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RESEARCH ARTICLE

Comparing Direct Abiotic Amelioration and Facilitation as Tools for Restoration of Semiarid Grasslands

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Abstract

Desertification can be an irreversible process due to positive feedback among degraded plant and soil dynamics. The recovery of semiarid degraded ecosystems may need human intervention. In restoration practices, the abiotic conditions often need to be improved to overcome the positive plant–soil feedback loops. Using nurse-plants to improve abiotic conditions for introduced individuals (facilitation) has been suggested as an alternative to direct abiotic amelioration. Here, we compared direct abiotic amelioration and facilitation as tools for restoration of semiarid grasslands in Spain. Seedlings and seeds of *Lygeum spartum* and *Salsola vermiculata* were planted and sown in a stably degraded semiarid area in Northeast Spain. Two levels of direct abiotic amelioration (ploughing and damming) and indirect abiotic amelioration through facilitation by *Suaeda vera* nurse shrubs were compared with a control with no amelioration treatment. The control treatment showed low plant establishment, confirming the practical irreversibility of the degraded state. Plant establishment was significantly higher in the three treatments with interventions than in the control treatment. The best treatment depended on the plant trait considered, but damming was in most cases better than plant facilitation. However, facilitation maintained the nutrient-rich topsoil layer. Given the relative success of facilitation, revegetation using the facilitative effect of nurse-plants would, in principle, be recommended for restoring semiarid grasslands. Direct abiotic amelioration would be needed under extreme degradation or harsh climatic conditions.

Key words: abiotic amelioration, desertification, facilitation, grasslands restoration, Middle Ebro Valley, nurse effect.

Introduction

Desertification is a serious threat for environmental conservation and sustainability of rural populations (UNEP 1994). It has been suggested that desertification can be an irreversible process, when the degraded state becomes stable (Rietkerk & van de Koppel 1997; van de Koppel et al. 1997; Rietkerk et al. 2004). Plant–soil interrelationships cause positive feedback loops (Rietkerk et al. 1997), as occurs when well-preserved vegetation cover maintains soil in good condition, which in turn allows vegetation to establish and survive. This positive plant–soil feedback also implies that reduced vegetation cover can lead to soil degradation, which in turn hampers plant establishment. Events such as overgrazing and drought can promote the shift between the vegetated and the degraded stable states (Rietkerk & van de Koppel 1997; Bestelmeyer et al. 2006; Kéfi et al. 2007) and the positive feedbacks might stabilize the degraded situation (Holmgren & Scheffer 2001). Once a degraded state is reached, initial conditions can often not be recovered without human intervention (Hobbs & Harris 2001). Restoration practices could help the ecosystem to reach the desired vegetated stable state (Hobbs & Harris 2001; Suding et al. 2004; King & Hobbs 2006).

Direct abiotic amelioration is a common reclamation practice for arid and semiarid ecosystems. The practices for abiotic amelioration include treatments that break and roughen the soil surface, create dams and microcatchments, and increase organic matter (Shachak et al. 1998; Suding et al. 2004). These treatments are carried out to increase water infiltration, minimize water and nutrient leakage, and reduce salt content and soil erosion (Shachak et al. 1998; Snyman 2003; van den Berg & Kellner 2005; King & Hobbs 2006). With these practices, soil conditions are improved and the feedback loop that maintains the degraded state stable is reversed, and plant establishment is enhanced. However, these techniques are often expensive, not always successful, and require substantial intervention in the ecosystem (Le Houerou 2000; Snyman 2003; Suding et al. 2004; Byers et al. 2006).

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Facilitation among plants is a well-known biotic interaction in arid and semiarid ecosystems (Bertness & Callaway 1994; Pugnaire et al. 1996; Holmgren et al. 1997). The use of facilitative interactions between a nurse-plant and the plant species of interest has been proposed as a successful restoration technique in arid and semiarid environments (Maestre et al. 2001; Padilla & Pugnaire 2006). Considering that the abiotic conditions are usually better under the vegetation canopy than in the bare soil (Schlesinger et al. 1996; Rietkerk et al. 2000), vegetation remnants can be employed as microenvironments with more suitable abiotic conditions, without the need of direct interventions (Byers et al. 2006). The successful use of facilitation by nurse-plants for restoration programs have been described in many arid and semiarid regions (e.g., Maestre et al. 2001; Huber-Sannwald and Pyke 2005; King and Stanton 2007). However, facilitative and competitive interactions between nurse-plants and seedlings occur simultaneously (Holmgren et al. 1997), and under some conditions, competition could exceed facilitation (Maestre et al. 2005). So, although the nurse effect is promising to be used to restore degraded arid ecosystems, more experiments are needed to determine whether, and under what conditions, the use of facilitation is an efficient technique when compared with direct abiotic amelioration.

The purpose of this study was to compare the effectiveness of direct abiotic amelioration and biotic facilitation as tools for restoration of semiarid ecosystems that show a stable degraded state. With this work, we aim to advance knowledge to enable the development of the best restoration practices for stably degraded semiarid ecosystems.

Methods

Study Site

The study was conducted in "El Planerón" Natural Reserve (Middle Ebro Valley, Northeast Spain). The reserve (700 ha) was founded in 1992 by SEO/Birdlife. The landscape is a mosaic of natural vegetation and croplands with organic cereal production and livestock grazing (mainly sheep) applied traditionally in the area. The reserve, with a semiarid Mediterranean climate, is located in the most northern semiarid area in Europe and one of the most arid areas in Spain. The mean rainfall at 258 m above sea level (asl) is 321 mm/yr and the mean annual temperature 14.7°C (average values of the period 1960–1991).

The topography is predominantly flat, and soils have high clay content, which leads to low infiltration capacity and surface accumulation of soluble salts. The natural vegetation has high ecological value. The main plant community is a steppe dominated by the perennial grass Gramineae (*Lygeum spartum* L.) with high species richness. The scrub Chenopodiaceae (*Salsola vermiculata* L.) abounds in areas at intermediate successional stages. The area was overgrazed for centuries, but more recently, human pressure has decreased due to rural depopulation and the sustainable management of the reserve. The current stocking rate in the reserve, estimated at 0.3 heads$\cdot$ha$^{-1}\cdot$yr^{-1}, is moderate. Although grazing is restricted in the areas with poor ecosystem conditions, many areas remain degraded, and a low capacity for vegetation recovery has been encountered. Plant establishment is impeded and only halophytes, such as Chenopodiaceae (*Suaeda vera* J. F. Gmel), survive under these conditions.

Experimental Design

The experiment was established in 2 ha of a degraded area inside the Planerón Natural Reserve (lat 41°22′33″N, long 0°36′42″W; 222 m asl). The experimental design consisted of two parts: one experiment with 4-month-old seedlings and one experiment with seeds of local provenance. In each experiment, four treatments were established: (1) the "plough" treatment: a mouldboard plough treatment applied on previously leveled field. This treatment increases soil surface roughness and macroporosity of the tilled layers but inverts the upper 30–40 cm of the soil profile, resulting in a transitory effect on soil physical characteristics (Moret & Arrúe 2007); (2) the "dam" treatment: linear microcatchments of 2–5 m wide were built, spaced a few meters apart. This technique reduces run-off and increases water and nutrient availability (Shachak et al. 1998) but is less severe than the tillage because it does not invert the upper soil profile; (3) the "nurse" treatment: soil conditions were not modified, and seeds and seedlings were located under the canopy of mature *Su. vera* nurse-plants; and (4) the "control" treatment: soil conditions were not modified, and seeds and seedlings were planted in the bare soil at least 1.5 m away from existing vegetation. Thus, the experimental design was composed by two kinds of direct abiotic amelioration commonly employed in restoration programs (plough and dam), one treatment of indirect abiotic amelioration by plant facilitation (nurse) and one treatment (control) where no abiotic amelioration was performed (Fig. 1a–c).

In the experiment with seedlings, we followed common restoration practices by digging parallel rows 4 m apart and around 50 m long in each treatment. We planted the seedlings along the rows every 2 m (Fig. 1d). In the dam treatment, the rows of seedlings were located in the spaces between the dams. In the nurse treatment, the seedlings were located underneath the nurse-plants selected, which were in all cases 1.5 m apart from each other. Altogether, 200 seedlings of *Sa. vermiculata* and *L. spartum* were planted (25 seedlings per plant species and treatment) in October 2006. The seedlings were grown in a greenhouse of the regional government from seeds of natural populations of the region. Seedlings of the two species were alternated to ensure the same treatment for both plant species. Survival was recorded in February (4 months after planting) and September 2007 (11 months after planting). Plant size was measured in December 2006 (considered the initial size), June 2007 (8 months after planting), and

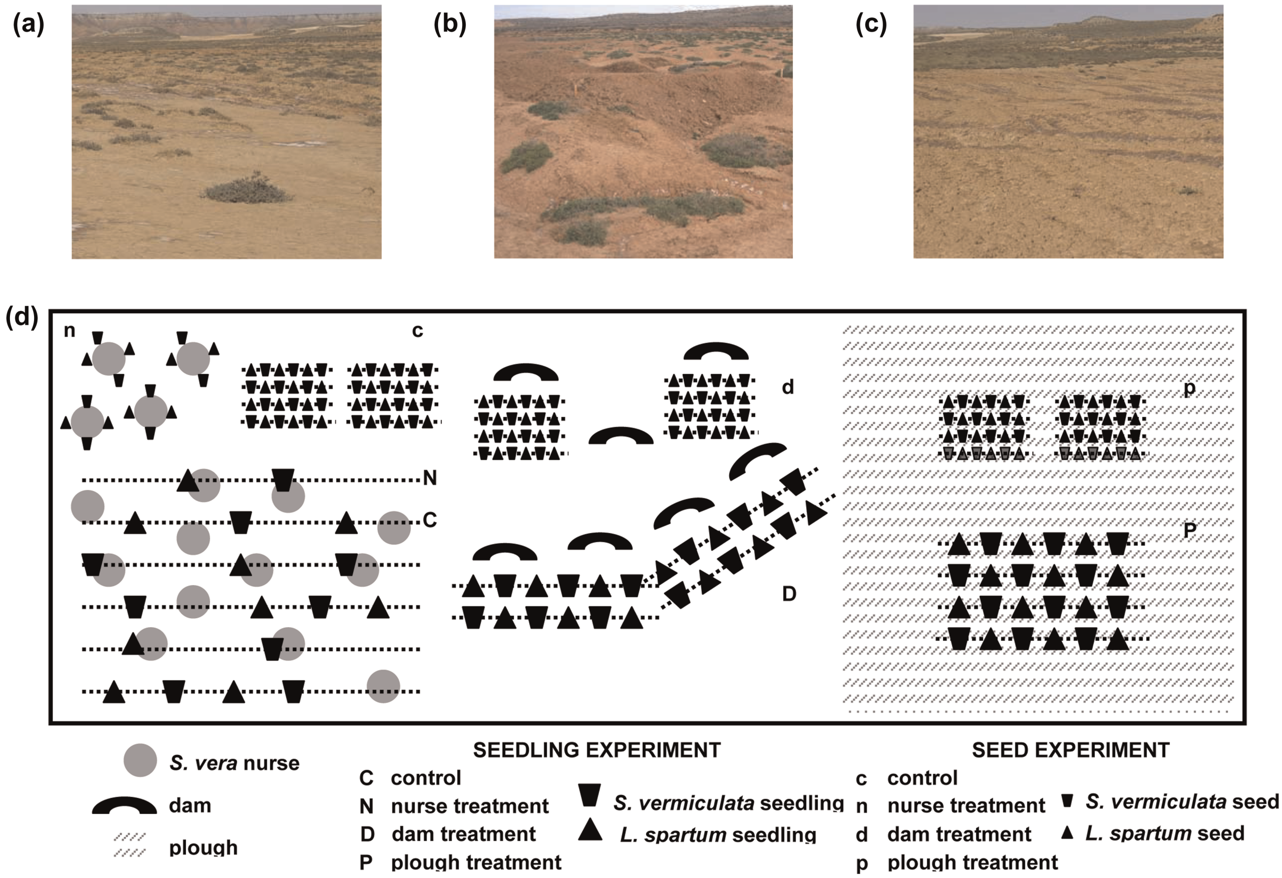

Figure 1. The study site prior to the start of the experiment; (a) control and nurse treatments, (b) dam treatment, (c) plough treatment, and (d) schematic diagram of the experiment. Sample size is larger than represented in the scheme (see text for details).

September 2007. The plant size parameter was the aboveground crown volume, a nondestructive estimate linearly related to the aboveground biomass (Bonham 1988). The crown shape of *L. spartum* was approximated to a cylinder, whereas the crown form of *Sa. vermiculata* was approximated to an inverted cone (Bonham 1988). The growth of each seedling was calculated as:

$$\text{Growth} = \frac{\text{crown vol}_{\text{end}} - \text{crown vol}_{\text{ini}}}{\text{crown vol}_{\text{ini}}}.$$

In February 2007, 800 seeds of *L. spartum* and *Sa. vermiculata* from local provenance were sown in the four treatments near the seedling experiment (100 seeds per plant species and treatment). The seeds were collected in May 2006 (*L. spartum*) and September 2006 (*Sa. vermiculata*) in El Planerón Natural Reserve and stored refrigerated in a controlled dry environment until sowing. Seeds were sown in lines, with a minimum distance of 20 cm between them (Fig. 1d). The location of every seed was recorded in a scheme to follow the germination, survival, and growth of every seed. Germination rate was recorded in March 2007. Survival and plant size were recorded in June and September 2007. For the seedlings recruited from seeds, the plant size was estimated with the plant height because the seedlings were too small to accurately measure crown volume.

Soil Analysis

To check for differences in soil properties among treatments, five soil samples (20 cm deep) were collected in February 2007 for each treatment (20 samples in total). Samples were dried and sieved (2 mm) in the laboratory. $CaCO_3$ content was calculated by Bernard calcimeter. We also estimated the pH in water 1:2.5, the electrical conductivity of the saturated soil paste extract, the organic matter content, the total N content (Elementar vario MAX CN; Hanau, Germany), and the C:N ratio.

Statistical Analysis

In the seedling experiment, the survival after transplanting (February 2007) and the survival at the end of the first year after planting (September 2007) were tested for dependence on treatment and plant species. We employed forward logistic regression introducing survival of individuals as the binary dependent variable and treatment and plant species identity as categorical independent variables. When survival of the two plant species was significantly different, the two plant species were analyzed separately using logistic regressions. Differences in growth in June and September 2007 for the surviving individuals among treatments and plant species were investigated with a two-way analysis of variance (ANOVA). In the seed experiment, we tested for significant effects of treatments and plant species on germination in March, survival in June and September, and height of individuals in June and September with the same statistical procedures as outlined for the seedling experiment. Soil variables were arcsine transformed to reach normality when required, and significant differences among treatments were tested using one-way ANOVA. When ANOVA was significant, a post hoc Tukey test was applied for statistical differences among groups with homogeneity of variances. When homogeneity of variances could not be assumed, the post hoc Games–Howell test (Games & Howell 1976) was employed. We performed the statistical analyses using SPSS 14.0 (SPSS 2005) and R 2.6.0 (R Development Core Team 2005).

Climatic Conditions During the Experiments

The year of this experiment (i.e., from October 2006 to September 2007) was wetter than 75% of years recorded (the rainfall at 258 m asl was 387.1 mm/yr, which was just above the upper quartile of the annual rainfall) and warmer than 75% of years recorded (the mean annual temperature was 15.3°C, located above the upper quartile). However, the monthly values show that the period from October 2006 to June 2007 was very warm (except December 2006). The rainfall in the fall 2006 was very low, whereas the spring 2007 and the beginning of summer were very rainy. Thus, the first 4 months after planting were unfavorable for plant establishment because of water scarcity by the combination of warm and dry conditions, whereas the next spring and summer were climatically favorable for plant establishment.

Results

Seedling Experiment

In February 2007, nurse and dam treatments had significantly higher seedling survival than the control. There were no differences between plough and control treatments at the same period. *Lygeum spartum* seedlings had significantly higher survival than *Salsola vermiculata* seedlings (Table 1; Fig. 2).

In September 2007, *L. spartum* had higher seedling survival than *Sa. vermiculata* (Table 1; Fig. 2). Because species had significantly different survival in February and September 2007, we analyzed the survival trend of each plant species separately. *Salsola vermiculata* survival in February 2007 in the dam treatment was higher than the survival in the control (Table 1; Fig. 2a). There were no significant differences between treatments when *Sa. vermiculata* survival in September 2007 was analyzed independently (Table 1; Fig. 2a). *Lygeum spartum* seedling survived in February 2007 was significantly higher in dam treatment than in control, nurse, and plough treatments (Table 1; Fig. 2b). The seedling survival trend maintained

Table 1. Seedling experiment.

	Survival																	
	All Seedlings						*Salsola vermiculata*						*Lygeum spartum*					
	February 2007			*September 2007*			*February 2007*			*September 2007*			*February 2007*			*September 2007*		
	$-2LL = 221.82$ (58)			$-2LL = 193.54$ (40)			$-2LL = 101.5$ (23)			$-2LL = 57.26$ (11)			$-2LL = 118.34$ (35)			$-2LL = 116.95$ (29)		
Effect	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*
Treatment	3	19.423	<0.001	3	7.256	0.064	3	7.732	0.052	3	5.011	0.171	3	12.370	0.006	3	6.163	0.104
Nurse	1	4.936	0.026	1	0.030	0.863	1	2.332	0.127	1	<0.001	0.998	1	2.717	0.099	1	<0.001	0.988
Dam	1	12.287	<0.001	1	1.083	0.298	1	6.076	0.014	1	<0.001	0.998	1	5.980	0.014	1	4.973	0.026
Plough	1	0.031	0.859	1	1.932	0.165	1	0.727	0.394	1	<0.001	0.998	1	0.922	0.337	1	0.247	0.619
Plant species	1	4.050	0.044	1	9.564	0.002	—	—	—	—	—	—	—	—	—	—	—	—

	Relative Growth					
	June 2007 (40)			*September 2007 (40)*		
Effect	*df*	*F*	*p*	*df*	*F*	*p*
Treatment	3,33	2.270	0.098	3,33	6.117	0.002
Plant species	1,33	2.210	0.146	1,33	2.575	0.118
Treat × plant species	2,33	2.633	0.087	2,33	2.203	0.148

Significance of nurse, dam, and plough treatments compared to the control. Significance of "plant species" indicates a greater survival of *L. spartum* with respect to *Sa. vermiculata*; number of surviving seedlings per analysis are given in parentheses; $-2LL = -2$ log likelihood.

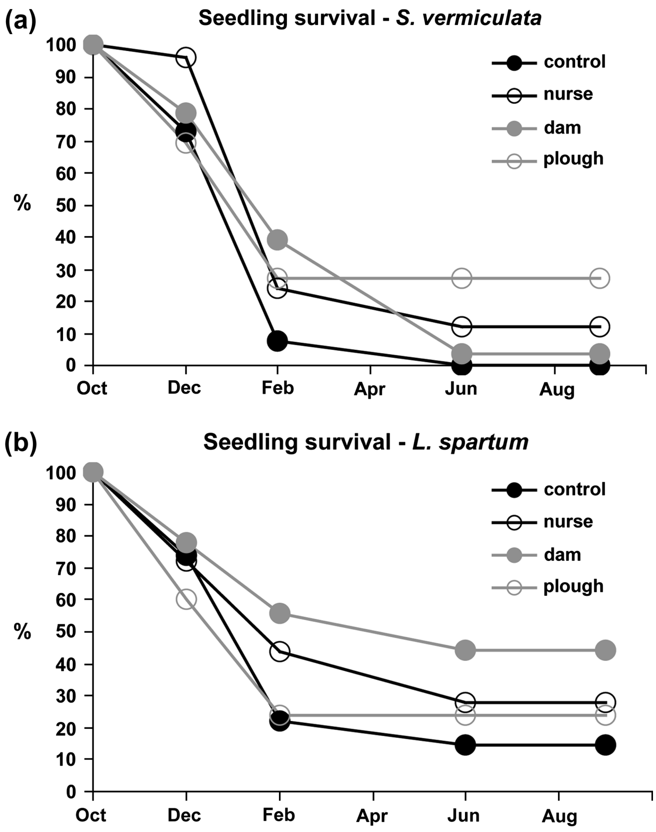

Figure 2. Seedling experiment; survival in the four treatments between October 2006 and September 2007; (a) *Salsola vermiculata* and (b) *Lygeum spartum*.

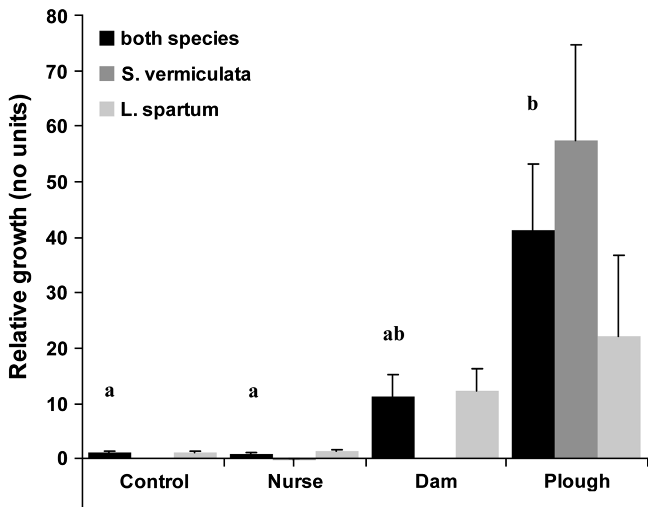

Figure 3. Seedling experiment; relative growth in September 2007 per treatment. Different letters indicate significant differences in the post hoc test between restoration treatments.

a similar difference among treatments during the whole study period (Table 1; Fig. 2b).

The seedling growth in June 2007 did not differ among treatments or plant species, and no interaction between treatments and plant species was found (Table 1). The seedling growth in September 2007 differed among treatments but not between plant species, and no interaction between plant species and treatments was found (Table 1). The post hoc Games–Howell test showed significantly higher growth in the plough treatment than in the control and nurse treatments (Fig. 3). The dam treatment had intermediate growth values, which were not significantly different from the other treatments.

Seed Experiment

The nurse and dam treatments positively affected seed germination (recorded in March 2007) compared to the control (Table 2; Fig. 4). In the plough treatment, zero germination was observed, and thus, this treatment was not included in the analysis. In addition, the logistic regression showed that there were no significant differences in germination between plant species (Table 2).

The seedling survival in June 2007 was not significantly different among treatments or plant species (Table 2). The logistic regression for the prediction of survival in September 2007 only included the plant species identity (Table 2), indicating that *L. spartum* had a higher survival rate than *Sa. vermiculata* (Fig. 4).

There were differences among treatments in the survival of *Sa. vermiculata* in September 2007 because only the seedlings of the dam treatment survived after the summer (Fig. 4a). On the contrary, *L. spartum* survival in September 2007 did not differ significantly among treatments (Table 2; Fig. 4a).

Plant height in June 2007 (3 months after sowing) was significantly different among treatments (Table 2; Fig. 5a) and between plant species (*L. spartum* grew more; Table 2; Fig. 5b), whereas the interaction between treatment and plant species was at the limit of significance ($p = 0.050$, Table 2). The post hoc Games–Howell test showed significantly taller plants in the dam than in the nurse treatment in June (Fig. 5a). The plant height in September 2007 (7 months after sowing) was significantly greater in the dam than in the nurse treatment (no plants survived in the control treatment; Fig. 5b), and the difference between plant species was not significant (Table 2).

Soil Analysis

There were no significant differences in $CaCO_3$ content and pH among treatments (Table 3), meaning that the parental soil was similar in the four treatments. Electrical conductivity was very high, indicating elevated salinity, but significant differences were not found among the four treatments. The organic matter and N content showed significant differences among treatments. The post hoc Tukey test showed that the nurse treatment had a significantly higher organic matter and N content than the control, plough, and dam treatments. Plough and dam

Table 2. Seed experiment.

	Germination			Survival											
	All Seedlings			All Seedlings						Salsola vermiculata			Lygeum spartum		
	February 2007			June 2007			September 2007			September 2007			September 2007		
	−2LL = 398.17 (72)			−2LL = 40.48 (62)			−2LL = 72.50 (35)			(7)			−2LL = 43.09 (28)		
Effect	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*	*df*	*Wald*	*p*
Treatment	3	19.206	<0.001	2	2.382	0.304	2	4.844	0.089	—	—	—	2	3.226	0.199
Nurse	1	14.090	<0.001	1	2.260	0.133	1	<0.001	0.999	—	—	—	1	0.816	0.366
Dam	1	18.616	<0.001	1	1.660	0.198	1	<0.001	0.999	—	—	—	1	0.051	0.821
Plough	1	<0.001	0.995	—	—	—	—	—	—	—	—	—	—	—	—
Plant species	1	2.212	0.137	1	<0.001	0.997	1	9.805	0.002	—	—	—	—	—	—

	Plant Height					
	June 2007 (60)			September 2007 (35)		
Effect	*df*	*F*	*p*	*df*	*F*	*p*
Treatment	2,54	15.903	<0.001	1,32	8.679	0.006
Plant species	1,54	56.826	<0.001	1,32	3.320	0.078
Treat × plant species	2,54	3.164	0.050	—	—	—

Significance of nurse, dam, and plough treatments with respect to the control. Significance of "plant species" indicates a greater survival and size for *L. spartum* with respect to *Sa. vermiculata*; number of surviving seedlings per analysis are given in parentheses; −2LL = −2 log likelihood.

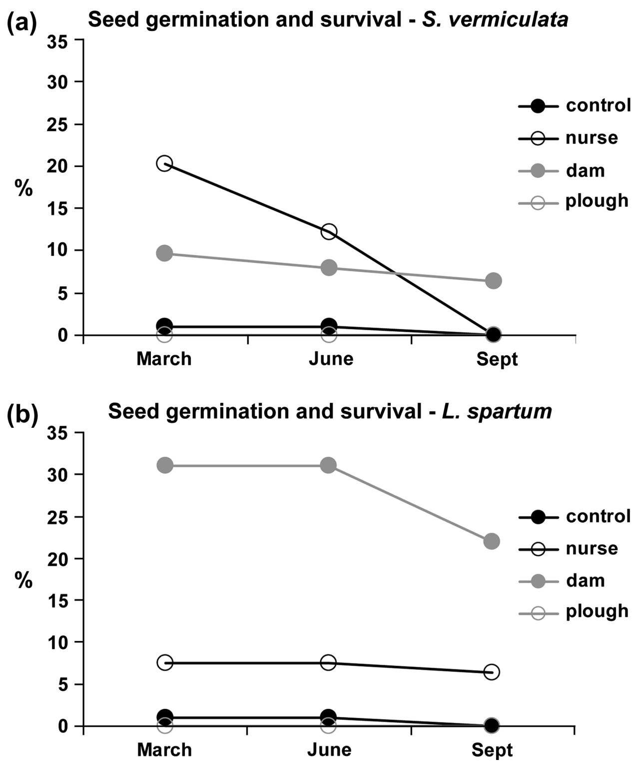

Figure 4. Seed experiment; germination (recorded in March 2007) and survival in June and September 2007 in the four treatments; (a) *Salsola vermiculata* and (b) *Lygeum spartum*.

treatments showed a significantly lower organic matter content than control treatment, and plough treatment had a significantly lower N content than the control treatment (Table 3).

Discussion

Our results showed the difficulty of restoring semiarid ecosystems when both vegetation and soil have been degraded. The success in plant establishment 1 year after the starting of the restoration experiment was low and variable (between 0 and 50%), depending on the treatment and plant species. Most of the mortality occurred in the first months after planting; a period previously reported as difficult for transplanted vegetation because it needs to adapt to the harsh conditions of the degraded ecosystem (Snyman 2003; Vilagrosa et al. 2003). Moreover, this particular period (autumn 2006) was particularly dry and warm, therefore with a large water deficit and this could have contributed to the high mortality encountered. The second half of the year had benign climatic conditions that corresponded with high survival and growth of transplanted plants. Our results confirmed the relevance of climatic conditions for the success of the restoration activities (Holmgren & Scheffer 2001). On the other hand, the control treatment had systematically the worst survival and growth results. This suggests that desertification might be practically irreversible implying that the recovery of degraded semiarid ecosystems requires direct or indirect (i.e., through facilitation)

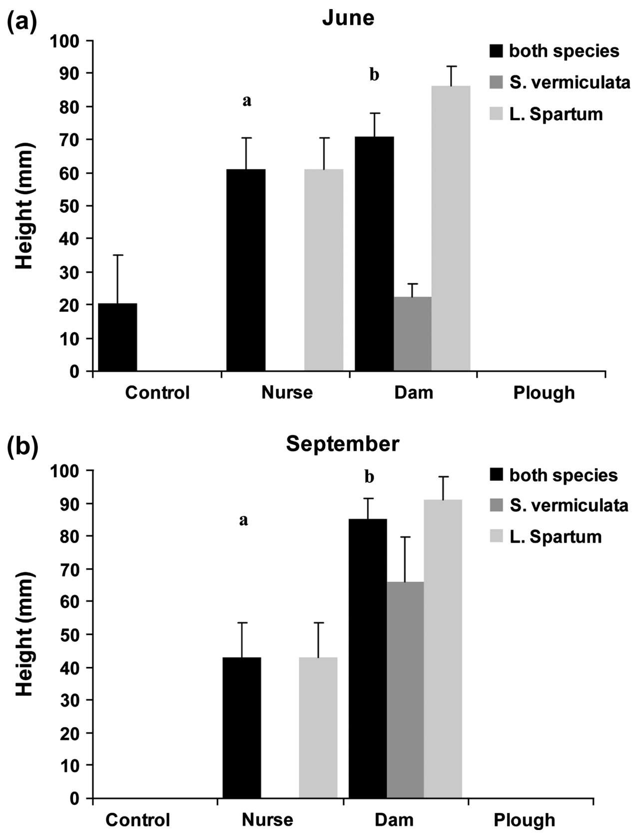

Figure 5. Seed experiment; (a) plant height in June 2007 per treatment, (b) plant height in September 2007 per treatment. Different letters indicate significant differences in the post hoc test between restoration treatments.

abiotic amelioration (Hobbs & Harris 2001; Byers et al. 2006; King & Hobbs 2006).

Direct abiotic amelioration can lead to success in restoration of arid and semiarid ecosystems (Yates et al. 2000; van den Berg & Kellner 2005). In our experiment, direct abiotic amelioration increased the survival and growth of introduced plants. In particular, the dam treatment gave consistently better results than the facilitation treatment. The clayey soils where the experiment took place are extremely hard and impermeable, and thus, the physical amelioration allowed plants to survive. However, soil analysis showed that salinity, extremely high in the clayey soils of the Middle Ebro Valley, did not decrease with treatments. In addition, the abiotic amelioration, which was expected to increase the water infiltration in the soil, had a secondary negative effect: the decrease in organic matter and nitrogen content due to the removal of the topsoil layer. This could explain the poor success of the plough treatment. The addition of organic matter together with the physical treatment of the soil to increase water infiltration could repair the loss of the topsoil layer caused by the direct soil treatment (Holmes 2001; van den Berg & Kellner 2005).

Nurse-plants facilitate juvenile plant establishment in arid environments by buffering environmental conditions, increasing nutrient and water availability and protecting the seedlings against grazing (Bertness & Callaway 1994; Pugnaire et al. 1996; Armas & Pugnaire 2005; Padilla & Pugnaire 2006). The direct applications of facilitation in the restoration of arid ecosystems are promising (Valladares & Gianoli 2007), and recently, restoration experiments have provided interesting guidelines for applying facilitation theory in practice (Maestre et al. 2001; Gomez-Aparicio et al. 2004; Huber-Sannwald & Pyke 2005). However, as far as we know, the direct comparison of facilitation and abiotic amelioration results on restoration success had not been addressed before. In our experiment, biotic facilitation appeared a successful technique to improve juvenile plant establishment in semiarid grasslands. Another advantage of facilitation as a restoration technique is the limited intervention on the ecosystem, which is always desirable for economic and ecological reasons. However, the results with the direct abiotic amelioration in the dam treatment were, in general, more successful. It could be concluded that facilitation had an intermediate success between the two abiotic treatments.

The interplay between competitive and facilitative effects among plants can change along an aridity gradient (Holmgren et al. 1997; Maestre et al. 2005). The dry and warm autumn 2006, when the experiment started, could have led to the shift from facilitation to competition between nurse-plants and juveniles (Maestre et al. 2005), explaining why the nurse treatment was less efficient than

Table 3. $\bar{X}$ ± SE of soil properties for each treatment and ANOVA results.

	Treatment					
	Plough	*Dam*	*Nurse*	*Control*	$F_{3, 16}$	*p*
$CaCO_3$ (%)	14.379 ± 0.200	15.512 ± 0.717	15.657 ± 0.264	15.234 ± 0.111	2.054	0.147
pH	8.734 ± 0.059	8.58 ± 0.137	8.476 ± 0.020	8.38 ± 0.078	3.210	0.051
EC (dS/m)	7.450 ± 0.657	4.464 ± 1.192	6.390 ± 0.478	5.83 ± 0.615	2.515	0.095
OM (%)	0.399 ± 0.037^{a}	0.332 ± 0.041^{a}	0.972 ± 0.065^{b}	0.638 ± 0.036^{c}	36.581	<0.001
N (%)	0.041 ± 0.004^{a}	0.043 ± 0.002^{ac}	0.096 ± 0.008^{b}	0.061 ± 0.005^{c}	26.451	<0.001

Values that do not have the same superscript letters are significantly different in the post hoc test. EC = electrical conductivity; OM = organic matter.

the direct abiotic amelioration for some measurements. This could also explain why plant growth was greater with the direct abiotic amelioration than with the facilitation by nurse-plants. On the other hand, we observed "islands of fertility" around vegetation patches in a similar way as found previously (Bochet et al. 1999; Maestre et al. 2001). In this experiment, we only observed the first-year effect of different treatments on restoration success. However, the fact that the nurse treatment preserved the nutrient-rich topsoil, whereas the direct abiotic amelioration destroyed it, suggests the possibility of long-term success of the nurse treatment, although more studies are necessary to disentangle the relative role of nutrient and water availability as limiting factors.

The selection of the nurse-plant species is an important decision in restoration programs. Here, we selected *Suaeda vera* based on the natural availability in the degraded areas, which allowed a desirable low intervention in the nurse treatment. However, we did not observe other plant species naturally established below *Su. vera* in the degraded area under study, despite the increment in organic matter and nutrients around it. This could be due to an insufficient soil amelioration of this plant species (Caravaca et al. 2005). Another explanation would be the propagule limitation hampering the spontaneous regeneration of a degraded area (Moore & Elmendorf 2006). Our study supports this last hypothesis, as *Su. vera* was a successful nurse-plant in this experiment. Clearly, the selection of the nurse-plant species requires careful evaluation in every study case, as generalizations about the expected results with a different nurse-plant species are not possible.

Interestingly, the results of the three treatments investigated were not always equal depending on the plant species, life stage, and measurement under consideration. The most remarkable case was the plough treatment that gave good results in 4-month-old seedlings, but seed germination was hampered in this treatment. This was probably due to the creation of a hard soil crust after ploughing (personal observation) that could impede seedling emergence. The plant species and life stage selected also appeared important to guarantee the success of plant establishment. *Lygeum spartum* was consistently better established than *Salsola vermiculata*, probably because *L. spartum* is quite tolerant of salty conditions (Pugnaire & Haase 1996). Moreover, *L. spartum* is a geophyte, which allows this plant species to survive with buds buried during unfavorable climatic conditions.

We achieved greater restoration success with seedlings than with seeds (20% of seedlings and 4.3% of seeds survived at the end of the experiment). The early stages of plant life are extremely difficult in arid or degraded environments (Barbera et al. 2006). By introducing seedlings, the crucial limiting stage is surpassed, and the restoration process increases the chances of success. As a consequence, the use of seedlings of well-adapted plant species would be recommended for the restoration of semiarid grasslands. Finally, it is necessary to stress that this study focused on the success of restoration at plant establishment (i.e., the first year after seed sowing and seedling planting). Although establishment is the most critical stage for plants in arid and semiarid environments, where most of the mortality occurs, the long-term success of the different treatments and plant species cannot necessarily be predicted from the establishment stage. The ideal management of a restored area would include periodic evaluations in the years following plant survival.

Implications for Practice

- Restoration of semiarid grasslands with a stable degradation state can be achieved by using either direct abiotic amelioration with dams or facilitation by nurse-plants. The latter method is preferred because it retains the fertility islands and is more economic and less intrusive than the former.
- Soil modification in direct abiotic amelioration can have positive and negative effects: it can increase water infiltration but decrease organic matter. Moreover, soil salinity is not improved in the short term.
- Seedlings can give better results than seeds in the restoration experiment because they are less dependent on the climatic and abiotic conditions.
- In the specific semiarid grasslands studied, the autochthonous end-successional perennial grasses give better results in restoration than the midsuccessional scrubs.

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