < 0.001$ ) affect cork oak growth parameters. During the early growing seasons in 2010 and 2011, the average height of trees in the seedling units was significantly greater than height measured on trees in the direct seeding units, with differences of +21.85 and +24.55 cm, respectively (Table 2, Figure 5). In contrast, in the later years of the study, height growth appeared to be faster under the trees grown from direct seeding; with the difference in average height of trees from the two regeneration methods in 2015 and 2018 was 34.56 and 82.16 cm, respectively. Similar to height, regeneration method had a significant influence on the DBH of trees in 2018 ( $\chi^2(1) = 30.46$ ,  $p < 0.001$ ). Indeed, trees from directed seeding units exhibited greater growth in DBH (+7.75 cm) than those from seedlings. Conversely, the difference in DBH measured in 2015 was marginal, although it remained greater in direct seeding units.

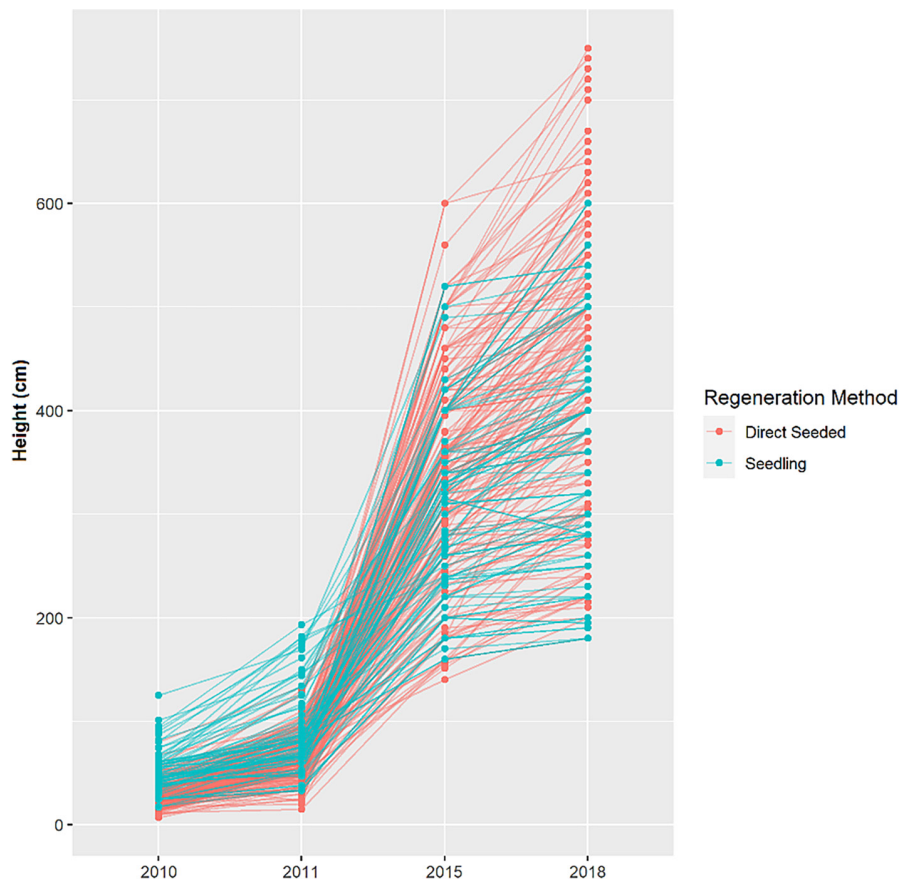
For the most part, shelter treatment did not have a strong influence on cork oak tree height and DBH over the course of the study (Table 3, Figure 6). In fact, only height measured in 2011 presented a statistically significant difference ( $\chi^2(3) = 14.46$ ,  $p < 0.01$ ) between the shelter treatments. Compared to trees in the unsheltered units, trees installed with 1.20 and 1.50 m high shelters exhibited on average significantly ( $p < 0.001$ ) greater

**Table 1.** Evaluation of the effect of regeneration method and tree shelter treatment on cork oak growth parameters

	Test	Variable	<i>n</i>	df	$\chi^2$ or F	p-value
Regeneration method	K-W	Height2010	250	1	80.547	2.2e-16
	K-W	Height2011	250	1	22.862	1.74e-06
	Welch's ANOVA	Height2015	250	1	7.1497	0.007996
	K-W	Height2018	250	1	20.855	4.955e-06
	K-W	DBH2015	250	1	1.651	0.1988
	Welch's ANOVA	DBH2018	250	1	30.46	1.08e-07
Treatment	K-W	Height2010	250	3	5.6833	0.1281
	K-W	Height2011	250	3	14.457	0.002345
	K-W	Height2015	250	3	3.453	0.3269
	K-W	Height2018	250	3	1.1883	0.7558
	K-W	DBH2015	250	3	3.5353	0.3162
	K-W	DBH2018	250	3	3.0427	0.3851
Regeneration method × treatment	K-W	Height2010	250	7	92.519	2.2e-16
	Welch's ANOVA	Height2011	250	7	14.95	6.469e-12
	Welch's ANOVA	Height2015	250	7	1.4066	0.2032
	K-W	Height2018	250	7	22.262	0.00229
	K-W	DBH2015	250	7	10.359	0.1691
	Welch's ANOVA	DBH2018	250	7	4.7412	5.204e-05

**Table 2.** Variation in height and DBH of cork oak over the course of the study under the two regeneration methods

Parameter	Regeneration method	Year	Min	Max	Mean
Height (cm)	Direct seeded	2010	7	80	28.85 ± 12.04
	Seedling	2010	17	125	50.70 ± 19.44
	Direct seeded	2011	15	133	65.09 ± 22.32
	Seedling	2011	33	193	89.74 ± 39.55
	Direct seeded	2015	140	600	340.83 ± 99.61
	Seedling	2015	160	520	306.27 ± 85.50
	Direct seeded	2018	180	750	437.96 ± 128.61
	Seedling	2018	180	600	355.80 ± 111.18
DBH (cm)	Direct seeded	2015	2	36	16.80 ± 8.34
	Seedling	2015	2	33	15.27 ± 7.31
	Direct seeded	2018	4	62	28.85 ± 11.97
	Seedling	2018	5	43	21.10 ± 9.47



**Figure 5.** Height growth rates of cork oak between 2010 and 2018 using different regeneration methods

height differences at +22.15 cm (+37.49%) and +20.78 cm (+35.17%), respectively.

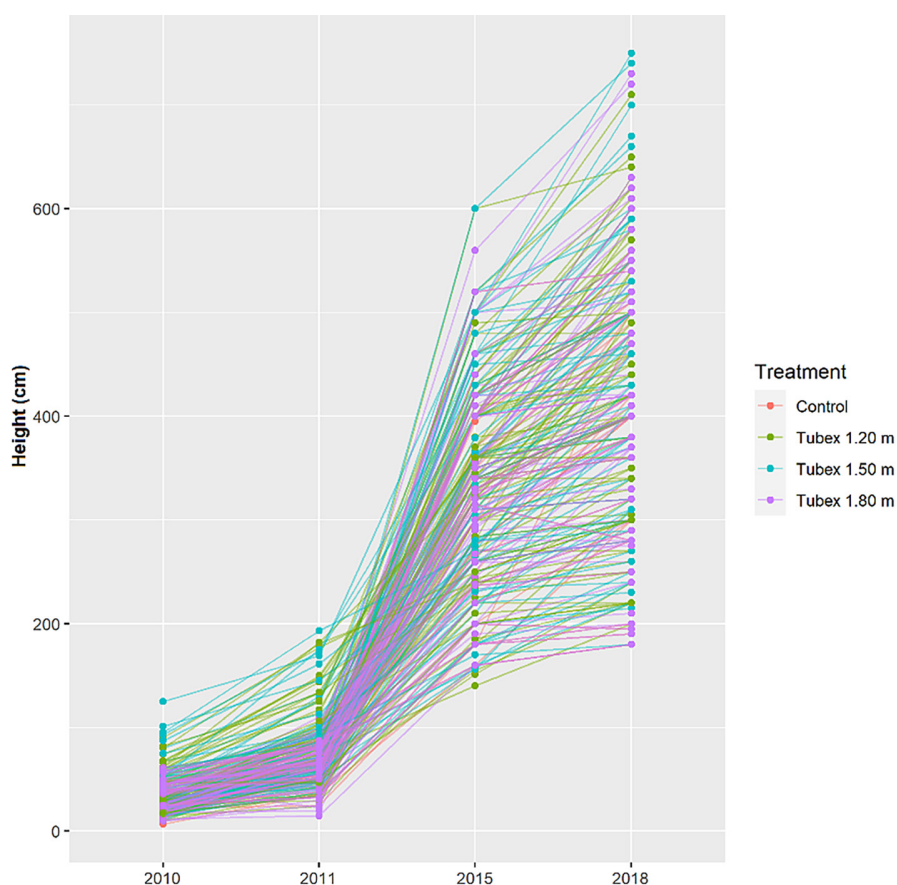
Consistent with the observations of height and DBH measured in the respective years between 2010 and 2018, the results (Table 4) of the influence of regeneration methods on the overall growth rate showed a very strong influence ( $p < 0.001$ ) of the regeneration method,

while the shelter treatment showed a non-statistically significant effect on the growth rate of cork oak. Specifically, germination and subsequent growth of cork oak trees grown from direct seeding exhibited faster growth rates for both height ( $1701.63 \pm 1039.51\%$ ) and DBH ( $102.28 \pm 116.73\%$ ) than trees in the seedling units. Similar to observations on the influence



**Table 3** Variation in height and DBH of cork oak over the course of the study under the various tree shelters

Parameter	Treatment	Year	Min	Max	Mean
Height (cm)	T0	2010	7	61	37.43 ± 12.75
	T1	2010	10	90	35.32 ± 18.58
	T2	2010	11	125	39.81 ± 22.52
	T3	2010	10	61	31.83 ± 13.11
	T0	2011	25	87	59.08 ± 16.10
	T1	2011	24	182	81.23 ± 36.03
	T2	2011	34	193	79.86 ± 35.62
	T3	2011	15	110	64.97 ± 20.76
	T0	2015	160	520	303.19 ± 84.27
	T1	2015	140	600	335.7 ± 93.87
	T2	2015	156	600	336.54 ± 105.96
	T3	2015	160	560	330.3 ± 93.38
	T0	2018	180	600	389.32 ± 112.43
	T1	2018	200	710	419.12 ± 127.44
	T2	2018	180	750	418.36 ± 134.69
	T3	2018	180	730	407.68 ± 131.87
DBH (cm)	T0	2015	2	27	14.41 ± 7.38
	T1	2015	2	35	17.41 ± 7.96
	T2	2015	2	36	16.11 ± 8.46
	T3	2015	2	34	16.35 ± 7.88
	T0	2018	5	43	23.73 ± 9.11
	T1	2018	7	61	28.00 ± 11.78
	T2	2018	4	62	26.97 ± 12.93
	T3	2018	5	56	25.32 ± 11.52



**Figure 6.** Height growth rates of cork oak between 2010 and 2018 using different shelter treatments

**Table 4.** Evaluation of the effect of regeneration method and tree shelter treatment on cork oak growth rate

	Test	Variable	<i>n</i>	df	$\chi^2$	p-value
Regeneration method	K-W	Height	250	1	92.76	2.2e-16
	K-W	DBH	250	1	23.424	1.3e-06
Treatment	K-W	Height	250	3	4.1468	0.246
	K-W	DBH	250	3	1.8074	0.6133
Regeneration method × treatment	K-W	Height	250	7	102.64	2.2e-16
	K-W	DBH	250	7	30.294	8.386e-05

of regeneration method, the effect of the interaction between regeneration method and shelter treatment was highly significant on both height and DBH. While Dunn's post-hoc test revealed significant differences ( $p < 0.001$ ) between the different shelter-regeneration method groups, the highest growth rates for height were identified under plants installed with the 1.20 m and 1.80 m shelters grown through direct seeding at  $1486.72 \pm 1103.67\%$  and  $1479.13 \pm 1017.23\%$ . In contrast, DBH showed the highest growth in the unsheltered control units of the direct-seeded plants at  $111.10 \pm 156.12\%$ .

#### Relationship between height and DBH

Results presenting Pearson correlation coefficients calculated to assess the relationship between cork oak growth parameters after the shelter laser lines were broken in 2015, as well as at the end of the study period. Overall, there was a strong positive correlation between height and DBH in both years for trees planted using both regeneration methods. Nevertheless, the increase in height relative to the increase in DBH was greatest for trees planted using the direct seeding method in 2015 ( $r(167) = 0.90$ ,  $p < 0.001$ ). Similarly, increases in cork oak height in 2015 and 2018 were highly correlated with increases in DBH and thus overall girth ( $r > 0.70$ ,  $p < 0.001$ ) across all tree shelter treatments.

#### Cork oak height prediction

The results of the multiple linear regression analysis used to test the ability of the different variables to predict cork oak height growth. In addition, the fitted model for height growth estimation at the beginning of the study between 2010 and 2011, between 2015 and 2018, and the overall height growth rate. The corresponding regression models for the respective height estimates are presented in Eqs. (1–3).

$$\begin{aligned} \text{Height}_{2011} = & 18.62 + 1.10(\text{Height}_{2010}) + \\ & + 36.67(\text{T1}) + 14.90(\text{T2}) - \\ & - 18.61(\text{T1\_DirectSeeded}) + \\ & + 15.35(\text{T2\_Seedling}) + \\ & + 16.62(\text{T3\_DirectSeeded}) \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Height}_{2018} = & 0.82 + 0.91(\log\text{Height}_{2015}) \\ & - 0.14(\text{Seedling}) - 0.06(\text{T1}) - \\ & - 0.08(\text{T2}) - 0.08(\text{T3}) \end{aligned} \quad (2)$$

$$\begin{aligned} \text{HeightGrowthRate} = & 10.52 - \\ & - 0.99(\log\text{Height}_{2010}) - 0.32(\text{Seedling}) \end{aligned} \quad (3)$$

For height predictions at the start of the study, the overall regression (adjusted  $R^2 = 0.60$ ,  $F(6, 243) = 63.19$ ,  $p < 0.001$ ) as well as the predictor variables were statistically significant. Correspondingly, the model revealed that cork oaks from seedlings installed with the 1.20 m shelter will be taller in 2011 than trees from other regeneration units with different shelter treatments, including those installed with the same shelter but from direct acorn seeding. As with the 2011 predictions, a statistically significant regression was obtained (adjusted  $R^2 = 0.79$ ,  $F(5, 244) = 193.30$ ,  $p < 0.001$ ) for the 2018 prediction, with trees installed with 1.20 m shelters being predicted to be taller at the end of the study, exhibiting greater height. Overall, the prediction of height growth rate (adjusted  $R^2 = 0.73$ ,  $F(2, 247) = 335.40$ ,  $p < 0.001$ ) revealed that trees grown from seedlings had generally faster growth rates.

## DISCUSSION

The adoption of tree shelters on a large scale has to meet the requirements of good plant establishment, improved production, as well as reasonable cost, the latter being non-negligible compared to the alternative of planting without a shelter. In this study, the effect of tube shelters was strongly apparent on the establishment and

survival rates of young cork oak, particularly under direct seeding plots, in contrast to the success rate of seedlings from seedlings where unsheltered seedlings performed better. The positive effect of tube tree shelters on seedling survival has been reported by several authors in the literature. Indeed, Dorji et al. (2020) observed unsheltered brown oak seedlings with significantly lower survival rates compared to sheltered seedlings, with the former suffering more than 90% of severe browsing, which is a major hindering factor for regeneration in Moroccan ecosystems. Even when compared to other browsing control measures, such as the use of mesh screens, they have been shown to be more effective against herbivory, as demonstrated by Thyroff et al. (2022) who reported that live oaks installed with tree shelters performed better than those with protective mesh. In the dry southern region of Morocco, Defaa et al. (2015) reported that tree shelters increased argan seedling survival by up to 20% compared to unsheltered seedlings. It should be noted that the positive effect of shelters on tree survival is not always the case. Indeed, Mechergui et al. (2012, 2017) noted that tree shelters did not have a significant effect on the survival rate of zeen oak and holm oak seedlings in the field, as did Ceacero et al. (2014) who studied the survivability of sheltered holm oaks in the face of weed competition.

The positive effect of shelters on tree height was greatest during early growth, with differences of over 35% observed compared to unsheltered trees. Similar positive observations were reported by Mechergui et al. (2013) who found that sheltered cork oak seedlings were up to 90% taller than unsheltered seedlings after two growing seasons. Faster and earlier height growth is attributed to the response to shade conditions created by tree shelters, as it accelerates access to improved light outside the shelter (Mayhead and Boothman 1997; McCreary and Tecklin, 2001; McCreary et al. 2002). In addition, shelters lead to a decrease in radial plant growth, with more resources allocated to height growth (Mariotti et al. 2015; Mechergui et al. 2013, 2019).

Nevertheless, the effects on height were transient, although this was offset by faster growth rates in DBH. During the final growing seasons, height differences were not significant between unsheltered and sheltered trees. These results are consistent with those of Mayhead

and Boothman (1997) and Ponder (2003) who observed that the height growth rate of protected North American oaks decreased, particularly after exiting shelters. This could be attributed to the fact that after leaving the shelter environment, plants are exposed to outdoor conditions, resulting in a shift in resource allocation from height growth to radial growth (Ponder 2003; Mechergui et al. 2012, 2013, 2019; Yagi 2022) and back to adapt to the outdoor environment imposing greater physiological stresses (Mariotti et al. 2015).

Unlike shelter treatments, regeneration methods strongly influenced both survival and growth of cork oaks throughout the study period. Survival and growth of cork oak was generally higher in acorn-sown seedlings than in planted seedlings. This was particularly pronounced at the end of the study, during the last growing season, when mortality was observed on 48% of the trees from planted seedlings compared to only 15% of the trees from emerged seedlings. This is in contrast to several studies, including González-Rodríguez et al. (2011) and Arosa et al. (2015), conducted on cork oaks regeneration, where nursery-grown trees performed better than trees emerged from acorns. Nevertheless, Belghazi et al. (2011) reported similar results in their study examining the performance of cork oak tree following planting using both methods in Morocco, although the difference (10%) was considerably smaller than in this study (48%).

Although seedling planting is considered the conventional approach to the artificial regeneration of forests, several research studies indicate that direct seeding can represent a reliable and especially inexpensive method to restore particularly degraded forest ecosystems (Barnett 2014; Atondo-Bueno et al. 2018), which is a characteristic of many Mediterranean forests (González-Rodríguez et al. 2011; Hallett et al. 2011). Direct seeding of acorns can give emerging cork oak seedlings the ability to quickly establish a taproot, which is essential for deep soil exploration in search of water and nutrients. This characteristic is particularly important in the studied area, which is located in a region characterized by frequent drought episodes and therefore water stress (Zine El Abidine et al. 2020). In addition, this regeneration technique helps to limit the transplanting shock that is often experienced by nursery-grown seedlings whose root and shoot

systems have been reported to exhibit stability problems (Balisky et al. 1995; Ammer and Mosandl 2007). While the study area under consideration is located in predominantly lowland terrain, cork oak ecosystems in Morocco extend to high altitude regions, where remoteness and inaccessibility of the areas may hinder restoration activities through seedling planting. In these regions, the direct seeding method has the most notable advantage over seedling planting because it reduces the time, logistical challenge, and monetary costs associated with purchasing and transporting nursery-grown seedlings.

Despite the documented benefits of direct seeding, limitations associated with this approach exist. Studies have shown that mortality can be exacerbated under drought-induced water-starved conditions, particularly on sandy soils (Barnett 2014; Kushla 2015). This could have been the case in this study during the 2014–2015 growing season when cork oak mortality in trees resulting from acorn seeding (32%) was considerably higher than in trees resulting from seedling planting (14%). Indeed, this was by far the year with the lowest total precipitation in the region. In addition, the low water holding capacity of the predominantly sandy soils in the study area may have resulted in increased water stress and thus negatively impacted the young cork oak plantations. Another important factor that can significantly limit the success of direct-seeded plantings is seed quality. Indeed, cork oak seedling emergence has been shown to be affected by seed size and therefore available reserves, with studies reporting a generally positive relationship between acorn size and germination and early seedling growth (González-Rodríguez et al. 2011; Ramos et al. 2013; Arosa et al. 2015). Predation on seeds is one of the major factors in decreased viability (Zhang et al. 2016). During the early development of seeded acorns, predatory insects can feed on the seed reserves (cotyledons) and possibly the embryo, resulting in germination failure and/or decreased success of early seedlings due to depletion of reserves (Branco et al. 2002; Mezquida et al. 2020). Despite the presence of white grubs (*Sphodroxia maroccana*) in the study area, attacks on seeds or young seedlings were limited. Nevertheless, future work integrating the aspect of predation and therefore seed quality would be complementary to the present study.

## CONCLUSION

This study was conducted to explore the implications of adopting tree shelters in young forest plantations following the launch of the reforestation program in the 2009–2010 season by the Moroccan Forest Service. Although the costs of implementing tree shelters can be relatively high, especially for largescale reforestation programs, this study showed that they can promote survival and rapid growth. In addition, studies have demonstrated that even for a slow-growing species, they can significantly reduce establishment time after transplanting seedlings to the field (Taylor et al. 2006). Nevertheless, the benefits of tree shelters, particularly on height growth, may be short-lived. Once seedlings emerge from the shelters, growth rates appear to be similar to those of unsheltered seedlings. Consequently, the potential for tree seedlings to sustain strong growth after emerging from shelters is dependent on limiting factors that impede growth such as herbivory, competing vegetation, as well as adverse environmental conditions, particularly water stress. These factors must therefore be taken into account in forest regeneration programs that seek to implement them. Although this study was conducted over an 8-year period, future studies on the involvement of tree shelters in young plantations should be conducted over longer periods of time to better assess long-term implications. In addition, the focus on possible positive or negative effects on the aboveground-belowground balance of trees could provide useful information to forest managers, as well as to scientists in the field.

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