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Performance of *Quercus ilex* saplings planted in abandoned Mediterranean cropland after long-term interruption of their management

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Abstract

Quercus ilex is a slow-growing, sclerophyllous evergreen oak that is a major structural component of the natural forests and woodlands in western European and northern African Mediterranean regions, and thus a valuable species for revegetation of abandoned cropland. In a field experiment consisting in four combinations of summer irrigation (presence–absence) and artificial shading (presence–absence), we managed 12 plots planted with 50 seedlings each for 3 years, and four plots remained as unmanaged, control plots. Then these treatments were interrupted for 6 years. We measured survival, above-ground growth, and reproductive capability to test the hypothesis that the manipulation of the environment during *Q. ilex* establishment improves its performance and to suggest adequate forestation practices. Sapling mortality did not differ among treatment plots during the post-treatment period. Previous artificial shading decreased sapling annual growth rate in height, crown projected area, and volume, but not in stem diameter, after it was interrupted. Some evidence points to both abiotic and competition effects as responsible for the growth pattern. Plot cover by the saplings was only marginally affected by the treatments after the treatment plus post-treatment period. Previous summer irrigation and artificial shading increased the percentage of reproductive saplings among treatment plots, and this effect was independent of sapling size. There was a trade-off between growth and reproductive capability. Management of plantations during the first year only would likely provide a better investment/benefit ratio. Artificial shading provided more benefits than summer irrigation during the treatment period but, in the long run, these benefits were approximately equal. We do not advise applying both treatments simultaneously and the technique to be chosen would depend on the relative costs of irrigation and artificial shading. Long experiments under field conditions like the one presented here are scarce in the scientific literature but very valuable to optimize active restoration of Mediterranean abandoned cropland and other ecosystems of the world.

Keywords: Growth; Artificial shading; Mortality; Reproduction; Summer irrigation; Trade-off

1. Introduction

Abandoned cropland and other deforested areas can be left to undergo secondary succession or passive restoration (Debussche et al., 1996), or they can be

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planted with native shrubs and trees to reduce soil erosion, increase biological diversity and create carbon sinks (active restoration, Vieira et al., 1994; Whisenant et al., 1995; Bakker et al., 1998; Bakker and Berendse, 1999; Maestre et al., 2001). However, the environmental conditions of these areas differ largely from those of the sites where natural regeneration of trees occurs (Gordon et al., 1989; Aronson et al., 1998; Brown et al., 1998; Holl, 1998; Rey Benayas et al., 2002), and the success of revegetation projects requires appropriate management (Zutter et al., 1986; Morris et al., 1993; Raza, 1993; Fleming and Wood, 1996; Peñuelas et al., 1996; Navarro-Cerrillo et al., 1997; Geyer and Long, 1998; Lemieux and Delisle, 1998; Imo and Timmer, 1999). Since management is expensive, it is usually applied during a limited period after plantation takes place. Then, management is interrupted and the seedlings face a different environment than when they were first established. Thus, it is important to assess the response of the introduced seedlings once that active management ceases.

Two important factors that limit the establishment and growth of woody seedlings in Mediterranean environments, particularly in abandoned cropland, are excessive radiation inputs and reduced water availability (Tenhunen et al., 1987; Sala et al., 1994; Castro-Díez et al., 1997; García-Fayos and Verdú, 1998; Rey Benayas, 1998; Valladares and Pearcy, 1998; Valladares and Pugnaire, 1999; Joffre et al., 1999, 2001; Zavala et al., 2000). A valuable species for the revegetation of these types of habitats is *Quercus ilex* L. sp. *ballota* (Desf.) Samp., a sclerophyllous, slow-growing evergreen oak with resprouting capabilities that is a major structural component of the natural forests and woodlands in western European and northern African Mediterranean regions.

Rey Benayas (1998), in a 3-year field experiment, found that artificial shading and summer irrigation resulted in a large mortality reduction of planted *Q. ilex* seedlings. Similarly, these treatments, chiefly artificial shading, resulted in overall positive effects on seedling growth. In this experiment, a set of different phenotypes were shaped as a result of the management practices. In the present study, we assessed the performance of the saplings 6 years after the artificial shading and irrigation treatments were interrupted. We expect that *Q. ilex* silviculturally induced phenotypes respond differentially to Mediterranean climate stress because plant performance can be influenced not only by current but also by previous environmental conditions (Bazzaz, 1996; Metcalfe and Monaghan, 2001; Weinig and Delph, 2001). Further, we tested the hypothesis that the manipulation of the environment during *Q. ilex* establishment improves its performance.

Our main objective is to highlight the response of planted *Q. ilex* seedlings in abandoned Mediterranean cropland when management for aiding their establishment is interrupted. We measured sapling mortality, sprouting, growth, and sexual reproduction, traits that are of direct interest for suggesting adequate practices for plantation management. Our study has the value of being based upon a long experiment (9 years in total) under field conditions, which is scarce in the scientific literature as compared to short-term glasshouse or garden experiments. We call attention to the interest of monitoring an experiment of an slow-growing tree until the reproduction stage.

2. Methods

2.1. Study site and field experiment

The study site was located at La Higueruela, a Consejo Superior de Investigaciones Científicas research station in Toledo, central Spain (40°3′N, 4°24′W, altitude 450 m). In the area, climate is continental Mediterranean, characterized by a long summer drought that imposes severe water stress on the vegetation and cold winters. An introduction of *Q. ilex* seedlings in abandoned cropland was conducted in 1993 and experimental management extended for three consecutive years. Total annual precipitation averaged 403.1 ± 81.0 mm and mean temperature averaged 14.9 ± 1.1 °C during this period. After management was interrupted (1996–2001), total annual precipitation averaged 505.2 ± 85.9 mm and mean temperature averaged 15.1 ± 0.3 °C. The soil is a luvisol type, and derives from arkoses. The use of the land in the area is mostly agricultural.

We conducted our experiment on a 1 ha plot on previous cropland which had been cultivated for grain for many years until forestation took place in March of 1993. Then, the introduced seedlings were subjected to different treatments for 3 years. The experimental design included four combinations of summer irrigation (presence or absence) and artificial shading (presence or absence), with four replicates per combination. Weeds were never clipped during the experiment. The plots were 10 m × 10 m. Fifty 1-year-old seedlings were planted with a regular distribution within each of the 16 plots. The seedlings were planted with 20 cm diameter plugs buried 40 cm deep. They developed from acorns that were collected in a single nearby locality to minimize the variation in genetic composition.

The treatments were: (1) sprinkler irrigation at the peak of the dry season (60 mm twice, in July and August; 120 mm per year total), the water being added uniformly to the entire plot area; (2) artificial shading (black polyethylene net placed 2 m above the ground, which reduced incident radiation by 68%). Herbivores were excluded from all plots because hares and rabbits cause severe damage to seedlings.

The artificial shading and summer irrigation were interrupted in the winter of 1996. All seedlings were under natural water and radiation inputs from then on. We maintained the protection from herbivores. The experiment was revisited in December 2001 to evaluate the performance of the introduced seedlings 6 years after the treatment period.

2.2. Measurements

The parameters that were examined for the saplings in the different treatment plots were the following:

1. *Mortality:* we counted again all dead seedlings in every plot and these counts were referred to percentage per plot.
2. We also measured (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 × CPA). Growth was estimated as the average annual growth rates (AGR), i.e. $[(\text{final measurement} - \text{initial measurement})/(\text{initial measurement} \times 6\,\text{years})] \times 100$. The measurements attained by the seedlings under the four treatment conditions after 3 years are reported in Fig. 3.
3. *Plot cover:* the sum of the CPA of the surviving saplings divided by the area of the afforested plot.
4. Percentage of apparently dead saplings at the end of the treatment period that resprouted during the post-treatment period.
5. Percentage of reproductive saplings per plot, provided that they presented acorns. This percentage was calculated over the number of alive seedlings.

2.3. Data analysis

We tested the effects of summer irrigation and artificial shading applied during the treatment period, and their interaction, on the above measurements. After inspection of normality and Levene's test of homogeneity of variances, two-way ANOVA and Tukey's tests for comparisons between treatment combinations were used for most of the measurements. When data did not satisfy the ANOVA requirements (AGR in crown projected area and in volume), we log-transformed the data, tested again the requirements, and then ran the two-way ANOVA and Tukey's tests.

We used an ANCOVA that included sapling volume as a covariable to test the effect of previous treatments on the number of reproductive saplings per plot. We also used an ANCOVA that included mortality—a surrogate measure of competition intensity since it is related to density of individuals—as a covariable to test the effect of previous treatments on AGR. This ANCOVA was applied when we found a significant correlation between mortality and AGR. We also looked at the correlations between AGR and size measurements of the saplings. Resprouted individuals were excluded from the analyses of AGR and final biometry measurements of the saplings. Our analytical unit was always the plot. Statistical analyses were performed with the SPSS (version 7.0) and STATISTICA (version 6.0) software packages (SPSS Inc., 1999; StatSoft Inc., 1984–2003).

3. Results

3.1. Sapling mortality and resprouting

The irrigation and artificial shading applied during the 3-year treatment period resulted in overall positive

Table 1
Results of the ANOVA used to test the differences in mortality and resprouting of planted seedlings under different combinations of previous summer irrigation and artificial shading

Source	d.f.	Mortality[a] (years 1–9)		Mortality[b] (years 4–9)		Resprout[c]	
		F	*P*	*F*	*P*	*F*	*P*
Summer irrigation	1	8.259	0.014	0.301	0.593	1.349	0.268
Artificial shading	1	20.779	0.0007	0.979	0.343	2.566	0.135
Irrigation × shade	1	8.838	0.0116	0.975	0.343	0.672	0.428
Error	12						
Model		12.625	0.001	0.751	0.543	1.529	0.26

[a] Total mortality counts including a 3-year treatment period and a 6-year post-treatment period.

[b] Mortality counts during the 6-year post-treatment period.

[c] The resprouting results refer to the 6-year post-treatment period.

effects on sapling survival after 9 years (Table 1 and Fig. 1). The total mortality counts were not significantly different between the irrigation, artificial shading, and combined treatment plots, and these plots had four times less mortality than the control plots (Fig. 1). Sapling mortality did not differ among treatment plots during the post-treatment period (Table 1 and Fig. 1).

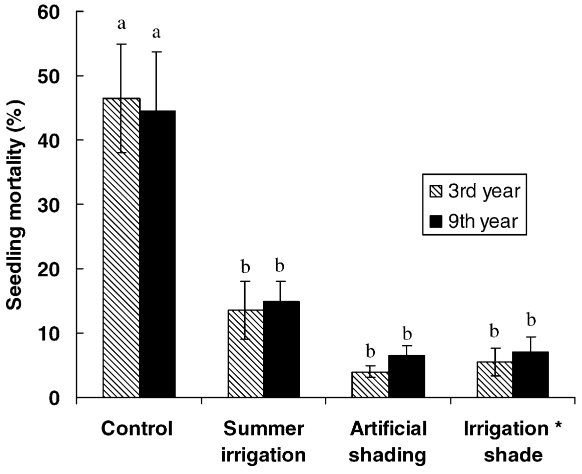

Fig. 1. Solid bars: cumulative mortality counts of planted *Q. ilex* saplings under different combinations of summer irrigation and artificial shading applied for 3 years and an additional 6-year post-treatment period. For reference, the figure includes the mortality counts at the end of the treatment period (stripped bars, Rey Benayas, 1998). Different letters mean statistical differences at $P = 0.05$ according to a Tukey's test. Note: mortality counts during the entire 9-year period is lower than mortality counts during the first three years in the control plots because resprouting outweighed additional mortality.

The percentage of apparently dead saplings at the end of the treatment period that resprouted during the post-treatment period was not statistically different among treatment plots (Table 1), even though a positive trend for more resprouting under previous artificially shaded plots must be noted. The values of resprouting in the different treatment plots were (mean ± S.E.)—control: 10.96 ± 3.15%; irrigation: 15.3 ± 6.06%; artificial shading: 20.8 ± 12.5%; and combined treatment: 45.8 ± 20.84%.

3.2. Sapling growth and plot cover

The results of the ANOVA used to test the differences in AGR among treatment plots indicate that, except for stem diameter, previous artificial shading decreased sapling AGR during the post-treatment period, whereas summer irrigation had little effect on all growth measurements (Table 2 and Fig. 2). AGR in stem diameter was not correlated with mortality ($r = 0.28, P = 0.3, n = 16$). However, AGR in height, CPA, and volume were positively correlated with mortality ($r = 0.6$ and $P = 0.013, r = 0.79$ and $P = 0.0001, r = 0.76$ and $P = 0.01$, respectively; $n = 16$), a density effect. When we introduced mortality in the models for AGR in height, CPA, and volume, the significance of the effect of artificial shading was reduced (height—ANOVA: $P < 0.0001$, ANCOVA: $P = 0.006$; CPA—ANOVA: $P < 0.0001$, ANCOVA: $P = 0.0015$; volume—ANOVA: $P < 0.0001$, ANCOVA: $P = 0.0019$; Table 2).

Over the entire period, the saplings did not differ among treatments for stem diameter and volume, and

Table 2
Results of the analyses used to test the differences in annual growth rates of the saplings during a 6-year post-treatment period after previous summer irrigation and artificial shading

Source	d.f.	Stem diameter[a]		Height[b]		CPA[b]		Volume[b]	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Summer irrigation	1	0.675	0.427	0.406	0.537	1.01	0.337	1.06	0.324
Artificial shading	1	1.239	0.288	11.74	0.006	17.441	0.0015	16.36	0.0019
Irrigation × shade	1	0.198	0.664	1.73	0.27	2.231	0.163	0.405	0.538
Error	11[c]								
Model		0.704	0.57	15.43	0.0001	16.763	0.0001	14.789	0.0001

[a] The analysis is two-way ANOVA.

[b] The analysis is ANCOVA that included mortality as a covariable.

[c] Twelve in the case of stem diameter.

the differences for height and CPA were only marginal (Table 3 and Fig. 3). Similarly, plot cover was little affected by the treatments (Fig. 4), and there was a significant interaction between summer irrigation and artificial shading (Table 3). The final biometry measurements of the saplings were positively correlated with their respective AGR except in the case of volume (stem diameter: $r = 0.69, P = 0.03$; height: $r = 0.57, P = 0.022$; CPA: $r = 0.55, P = 0.027$; volume: $r = 0.47, P = 0.07; n = 16$).

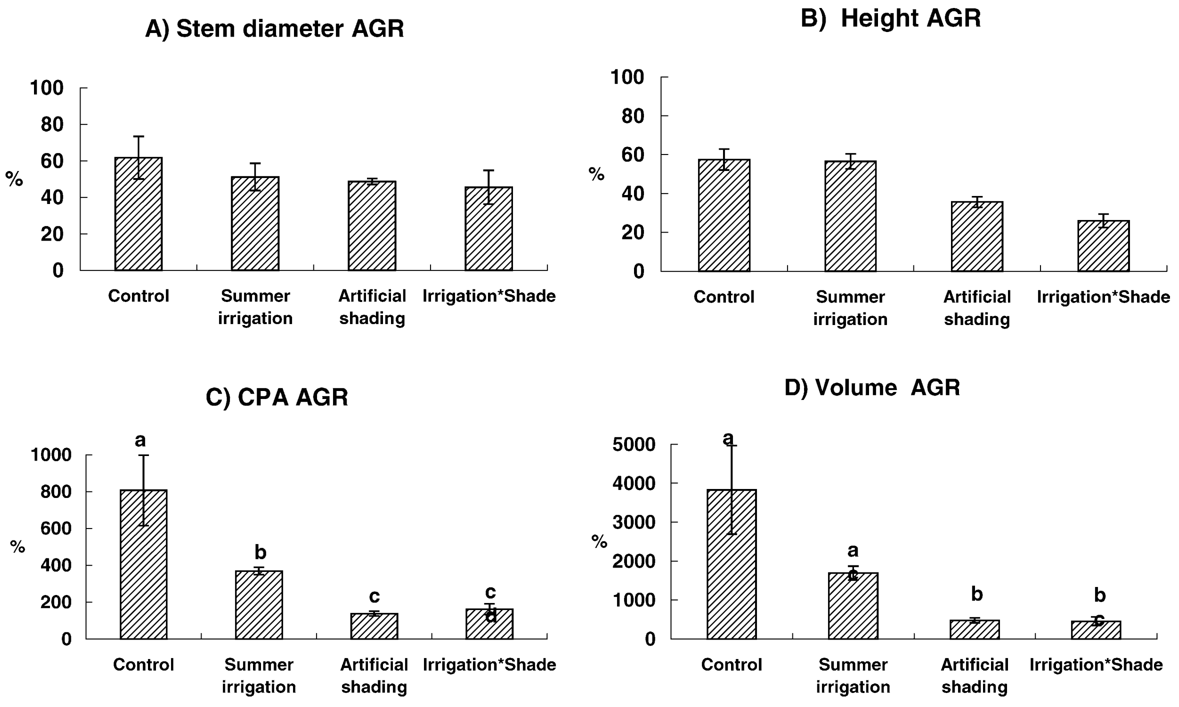

Fig. 2. Annual growth rate in (A) stem diameter, (B) height, (C) crown projected area (CPA), and (D) volume of planted *Q. ilex* saplings under different combinations of previous summer irrigation and artificial shading during the post-treatment period. When the ANOVA resulted significant, different letters above the bars indicate statistical differences at $P = 0.05$ according to a Tukey's test.

Table 3
Results of the ANOVA used to test the differences in the final biometry measurements attained by the saplings and plot cover under different combinations of previous summer irrigation and artificial shading

Source	d.f.	Stem diameter		Height		CPA		Volume		Plot cover	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Summer irrigation	1	0.229	0.641	0.613	0.449	0.155	0.701	0.059	0.812	0.539	0.4772
Artificial shading	1	2.137	0.170	2.136	0.170	6.198	0.029	3.207	0.099	0.322	0.5810
Irrigation × shade	1	1.689	0.218	4.691	0.051	1.373	0.264	1.624	0.227	6.544	0.0251
Error	12										
Model		1.352	0.3	2.48	0.11	2.575	0.1	1.63	0.23	2.468	0.11

3.3. Sapling reproduction

Sapling volume and the presence of acorns were correlated ($r_S = 0.41, P < 0.0001, n = 653$). The ANCOVA that included sapling size resulted in significant effects of previous artificial shading and the interaction of irrigation and shading on the percentage of reproductive saplings among treatment plots (Table 4). Previous summer irrigation and artificial shading favored the presence of reproductive saplings (Fig. 5).

Table 4
Results of the ANCOVA used to test the effects of previous summer irrigation and artificial shading and sapling size on the percentage of reproductive *Q. ilex* saplings

Source	d.f.	*F*	*P*
Summer irrigation	1	1.878	0.197
Artificial shading	1	8.118	0.016
Irrigation × shade	1	6.068	0.031
Sapling volume	1	8.951	0.012
Error	11		
Model		6.848	0.005

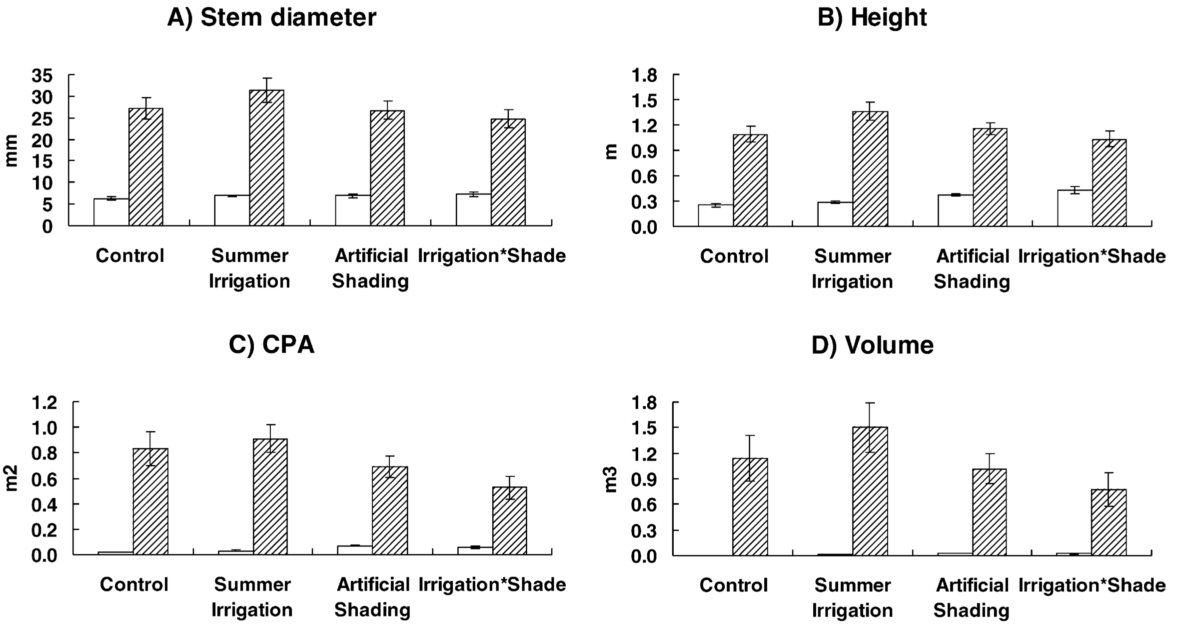

Fig. 3. (A) Stem diameter, (B) height, (C) crown projected area (CPA), and (D) volume attained by the planted *Q. ilex* seedlings under different combinations of previous summer irrigation and artificial shading. The biometry measurements represented by the solid bars refer to a 3-year treatment period and an additional 6-year post-treatment period. Tukey's tests did not detect differences at $P = 0.05$ among treatment plots after the treatment plus post-treatment period. For reference, stripped bars represent the biometry measurements at the end of the treatment period.

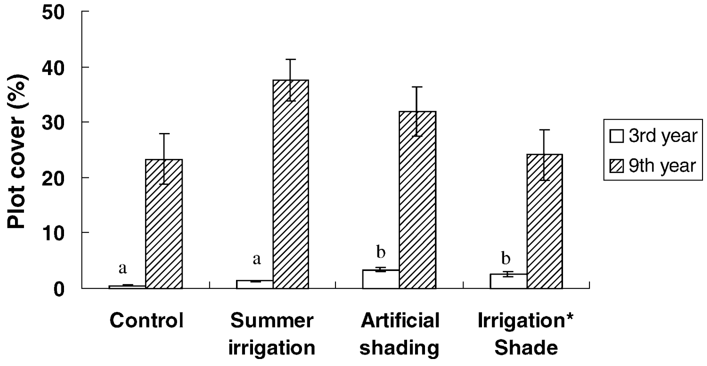

Fig. 4. Solid bars: plot cover by *Q. ilex* saplings under different combinations of previous summer irrigation and artificial shading applied for 3 years and an additional 6-year post-treatment period. For reference, stripped bars represent the plot cover at the end of the treatment period. When the ANOVA resulted significant, different letters above the bars indicate statistical differences at $P = 0.05$ according to a Tukey's test.

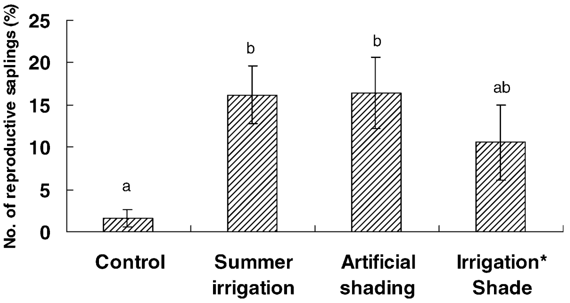

Fig. 5. Percentage of 9-year-old reproductive *Q. ilex* saplings under different combinations of previous summer irrigation and artificial shading. Different letters above the bars indicate statistical differences at $P = 0.05$ according to a Tukey's test.

4. Discussion

4.1. Performance of *Q. ilex* saplings is influenced by previous management practices

Overall, as predicted, our results indicate that the performance of introduced *Q. ilex* saplings in abandoned Mediterranean cropland is influenced by the previous environmental conditions created by management practices and, consequently, they responded differentially to climate stress. This result is in agreement with research on different species, growth forms, and ecosystem types, and for a variety of limiting environmental factors such as light, water, and nutrients (Ziegenhagen and Kausch, 1995; Sultan et al., 1998; Tognetti et al., 1998; Ryser and Eek, 2000; Valladares et al., 2000, 2002; Balaguer et al., 2001; Volis et al., 2002).

In response to the tested hypothesis, the saplings in plots that were managed to limit strong irradiance and water stress clearly performed better than the saplings in unmanaged plots during the treatment period (Rey Benayas, 1998), but the performance was not clearly better in response to later climate stress during the post-treatment period. Saplings that were acclimatized to different stress environments due to management practices exhibited similar mortality rates during the post-treatment period. Thus, previous environmental conditions did not affect later survivorship for a long period (O'Reilly et al., 1994; Villar, personal communication).

Growth rates were lower in previous less stressful environments due to artificial shading except for stem diameter. This result is further evidence that growth rates are flexible and usually regulated at optimal rather than maximal rates (Arendt, 1997). The reduction in above-ground growth may be a result of (1) previous management accelerated seedling development as compared to seedlings in control plots, and as a consequence of it, a trade-off between growth and reproduction could be observed, (2) a higher competition intensity between saplings, particularly for water, in previous managed plots, (3) an increase in below-ground growth, and (4) growth constraints determined by the previous environment. Since there were more reproductive saplings in previous irrigated or artificially shaded plots, independent of the size attained by the saplings across treatment plots, we conclude that the observed decrease in growth is a result of the capacity of *Q. ilex* saplings to adjust to environmental variation. This capacity has been reported for different traits related to morphology, anatomy, and physiology (Gratani, 1996, 1997; Castro-Díez et al., 1997; Gratani et al., 1997; Fotelli et al., 2000; Nardini et al., 2000; Crescente et al., 2002; Oliveira and Peñuelas, 2002).

Plants grow more slowly as they approach their maximum possible size. In our experiment, the final size measurements and AGR were positively correlated, and thus there is no evidence that age or development slowed down sapling growth except for a trade-off between growth and reproduction (McConnaughay and Coleman, 1999). The capacity to produce seeds was coupled with a diminished overall above-ground growth, and saplings in previous unmanaged plots took longer, on average, to reach the reproduction developmental stage. Other authors have shown different responses to environmental changes for different traits and trade-off between traits (Kudoh et al., 1996; Gunatilleke et al., 1997; Reekie et al., 1997; Ryser and Eek, 2000; Kaufman and Smouse, 2001; Relyea, 2002).

Two lines of evidence hint that part of the reduction in above-ground growth is a result of intra-specific competition between saplings: the overall positive correlations between growth and mortality, a density effect, and the drop in the significance of the previous treatment effects on growth when mortality was included in the AGR models. Thus, the current more stressful conditions in previously managed plots are both abiotic and biotic, saplings at the density studied here experience a stronger intra-specific competition for resources (Espelta et al., 1995; López et al., 1998).

The resources invested in above-ground growth under earlier less stressful environments due to management may have been later diverted to carbon storage and carbon-based defenses, enabling the saplings to utilize the resources more effectively when the environment became more stressful (Gratani, 1996; Leiva and Fernández-Alés, 1998; Estiarte and Peñuelas, 1999). This matches the observed lack of differences among treatment plots in diameter AGR, an attribute that has been shown to be related to carbohydrate storage and to root growth (Broncano et al., 1998; Cherbuy et al., 2001; Drexhage and Colin, 2001).

4.2. Long-term response of Q. ilex saplings

Independently of the ecological mechanisms that drive plant adjustment to their environments, managers must evaluate the success of different afforestation practices in terms of investment and benefits. Management decreased mortality only during the first year (Rey Benayas, 1998), and the benefits on above-ground seedling growth were to a large extent balanced out by the diminished growth rates when it was interrupted. After 9 years, the most significant result of management is the number of surviving individuals, mortality rates seem to be stabilized, above-ground growth was slower in early managed plots than in unmanaged plots, and plot cover was only marginally affected by summer irrigation and artificial shading. In the long run, this result suggests that it does not pay to manage plantations except for shortening the time that a given plot cover is attained. However, previous management provided a benefit in the proportion of saplings that are capable of producing seeds, and this was not related to sapling size.

5. Conclusions for management

Management is usually expensive and concentration of management reduces investment. Plots such as the ones assessed in this study may act as sources of propagules of *Q. ilex* in deforested agricultural landscapes thus aiding a later natural establishment of this species (Chambers, 2000; Robinson and Handel, 2000).

Since the first dry season was clearly a bottle-neck for the survivorship of the introduced seedlings, management of plantations during the first year only would likely provide a better investment/benefit ratio. Overall, artificial shading provided more benefits, i.e., plot cover, than summer irrigation during the treatment period. But in the long run, the benefits in plot cover and percentage of reproductive individuals tend to be approximately equal. These benefits were not added up in the combined treatment plots and thus we do not suggest to apply both treatments simultaneously. The use of artificial shading or irrigation should be based upon an analysis of the costs of each technique. Long experiments under field conditions like the one presented here will be very valuable to optimize resource investment in active restoration of Mediterranean abandoned cropland and other ecosystems of the world (Hooper et al., 2002).

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