



Effects of artificial shading and weed mowing in reforestation of Mediterranean abandoned cropland with contrasting *Quercus* species

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Abstract

Large areas of abandoned cropland in the world can be reforested with native shrubs and trees to gain a number of environmental benefits. In abandoned Mediterranean croplands, establishment and growth of woody plants are limited by high radiation and low water availability during summer, and weeds are strong competitors for resources, particularly water. We conducted a 3-year experiment in central Spain to study the response of three *Quercus* species (*Q. coccifera*, *Q. ilex* and *Q. faginea*) that differ in their habitat requirements under four treatment field conditions resulting from the combination of full-light versus artificial shading and weed presence versus weed mowing. We measured seedling survival, resprouting capability and growth, weed production, microclimate (incident photosynthetic active radiation (PAR), air temperature, soil water evaporation and effective precipitation) and soil moisture. Shading and weeds reduced PAR reaching the seedlings and soil water evaporation, and shading also reduced effective precipitation. Shading and mowing increased soil moisture. We found a clear positive synergic effect of shading and mowing on seedling performance. Weed competition limited seedling survival in all species more than high radiation, whereas the relative importance of these factors in limiting growth depended on the growth measure and species. As hypothesised, the effects of stress release on plot cover, an integrated performance index that combines survival and growth, were most noticeable in *Q. faginea*, the most mesic species, and least in *Q. coccifera*, the most xerophytic species. The release of weed competition allowed *Q. ilex* seedlings to invest resources in above-ground and, apparently, in below-ground growth. Shading increased simultaneous growth in diameter and volume only for *Q. faginea*. It is important that planted *Quercus* seedlings in abandoned Mediterranean cropland take advantage of a low competitive environment from weeds during the period before the first dry season. Once seedlings have established, an artificially shaded environment would provide benefits in terms of plot cover by the oaks, particularly for mesic species. Studies like this will be of great interest to optimize resource investment in active restoration of other ecosystems of the world.

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1. Introduction

The world extension of degraded land due to agricultural activities is calculated at ca. 12.4×10^6 km². Additionally, large areas of cropland have been abandoned in the last years due to productivity loss, social changes and set-aside programs (Bot et al., 2000; FAO, 2004). These deforested areas can be left to undergo secondary succession or passive restoration (Debussche et al., 1996); or they can be actively restored by planting and managing native shrubs and trees to reduce soil erosion, increase biological diversity and create carbon sinks (Vieira et al., 1994; Whisenant et al., 1995; Maestre et al., 2001). The environmental conditions of these areas usually differ from those where natural regeneration of shrubs and trees occurs, and different abiotic and biotic factors hinder the establishment of introduced woody seedlings (Gordon et al., 1989; Brown et al., 1998; Holl, 1998; Hooper et al., 2002). Thus, the success of revegetation projects usually requires an appropriate management plan (Zutter et al., 1986; Peñuelas et al., 1996; Lemieux and Delisle, 1998; Rey Benayas and Camacho, 2004). This issue is also important because large amounts of public and private funds are being invested in cropland reforestation.

Two important factors that limit the establishment and growth of woody plants in abandoned Mediterranean croplands are high radiation and low water availability in summer. Strong radiation can limit plant survival and growth in dry environments by photo-damage (Méthy et al., 1996) and by reducing soil water content through evaporation and transpiration (Joffre and Rambal, 1993; Lu and Zhang, 1998; Rey Benayas, 1998). Low winter temperatures may also damage plants (Oliveira and Peñuelas, 2002). Additionally, weeds that proliferate in this type of habitat strongly compete for resources, particularly water, with the introduced woody seedlings (Rey Benayas et al., 2003). Consequently, the provision of shading and the elimination of weeds would mitigate these environmental stresses. Numerous studies have addressed the issues of how the performance of planted or naturally established woody seedlings are affected by shade (Rey Benayas, 1998; Gottschalk, 1994; Bardon et al., 1999) and herb competition (Gordon et al., 1989; Morris et al., 1993; Owens et al., 1995; Geyer and Long, 1998; Holl, 1998; Lemieux

and Delisle, 1998). However, the interactive effects of shading and weeds on this performance may have complex interactions that have received little attention (Davis et al., 1999; Rey Benayas et al., 2002; Sack and Grubb, 2002). For instance, shading may have a positive direct effect on seedling establishment, but a negative indirect effect mediated by an enhancement of weed growth. In addition, weeds directly compete with seedlings for resources, a negative effect, but they also diminish radiation loads on the ground reducing evaporation in summer and may increase low winter temperatures at the ground level, indirect positive effects that may facilitate seedling establishment.

Different species have different tolerances to these limiting factors. We experimentally studied under field conditions the response of three *Quercus* species that are important elements of the woodlands and forests in the Western Mediterranean basin. They often comprise most of their community biomass, and thus they are of great interest for ecosystem restoration. These species differ in their habitat requirements, particularly with regards to water availability (Rambal et al., 1996; Valladares et al., 2002): *Q. coccifera* is an evergreen shrub 2–3 m tall growing in the most xeric sites; *Q. ilex* subsp. *ballota* is an evergreen tree up to 12 m tall that exhibits an intermediate preference of soil humidity; *Q. faginea* subsp. *faginea* is a deciduous tree up to 20 m tall that occupies the most mesic sites.

1.1. Objectives, questions and hypotheses

Our objective is to assess the combined effects of radiation load and weed competition on the performance of these *Quercus* species in order to suggest management practices to optimise investment in active restoration. This study is interesting because it is based upon a relatively long experiment (3 years) under field conditions, which are scarce in the scientific literature as compared to short-term, usually 1 year or less, greenhouse or garden experiments. Radiation load was manipulated by artificial shading and weed competition by mowing. Herb competition is usually mitigated with herbicides (Fleming and Wood, 1996; Geyer and Long, 1998), an unfriendly environmental practice that also eliminates the potential benefits of herbs to the soil. We asked whether the removal of only above-ground weed

biomass could be an effective practice to reduce damage on extensive plantations of tree seedlings.

We test the following hypotheses. First, we expect that both shading and mowing will increase water availability to the planted seedlings by decreasing evaporation from soil and transpiration from weeds. Secondly, those environments with lower radiation and water stress will show little and sustained seedling mortality through time. Similarly, the most stressful environments will show a high mortality that is concentrated in the earliest stages of seedling establishment. We ask what environments are perceived as most stressful by the seedlings of each species in our experiment. Third, mortality differences among species under stressful conditions will correspond with the ecological soil water preferences shown by the species distribution in the field, and the amelioration of the environmental harshness will dilute or eliminate the differences among species. Fourth, we expect that stress release will chiefly favour the performance of the most mesic species (*Q. faginea*) because environmental conditions will become more similar to its threshold of stress tolerance respect to the two other species (Arendt, 1997).

2. Methods

2.1. Study site

The study site was located in “El Encín” experimental station in Alcalá de Henares, central Spain (40°35'N, 3°25'W). The experiment was conducted in a 0.5-ha flat, deep soil and homogenous plot that was formerly a cropland. It had been cultivated for many years until *Q. coccifera*, *Q. ilex* and *Q. faginea* seedlings were planted on February 2001. The plot was ploughed prior to the plantation. Soil is classified as Calcic Haploxeralf (Bienes and Nieves, 2000). Climate is continental Mediterranean; mean annual temperature and total annual precipitation average 13.5 °C and 450 mm, respectively, with a cold winter (81 frost days on average) and a pronounced summer drought. During the experiment, mean temperature and precipitation were: 13.6 °C and 373 mm in 2001, 13.9 °C and 570 mm in 2002 and 14.8 °C and 306.2 mm in 2003. The plot was fenced to exclude medium and large size herbivores.

2.2. The experiment

The experiment was laid out as a random plot design. The four treatments resulted from the factorial combination of artificial shading (shaded versus full-light plots) and weed mowing (mowed versus weed plots). There were four replicate plots per treatment (16 plots in total). Size of each plot was 7.5 m × 7.5 m. The planted seedlings were cultivated from acorns collected in localities climatically similar to the experimental area to minimize the variation in genetic composition. Thirty 1-year-old seedlings, 10 per species, were planted with a regular distribution in each of the 16 plots, being separated from each other by at least 1 m. The plantation scheme followed always a constant species sequence to avoid that two seedlings of the same species were adjacently planted. The seedlings were planted with their 5-cm diameter and 18-cm deep plugs. They were protected with a plastic mesh of 1 cm × 1 cm. Seedling mortality within the first month of the experiment was attributed to transplanting problems, and these dead seedlings were replaced. Seedlings were randomly distributed among treatment plots in the experiment. Some of the main species of the weed community were *Tragopogon pratensis*, *Sylibum marianum*, *Fumaria officinales*, *Medicago sativa*, *Hordeum muralis*, *Dactylis glomerata* and *Chenopodium album*.

Shading was achieved with a neutral shade cloth placed 1.9 m above the ground to cover the entire plot area, and three additional net pieces on all plot orientations except northwards that were placed 0.5 m above the ground to avoid border effects (see Section 3 for estimations of the actual reduction of photosynthetic active radiation (PAR)). The current reduction in radiation is not limiting for plant growth even for exemplary heliophilous species such as *Retama sphaerocarpa* (Rey Benayas et al., 2002). Weeds were mowed eight times during the 3 years of the experiment, mainly in spring, to continuously reduce the competition on planted seedlings. Weed height was maintained lower than seedling height.

2.3. Measurements

We examined the performance of *Quercus* seedlings by measuring survival, resprouting capacity, growth and plot cover. We also measured incident

PAR, air temperature, evaporation, effective precipitation, weed production and height, and soil moisture in the different treatments.

Seedling survival was assessed at least every month (once every 2 weeks during the first summer), 32 times in total. We considered a seedling as dead when the shoot was clearly dry. As seedlings with dead shoots can resprout later under less stressful conditions during the fall or next spring, we also counted any new resprout.

Seedling growth was estimated as (i) stem diameter at 2 cm above the ground, (ii) height, (iii) crown projected area (CPA, the elliptical surface of the crown projected onto the ground) and (iv) volume (height \times CPA, an indicator of overall above-ground growth) on March 2001, the initial measurement, and November 2003, the final measurement. The initial size measurements of the seedlings were the following: *Q. faginea*: stem diameter (mm) = 4.53 ± 0.41 S.D., height (cm) = 20.73 ± 2.97 S.D. and CPA (cm²) = 11.71 ± 2.54 S.D.; *Q. ilex*: stem diameter (mm) = 4.76 ± 0.31 S.D., height (cm) = 17.42 ± 1.83 S.D. and CPA (cm²) = 5.78 ± 0.77 S.D.; *Q. coccifera*: stem diameter (mm) = 3.86 ± 0.33 S.D., height (cm) = 14.61 ± 1.65 S.D. and CPA (cm²) = 7.4 ± 1.44 S.D.

We calculated plot cover as an integrated performance index that combines seedling survival and growth at the end of the experiment. It describes the cover for every species and plot, i.e. the average final CPA times survival.

Incident PAR and air temperature (T) at 20 cm above the ground level were registered in every treatment with Ha–Li and HOBBO sensors, respectively. We chose this height above the ground because it approximately coincides with the average initial seedling height, and it also resulted to coincide with the average medium seedling height at the end of the experiment. We used one Ha–Li and one HOBBO sensor per treatment. PAR was registered after February 2002 every second and data were logged in the sensor data-loggers. We extracted the daily maximum PAR and averaged these values per month. T was registered every 2 min. We extracted the daily maximum T and the daily minimum T , and did the same calculations as for PAR.

Soil water evaporation was registered in every treatment with one Moisture Smart evaporimeter. In the

peak of the dry season, the amount of water evaporated was annotated once every 3–4 days; during the rest of the year, it was annotated at least once per month.

Effective precipitation (amount of precipitation that reached the ground) was measured by means of field pluviometers. Six pluviometers per plot were placed in all plots but in the full-light–mowed plots, where only three pluviometers were placed. After June 2001, we annotated the amount of precipitation that filled the pluviometers 42 times in total.

Weed production was determined by clipping weeds in three 20 cm \times 20 cm quadrats randomly selected in each plot. Ten samples were taken along the experiment during spring and summer periods. The samples were dried in an oven at 80 °C for 3 days and then weighed to estimate the accumulated aerial weed production. Additionally, we also measured the average height of the weed community in the weed plots along the experiment.

Soil moisture was measured with Watermark sensors every week along the experiment. Four sensors per plot were buried at 25 and 50 cm depth and at 25 and 50 cm distance from a reference *Q. ilex* seedling. When the sensors were introduced into the ground, they were completely hydrated.

2.4. Data analysis

Seedling survival was assessed by means of survival analysis, an individually based analysis, and ANOVA, based on the proportion of seedlings that died in every plot. A Cox's Proportional Hazards semi-parametric model using the maximum partial likelihood as the estimation method (Fox, 1993; Allison, 1995) tested the effects of species, shading, mowing and their interactions on survival. Two-way ANOVA were used to test treatment effects on seedling survival of every species in the most adverse periods for seedling establishment (during the first summer and during the first winter). A three-way repeated measure ANOVA was used to test the effects of species and treatments on seedling resprouting capacity during the second and third years.

Growth was estimated as relative growth rate (RGR) at the end of the experiment, i.e. $(\ln \text{ final measurement} - \ln \text{ initial measurement}) / \text{number of days}$. Statistical analyses of seedling growth were based upon a MANOVA, two-way ANOVA and

Kruskal–Wallis tests when data did not satisfy ANOVA requirements because of heterogeneity of variances or lack of replicates for some species and treatments due to excessive mortality. Statistical analysis of plot cover was based upon a three-way ANOVA to test species and treatment effects.

The lack of replicates precluded to test differences in incident PAR, air temperature and evaporation. Thus, these data are only illustrative of the environmental conditions under the different treatments. We used two-way ANOVA for testing among-treatment differences in effective precipitation and soil moisture. For effective precipitation, we used the total accumulated precipitation collected in our pluviometers. We did not consider the data from the most and least filled pluviometers (values above and below $\pm 3S.D.$) to avoid the “funnel effect” caused by the artificial shades. For weed production and height, we only looked at the effects of shading on the total amount of biomass accumulated (one-way ANOVA) and the average height of the weed community (a repeated measure ANOVA) along the experiment, since mowing obviously reduces standing weed biomass. For soil moisture, we used a repeated measure ANOVA on the data corresponding to the most critical period for seedling establishment (first dry season) and depth (25 or 50 cm) was an effect in this model.

3. Results

3.1. Incident PAR, air temperature and evaporation

Shading and weeds reduced the amount of PAR that reached the seedlings (Fig. 1) and the amount of water evaporated from the soil (Fig. 2). The differences are more pronounced in the summer season than in the winter. The reduction in maximum PAR in shaded versus full-light plots and weed versus mowed plots was 57.9% and 18.7%, respectively. Similarly, the reduction in total evaporation was 46.9% and 26.6%, respectively.

Shading and mowing reduced T . The reduction of maximum summer T in shaded versus full-light plots was 5.05 °C, and in mowed versus weed plots was 2.75 °C. The increase of minimum winter T in shaded

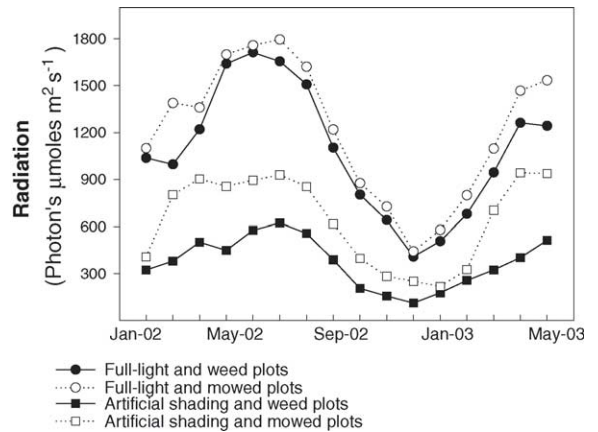


Fig. 1. Profile of PAR at 20 cm above the ground level in the four treatments. Each data point in the figure is the average of the daily maximum PAR in a month.

versus full-light plots was 0.35 °C, and in weed versus mowed plots was 0.85 °C.

3.2. Effective precipitation

Shading ($F_{1,12} = 142.24$, $p < 0.0001$) reduced the amount of precipitation that reached the ground, whereas mowing had little effect ($F_{1,12} = 4.06$, $p = 0.067$). The reduction in effective precipitation in shaded versus full-light plots and mowed versus weed plots averaged 19.8% and 3.4%, respectively. Albeit the effect of shading was statistically significant, differences were low both in summer

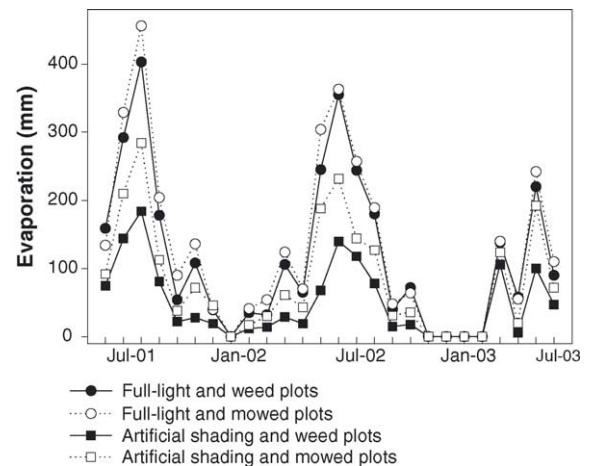


Fig. 2. Profile of total monthly evaporation in the four treatments.

(maximum difference was less than 2 mm and was found between the full-light and weed plots = 4.9 ± 0.18 mm and the shade and weed plots = 3.19 ± 0.29 mm) and in winter (full-light and weed plots = 28.9 ± 0.8 mm and shade and weed plots = 22.3 ± 1.4 mm).

3.3. Weed production and height

Shading did not significantly affect weed production along the experiment ($F_{1,6} = 1.19, p = 0.32$). Mean weed aerial production was $467.8 \pm 197.7 \text{ g m}^{-2}\text{year}^{-1}$ in the shaded plots and $427.2 \pm 164.3 \text{ g m}^{-2}\text{year}^{-1}$ in the full-light plots.

However, shading increased the height of the weed community ($F_{1,6} = 22.03, p = 0.0033$), and the weeds attained a progressively higher height along the experiment ($F_{1,12} = 109.79, p < 0.0001$). Weed height averaged $35.48 \pm 7.85, 70.19 \pm 9.08$ and 91.45 ± 8.51 cm in the shaded plots in years 1–3, respectively, and $33.5 \pm 8.7, 46.0 \pm 3.84$ and 59.71 ± 4.42 cm in the full-light plots in years 1–3, respectively.

3.4. Soil moisture

The repeated measure ANOVA on soil moisture during the first dry season indicated significant effects of shading ($F_{1,24} = 35.43, p < 0.0001$), mowing ($F_{1,24} = 28.86, p < 0.0001$), depth ($F_{1,24} = 298.85, p < 0.0001$) and time ($F_{2,48} = 961.07, p < 0.0001$). Shading and mowing increased soil moisture, mostly at 50-cm depth. Soil progressively desiccated along the dry season (Fig. 3) and, at the end of it, soil moisture was similar among treatments.

3.5. Seedling survival

Both treatments increased seedling survival, mowing showing a most pronounced effect, and there was a highly significant interaction effect (Table 1). The observed survival pattern was largely independent of the species except for a significant interaction with mowing that was lost when the non-significant triple interaction is removed from the analysis. Mowing increased more the survival of *Q. faginea* seedlings than the survival of *Q. ilex* and *Q. coccifera*.

As across all treatments, seedling survival in full-light or weed plots was similar among species

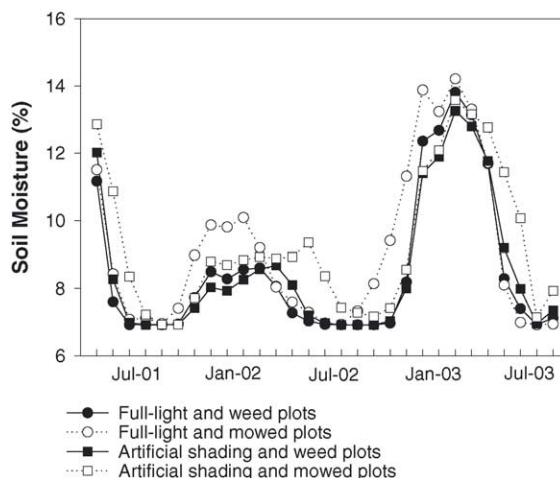


Fig. 3. Profile of monthly values of soil moisture at 50-cm depth in the four treatments. Each data point in the figure is the average of eight Watermark measurements.

($\chi^2 = 3.08$ and $p = 0.23$ in control plots, $\chi^2 = 2.09$ and $p = 0.35$ in shaded and weed plots, $\chi^2 = 1.13$ and $p = 0.57$ in full-light and mowed plots; d.f. = 2, $n = 120$ seedlings). In these plots, the observed survival distributions of every species along the experiment fit best a type-III Weibull distribution (Fig. 4); however, the observed distributions statistically differed from the theoretical one. Conversely, there were among-species differences in the shaded and mowed plots ($\chi^2 = 6.92, p = 0.031, \text{d.f.} = 2, n = 120$ seedlings), the species ranking of survival rates being *Q. faginea* = *Q. ilex* > *Q. coccifera* (Fig. 4). In these plots, the survival distributions fit a linear-hazard or type II exponential model (p -values for the model fit were 0.39, 0.99 and 0.99 for *Q. coccifera*, *Q. ilex* and *Q. faginea*, respectively).

Table 1
Results of the survival analysis based on a Cox's Proportional Hazards semi-parametric model

Source	d.f.	L-R χ^2	p
Artificial shading	1	88.14	0.0000
Weed mowing	1	217.19	0.0000
Species	2	3.56	0.17
Shading × mowing	1	33.47	0.0000
Shading × species	2	3.17	0.2
Mowing × species	2	8.78	0.01
Shading × mowing × species	2	3.56	0.17

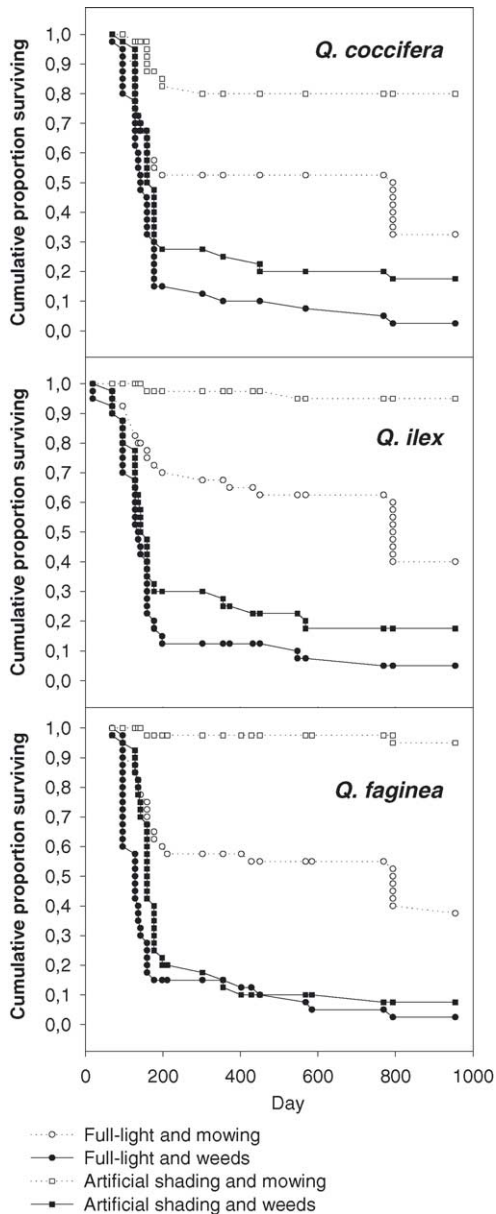


Fig. 4. Pattern of seedling survival in the four treatments for *Q. coccifera* (top), *Q. ilex* (middle) and *Q. faginea* (bottom). Final survival rates (%) are the following: (1) full-light and weed plots (●): *Q. coccifera* = 2.5 ± 5 , *Q. ilex* = 5 ± 5.8 , *Q. faginea* = 2.5 ± 5 ; (2) full-light and mowed plots (○): *Q. coccifera* = 32.5 ± 20.6 , *Q. ilex* = 40 ± 18.3 , *Q. faginea* = 37.5 ± 26.3 ; (3) artificial shading and weed plots (■): *Q. coccifera* = 17.5 ± 17.1 , *Q. ilex* = 17.5 ± 9.6 , *Q. faginea* = 7.5 ± 9.6 ; (4) artificial shading and mowed plots (□): *Q. coccifera* = 80 ± 21.6 , *Q. ilex* = 95 ± 10 , *Q. faginea* = 95 ± 10 .

The ANOVA used to test treatment effects on the mortality counts during critical periods resulted in overall positive effects of shading (marginally significant, $p = 0.08$ for *Q. coccifera* and *Q. ilex* and $p = 0.11$ for *Q. faginea*) and mowing ($p = 0.001$, 0.00001 and 0.0002 for *Q. coccifera*, *Q. ilex* and *Q. faginea*, respectively) on survival during the first dry season. The survival of *Q. ilex* seedlings during the first winter was lower under shading and weed conditions (interaction $F_{1,12} = 9.0$, $p = 0.011$).

We found a significant effect of mowing ($F_{1,29} = 4.34$, $p = 0.045$), but not of shading or species, on seedling resprouting. The proportion of resprouted individuals averaged 20.16 ± 6.61 and 3.28 ± 4.61 in mowed plots and weed plots, respectively.

3.6. Seedling growth and plot cover

MANOVA analysis indicated effects of species (Wilks $\lambda = 0.57$, $p = 0.042$), shading (Wilks $\lambda = 0.35$, $p < 0.0001$) and mowing (Wilks $\lambda = 0.26$, $p < 0.0001$) on all growth measurements. We found a consistent positive effect of shading on height growth in all species (results not shown). In the case of *Q. ilex*, this effect was only marginal ($p = 0.08$) in mowed plots. Growth in stem diameter was enhanced by shading only for *Q. faginea* seedlings, and by mowing for the evergreen oaks, but not for *Q. faginea* (Table 2; Fig. 5A). Growth in CPA and volume was increased by shading and mowing, but the effects of shading on *Q. ilex* and mowing on *Q. coccifera* and *Q. faginea* were not statistically significant (Table 2; Fig. 5B). In the interest of clarity, the measures attained by the seedlings at the end of the experiment are reported in Table 3.

Plot cover was positively affected by shading and mowing, and was dependent on species (triple interaction $F_{2,36} = 3.15$, $p = 0.054$). The effects of shading ($F_{1,36} = 67.66$, $p < 0.0001$) and mowing ($F_{1,36} = 84.3$, $p < 0.0001$) on plot cover were more noticeable for *Q. faginea* and less for *Q. coccifera* (Fig. 6).

4. Discussion

Overall, artificial shading and weed mowing, two techniques intended to facilitate the establishment of

Table 2

Results of the Kruskal–Wallis (*H*) and two-way ANOVA (*F*) used to test the differences in relative growth rate of planted seedlings under different combinations of radiation input and weed competition

	Artificial shading	Weed mowing	Interaction
<i>Q. coccifera</i>			
Stem diameter			
$H_{1,N=12}$	0.8	4.15	–
<i>p</i>	0.37	0.041	–
Volume			
$H_{1,N=12}$	8.08	0.12	–
<i>p</i>	0.0045	0.73	–
<i>Q. ilex</i>			
Stem diameter			
$F_{1,10}$	0.29	21.24	1.91
<i>p</i>	0.6	0.001	0.2
Volume			
$H_{1,N=14}$	0.42	6.67	–
<i>p</i>	0.52	0.01	–
<i>Q. faginea</i>			
Stem diameter			
$H_{1,N=10}$	3.68	2.19	–
<i>p</i>	0.05	0.14	–
Volume			
$H_{1,N=10}$	5.5	1.57	–
<i>p</i>	0.019	0.21	–

native *Quercus* species in abandoned Mediterranean cropland, ameliorated the environmental harshness of the treated plots and improved oak seedling performance. The results of our experiment are further evidence that high radiation and weed competition limit tree establishment in this type of environment because they reduce water availability to the seedlings. This holds true even for species that are very characteristic of dry sites such as *Q. coccifera* (Rambal, 1984).

4.1. Treatment effects on the abiotic environment

Shading reduced the amount of incident PAR that reached the seedlings whereas mowing increased it, particularly during the dry season (Fig. 1). Weeds provided a natural shade equivalent to one third of the artificial shade that was used in this study, and this might be beneficial for the introduced seedlings because of the reduction of photo-inhibition damage (Gratani, 1997). Other studies have shown how the herbaceous layer and its management strongly

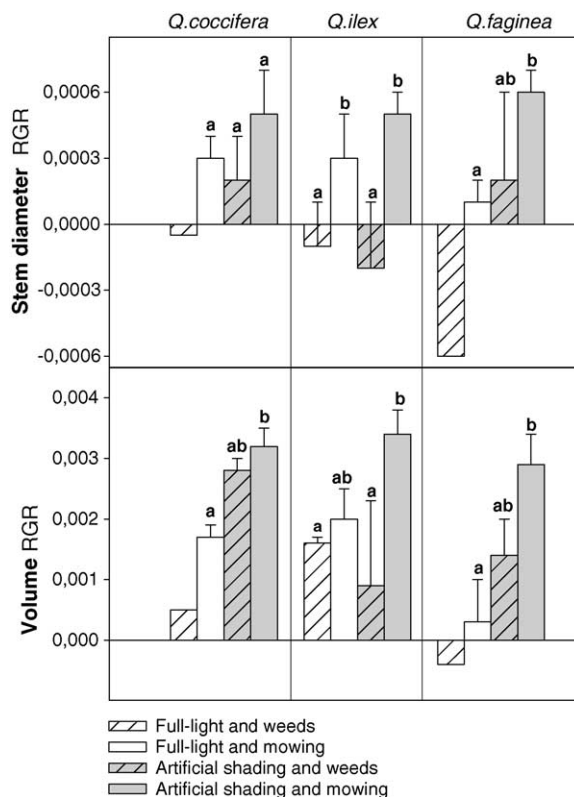


Fig. 5. Relative growth rate in (A) stem diameter and (B) volume of the planted seedlings in the four treatments. Superscripts indicate differences at *p* = 0.05 according to a Tukey’s test for *Q. ilex* and stem diameter and pair-wise Mann–Whitney’s test for the rest of the variables because they did not meet ANOVA assumptions. Bars with no standard error mean that only one plot for that treatment remained with seedlings alive and they were not considered in post hoc comparisons.

determine the amount of incident radiation that may penetrate (Beyschlag et al., 1990, 1992; Mitchley and Willems, 1995). The reduction in *T* is consistent with the reduction in PAR for shading but not for the mowing treatment. We interpret this effect as the consequence of (1) the limit layer at the weed height that hinders energy dissipation and (2) the heat produced by the metabolism of the edaphic communities in weed plots, which balanced out the cooling effect produced by the shade provided by weeds (Hunt et al., 2002; Jacobs et al., 2002).

The reduction in PAR corresponded with the observed reduction in water evaporation (Fig. 2). Shading and mowing reduced effective precipitation.

Table 3

Stem diameter, height and crown projected area (mean \pm S.D.) attained by the three species seedlings under different combinations of radiation input and weed competition at the end of the experiment

	Full-light and weeds	Full-light and mowing	Shading and weeds	Shading and mowing
<i>Q. coccifera</i>				
Stem diameter (mm)	4.0	4.9 \pm 0.7	4.3 \pm 0.8	6.7 \pm 1.7
Height (cm)	10.5	17.8 \pm 2.7	37.3 \pm 12.1	31.1 \pm 3.5
Crown projected area (cm ²)	125.7	408.2 \pm 55.2	688.9 \pm 97.3	1017.5 \pm 279.8
<i>Q. ilex</i>				
Stem diameter (mm)	4.2 \pm 0.1	6.2 \pm 0.7	4.2 \pm 0.9	8.1 \pm 1.0
Height (cm)	21.3 \pm 1.8	21.2 \pm 4.9	19.0 \pm 9.1	37.9 \pm 6.4
Crown projected area (cm ²)	208.9 \pm 15.6	382.5 \pm 92.2	206.1 \pm 119.2	1002.4 \pm 296.8
<i>Q. faginea</i>				
Stem diameter (mm)	2.4	4.7 \pm 0.4	6.3 \pm 3.7	8.1 \pm 0.5
Height (cm)	16.0	14.9 \pm 3.2	36.1 \pm 6.9	39.4 \pm 3.0
Crown projected area (cm ²)	94.2	265.8 \pm 72.1	631.5 \pm 506.5	1545.2 \pm 406.3

Note: there is not S.D. for *Q. coccifera* and *Q. faginea* in full-light and weed plots because only one replicate remained with seedlings alive.

We attribute this latter effect to the canalization of water by weeds (Wood et al., 1998). This reduction was noticeable only in the winter when low temperature and not drought limits plant growth (Tenhunen et al., 1987).

As hypothesized, shading and mowing increased soil moisture in the dry season (Fig. 3). This occurs because shading reduced evaporation, it did not

significantly increase weed production, and the reduction in weed transpiration due to mowing outweighs the increase in evaporation due to the lack of shading by weeds (Navarro, unpublished data). Additionally, the increase in soil moisture is more prominent in deeper soil layers, where water is more accessible to seedlings than to weeds (Brown et al., 1998; Picon et al., 2001; Rey Benayas et al., 2003).

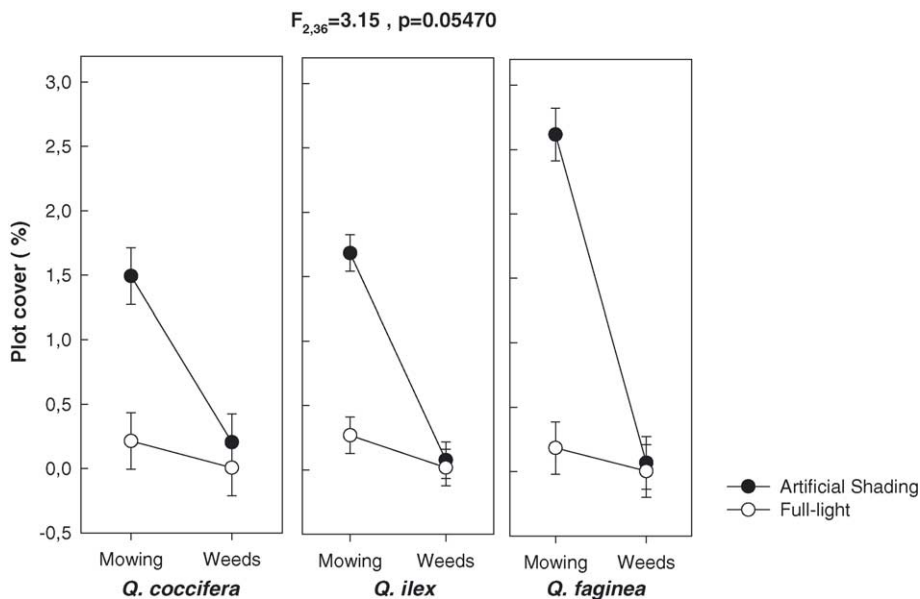


Fig. 6. Plot cover attained by the seedlings in the four treatments at the end of the experiment.

4.2. Species requirements and seedling response to the environment

Shading and mowing increased seedling performance. However, we found differences among treatments and species. Weed competition reduced more survival and resprouting capacity than high radiation (Table 1; Fig. 4), hinting that water shortage is an important limiting factor in this type of habitat (Pigott and Pigott, 1993; Rey Benayas et al., 2003). Contrary to our hypothesis, survival under stressful conditions was similarly low for all species (Fig. 4). This means that, in our experiment, the environmental harshness imposed by full-light or weed competition was usually above the capacity of reaction of all species. Other studies with these species support this statement (Balaguer et al., 2001). Inter-specific differences in survival only appeared in the most favourable environment (shaded and mowed plots) and, as expected, their performance ranked inversely to their soil water preferences in the field (Tenhunen et al., 1990).

As hypothesized, the most favourable environment showed a type-II exponential survival model with a hazard function independent of time (Fig. 4). However, a type-I Weibull survival model did not statistically describe the pattern of mortality in the stressful environments because most of the mortality did not occur at the beginning of the experiment but during the first dry season, i.e. a few months after the experiment started. The observed survival pattern in the most stressful environments will probably follow a type-I Weibull model in the long term. These results are consistent with other experiments that highlight the importance of the first growth season in the recruitment of woody plants (Jurena and Archer, 2003; Rey Benayas et al., 2002; Rey Benayas and Camacho, 2004). Low winter temperatures had little effect on mortality in our study.

As expected, under low stress conditions (shading and mowing) *Q. faginea*, the mesic species, had a better performance as measured by plot cover than *Q. ilex* and *Q. coccifera* (Fig. 6). This is consistent with the observed seedling survival in the most favourable environment. However, some differences in the measured variables of growth and species arose (Tables 2 and 3). Overall, mowing increased growth in stem diameter and volume, but some effects were

not statistically significant. Stem diameter has been shown to be related to carbohydrate storage and to root growth for a variety of species (Cherbuy et al., 2001; Drexhage, 2001). Rey Benayas et al. (2003) for *Q. faginea*, Rey Benayas (unpublished data) for *Q. coccifera* and Sanz (unpublished data) for our three *Quercus* species support this statement. Growth in volume, i.e. in height and CPA – a surrogate measure of photosynthetic surface – means investment of resources in light capture. Thus, the release of weed competition allowed *Q. ilex* seedlings to invest resources in above-ground and, apparently, below-ground growth simultaneously, and *Q. coccifera* seedlings in below-ground growth only. This matches the significantly higher resprouting rates in mowed plots, an evidence of previous below-ground growth (Rey Benayas and Camacho, 2004).

Interestingly, shading increased growth in diameter and volume for *Q. faginea* and in diameter for *Q. coccifera*, but it did not favour the growth of *Q. ilex* (Fig. 5). Stress release by shading was sufficient for aiding *Q. ilex* seedlings to survive but not to grow. This suggests that *Q. ilex* seedlings could not cope simultaneously with shortage of light imposed by the coincidence of artificial shade and weeds and water availability due to below-ground weed competition. It has been demonstrated for other Mediterranean species that the capacity to withstand severe drought decreased in the shade probably due to increased below-ground competition for water with established plants (Valladares and Pearcy, 2002). *Q. ilex* is a widespread species that can be found in a variety of light and moisture environments (Terradas and Savé, 1992), i.e. it is able to colonize habitats that are characteristic of both *Q. coccifera* and *Q. faginea*. “Intermediate” species usually perform worse at the edges of their ecological niches (Tretiach, 1993; Abrams, 1994). This hypothesis is also supported by a regional study based on analysis of the spatial distribution of the same *Quercus* species (Zavala, unpublished data). *Q. faginea* and *Q. coccifera* seedlings that survived may have been able to grow under shaded plots even in presence of weeds because their roots grew faster than in the case of *Q. ilex*, thus being able to escape from weed competition and take advantage of the moister soil conditions (Gordon et al., 1989; McCarthy and Dawson, 1990).

5. Conclusions for management

Managers must evaluate the success of different reforestation practices in terms of investment and benefits. The first dry season was clearly a bottle-neck for the survival of the introduced seedlings, and management decreased mortality up to five times for the three species during the first year. Weed competition limited seedling survival in all species more than high radiation. The relative importance of these factors in limiting growth depended on the growth measure and species but, overall, shading increased growth more than mowing. Of particular interest is the diameter growth, an attribute linked to root growth and carbon storage that may benefit the seedlings when management is interrupted (Bazzaz, 1996; Rey Benayas and Camacho, 2004). Plot cover was slightly higher in mowed plots than in shaded plots at the end of our experiment. However, the data at hand indicate that shading will surpass mowing in the long term because it increases more the seedling CPA.

Clearly, there is a synergic effect of shading and mowing. For management of *Quercus* plantations, it is important that the introduced seedlings of these species take advantage of a low competition environment from weeds before the first dry season (Paez and Marco, 2000; Jurena and Archer, 2003). Once the seedlings have been established, an artificially shaded environment would provide benefits in terms of plot cover by the oaks, the actual target pursued in this type of reforestations, particularly for the most mesic species.

Management is expensive and concentration of management reduces investment. Particularly, shading may be effective and practical in a nursery setting, but we acknowledge that nowadays it is far too expensive to use on a large scale. The senior author has developed and registered (P200301683-ES) a portable and reusable shading device to make this management technique practical at larger scales. The approach that we studied is feasible for creating little reforested patches in vast deforested agricultural regions. Plots as the ones assessed here may act as sources of propagules of *Quercus* species, thus aiding their later natural establishment (Chambers, 2000; Robinson and Andel, 2000). Similar approaches could be tried for other species and/or regions where high radiation and/or herb competition limit the establishment of natural woody vegetation. We invoke that the highlights

provided by long experiments under field conditions are very valuable for management of tree plantations. Studies like the one presented here will be of great interest to optimize resource investment in active restoration of Mediterranean abandoned cropland and other ecosystems of the world.

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