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Abstract:

Restoration ecology aims at recovering ecosystems that have been damaged, degraded or destroyed. In drylands, restoration commonly involves the establishment of a protective plant cover which will reduce ecosystem vulnerability to disturbances and stress. In the last decades, substantial advances have been made to improve plantation success by selecting suitable species and genotypes, producing high quality nursery seedlings, creating favourable microhabitats for seedling establishment, managing biotic interactions, and landscape-scale planning. Here, we review some of these advances and discuss some of the challenges ahead.

Key words: ecological restoration, water use efficiency, state and transition models, ecotechnology, facilitation

1. Introduction

Concerns over the state of dryland forests and woodlands and their capacity to provide services have prompted reforestation efforts worldwide. Historically, reforestation programs were aimed at increasing wood production and controlling hydrological flows. But throughout the 20th century, other uses were gradually taken into account, including the restoration of ecosystems. Restoration ecology is an emerging field of knowledge aimed at promoting the recovery of an ecosystem that has been degraded, damaged or destroyed (SERI, 2004; **Fig. 1**). It represents a natural link between ecological theory and practice (i.e., ecological restoration), and as such, it has been termed the acid test for ecology. The aims of ecological restoration for drylands are basically coincident with ecosystem-level actions to combat desertification.

There have been substantial improvements in the success and efficiency of ecological restoration in the last decades. In this text, we review some of these advances and identify some areas where further knowledge is needed. First, we discuss the objectives of ecological restoration within the framework of water use and drylands management. Then, we describe technological advances to improve restoration success from genetic individuals to ecosystems.

2. The objectives of ecological restoration

There are two major outcomes of the definition of ecological restoration. On one hand, it requires some sort of intervention. On the other hand, ecological restoration involves the identification of target or reference ecosystems; these are particular combinations of species and functions that society considers worth recovering. But can we identify and characterize reference ecosystems in drylands? Or else, should ecological restoration forget about reference ecosystems and rather focus on the recovery of particular ecosystem traits?

The identification of reference ecosystem, as other aspects of ecological restoration, is strongly conditioned by the social and cultural context. For example, ecosystems are dynamic, and thus the identification of a reference ecosystem is heavily dependent on the temporal and spatial scale considered. In drylands where European colonization is relatively recent, there is some consensus on valuing pre-European settlement ecosystems as targets for restoration, and substantial efforts have been directed towards using historical records, herbarium specimens, palaeoecological evidence, etc. to characterize them (SERI, 2004). But drylands have carried humans for millennia (Reynolds et al., 2007; Carrión et al. 2001). Anthropogenic activity have shaped, and sometimes degraded, ecosystems for a long time, and thus it is not always obvious that historical records, when available, can be used to target reference ecosystems. Extrapolation from refuges, a common procedure for phytosociologists, is not straightforward, as the conservation of relatively undisturbed habitats is frequently associated with particular soil and microclimatic conditions, and unique land use histories, which can hardly be generalized. In addition, restoration must plan decades ahead. Mid 21st century climatic conditions and disturbance regimes will likely differ from the current ones (Williams et al., 2007). Thus current reference ecosystems may become unsustainable in the next future. How to cope which such uncertainty? To be practical, we suggest that restoration should focus on the recovery of particular ecosystem properties, such as resistance and resilience to disturbances, which are especially relevant for the maintenance of ecosystem functions and services, including those related to water use.

Ecosystems can change after disturbance following disparate successional trajectories. Communities resulting from these trajectories may be relatively stable at a time scale of decades or centuries. Thus, several alternative pseudo-climacic communities, as an alternative to a single climax, are likely to result from disturbance under a given combination of soil and climatic conditions. These dynamics are well described by state and transition models (Westoby et al., 1989; **Fig. 2**). They are extremely useful for planning restoration as, ideally, they identify suitable targets for ecological restoration, trajectories to reach them, and mechanisms to promote changes (Yates and Hobbs, 1997).

State and transition models have been typically based on ecosystem structure, including biotic structure or biodiversity, with a few exceptions (Whisenant 1999). Merging them with information on the functionality, goods and services supplied by each state provides a useful framework to guide management practices (Cortina et al., 2006). Scorecards and expert judgment can then be used to prioritize ecosystem services related to water supply and quality.

Ecosystem traits are not the only criteria to identify restoration objectives, and usually not the most important. The short history of restoration ecology, including the naissance of its self-conscious practice in North America, shows that socio-economic and cultural drivers have been historically more important than ecological ones. Unfortunately, this observation is still valid in many dryland areas nowadays. Socio-economic drivers should not be perceived as a constrain, but rather as an opportunity, or an essential part of integrative ecosystem management. Coupled human-natural systems for biocomplexity (Callicott et al., 2007) and participatory approaches (Moote and Lowe, 2008) hold promise for understanding the complexity of the interactions, reduce conflict, increase our capacity for joint problem-solving, improve information exchange and collective learning, and finally generate more innovative and effective outcomes. At the dawn of the 21st century, restoration ecologists working in drylands face three major challenges: (1) to improve our knowledge on ecosystem dynamics needed to build informed state and transition models, (2) to identify feasible techniques that may direct succession towards a desired state, and (3) to create synergistic outcomes from different, and sometimes opposed interests.

In the context of state and transition models, transitions from degraded to target states may involve a diversity of specific objectives and actions, such as the introduction of species of interest, the suppression of unwanted species, and the creation of particular physical and biological structures. But actions aimed at increasing ecosystem resistance and resilience against disturbances and stress should receive highest priority in drylands. This can be achieved by ensuring a certain amount of protective plant cover, and improving the quality of such cover. But plant establishment in drylands is, by definition, strongly limited by water. Substantial efforts have been made in recent years to optimize water use is plantations at a range of scales, from individuals to ecosystems. We review some of these advances following a chronological sequence from species and genotype selection to plant production and field plantation techniques.

3. Options to optimize water use in dryland plantations

Selection of species and genotypes

Restoration has emphasized the use of local species and genotypes, as restoration seeks the recover of indigenous ecosystems (SERI, 2004). Another reason to prioritize native species is their adaptation to local conditions. However, this may not hold true when climatic changes are taken into account (Bakkenes et al., 2002). Drylands have experimented record high temperatures and drought in the last decades (De Luis et al. 2000). In some areas, these conditions have proven too extreme for some species, resulting in massive dieback (Peñuelas et al., 2001; MKenzie et al., in press). Extreme climatic events do not affect all species and all areas homogeneously. Species which are closer to its climatic limits may be more vulnerable to them. Species from sclerophyllous shrublands originating from Tertiary laurophyllous forests that adapted to dry climates may be particularly sensitive to changes in precipitation amount and distribution (Valladares et al., 2004). Valiente-Banuet and colleagues (Valiente-Banuet et al., 2006) have shown that they are more dependent on facilitation than Quaternary species, suggesting that the former may be less able to cope with increasing aridity than the later. In contrast, Peñuelas et al. (2001) found that Tertiary species were able to withstand the extreme 1994 drought in E Spain better than Quaternary species, although higher size probably conferred higher resilience to them.

Inability of native species to cope with extreme drought does not mean that alien species may thrive under these conditions. But it warns us on the need to find out if current flora will be capable of adapting to future climatic scenarios, and especially, to determine if vital ecosystem functions will be sustained. Despite the importance of this topic for restoration, tools for predicting future species distribution have been scarcely used by restoration practitioners (Harris et al., 2006).

Exotic species may play a role in ecological restoration, provided that they fulfill some requirements, particularly a low risk of naturalization (Ewel and Putz, 2004). They have been extensively used in drylands, where priority was given to the production of forage, firewood and other forest products (Dumancik and Le Houérou, 1980; Forti et al., 2006). But the use of exotic plantations as a restoration tool in these areas has received less attention.

Genotypes may also differ in their ability to withstand drought. For example, our studies on *Quercus suber* showed that water use efficiency (WUE, the capacity to fix C per unit of transpired water), in well watered seedlings ranged from 1.1 to 8.5 umol CO_2 mmol H_2O^{-1} (**Fig. 3**). If these differences were maintained, seedlings from a highly efficient family would transpire on average 7.7 times less water to produce the same amount of organic matter than less efficient seedlings. These results illustrate the variability of seedling traits and responses to stress in open wind pollinated trees such as *Q. suber*. But should we target highly efficient genotypes in restoration to reduce transpiration fluxes? The answer is not straightforward. First, it is unsafe to extrapolate results from individuals to a forest scale. Many other factors, in addition to instantaneous water use efficiency, affect whole ecosystem efficiency and watershed dynamics. Second, seedlings selected for WUE could show undesirable traits, such as low capacity to withstand drought. In the previous study, *Q. suber* seedlings responded differently to drought, some families increasing and others decreasing WUE (**Fig. 3**). Third, plant traits and ecological niches may change along ontogenetical development (Mediavilla and Escudero, 2004; Schupp, 1995). Finally, ecological restoration may have multiple aims, in addition to water production, and morpho-functional traits should adapt to them (**Table 1**).

<u>Nursery practices</u>

Plantation establishment and long-term performance, hence the capacity to withstand drought in drylands, are heavily dependent on seedling quality and management (Cortina et al., 2006). Thus, regulations on quality of woody seedlings have been recently adopted by public administrations (e.g., CE Directive 2006/21/CE, Spanish government RD 289/2003, Regional Government of Valencia Order 19/02/1997). These regulations ensure minimum levels of seedling quality. However, within the ranges defined by legislation and common practice, it is not clear which morpho-functional traits are associated with higher plantation success. A recent review of this topic for Mediterranean species showed that generalizations on the relationship between seedling performance and seedling size, biomass allocation belowground or nutrient content are difficult (Navarro et al., 2006). This is not unexpected, as seedling performance may be strongly dependent on species strategy and site conditions. However, there is some consensus on the need to produce plants with plenty of carbon, nutrients and water reserves, and fully operational photosynthetic machinery, which can readily colonize the soil after planting. Plant's ability to colonize the soil and reach deep soil horizons that may store water during seasonal drought is crucial for the survival of seedlings and adult trees of some species (Otieno et al., 2006; Padilla and Pugnaire, 2007)

Recent advances in nursery practices have incorporated protocols to reduce water consumption. These include efficient water-saving irrigation systems, water recycling, late seeding and using pregerminated seeds to reduce the time spend in the nursery, and reducing the amount and frequency of watering to precondition seedlings to drought. When successful, the latter have the advantage of producing high quality seedlings while saving substantial amounts of water.

The widespread use of growing media based on sphagnum peat represented a crucial step towards standardizing seedling production and improving their quality, and hence this type of substrates has become very popular in forest nurseries. But peat shows some drawbacks including high hidrophobicity when dry, as well as concerns on the sustainability of peat harvesting and long distance export. There have been many attempts to develop alternative substrates in the last years, such as composted bark and coco-peat, although peat continues to be the reference substrate in many regions. Following more strict regulations on peat harvesting, raising transport costs and climatic changes, we suggest that peat will gradually be substituted by substrates developed from local products, including composted sewage sludge and wood and bark refuse.

Creating rootable soil

Once in the field, efforts are directed towards creating a suitable environment for root colonization and resource capture. Past efforts to modify the hydrology of entire catchments have proven expensive and inefficient, and have frequently confronted social rejection. Machinery for soil preparation is now more efficient in improving soil conditions with minimum impact to extant vegetation, geomorphology and slope function. In addition, numerous techniques, some of them developed centuries ago, are being used to retain runoff water and conserve moisture.

The application of organic amendments can also help to establish plants. Planted seedlings can be limited by soil resources as degraded soils are frequently low in soil organic matter, nutrients and water storage capacity (Valdecantos et al., 2006). Sewage sludge and urban solid refuses have been successfully used to improve seedling growth (Valdecantos et al., 2004; González-Barberá et al., 2005), and prescriptions on efficient and safe application of these organic amendments are currently available (Bailly et al., 2004; Valdecantos et al., 2004). The interactions between plant nutritional status and water use are complex and generalizations difficult (Trubat et al., 2006); however, recent studies on adult *Pinus halepensis* show that organic amendments may improve water use efficiency as a result of enhanced nutritional status (Querejeta et al., 2008). Organic amendments can have negative effects on seedling performance because of increased salinity, soil cracking and increased competition with extant vegetation. These factors may explain why most studies report negative to no changes in seedling survival after sewage sludge application. Thus, organic amendments can be useful when fast seedling growth is a priority.

Improving microhabitat conditions

Seedling performance can be impaired by excessive radiation and temperature. Many types of treeshelters are currently available for this purpose (Bellot et al. 2002; Oliet et al. 2003). Ventilation is needed to avoid excessive temperatures, allow transpiration and keep atmospheric CO_2 concentrations high (Bergez and Dupraz 2000; Jiménez et al. 2005). Treeshelters may promote winter freezing as minimum winter temperatures can be slightly lowered inside them (Oliet et al. 2003; Jiménez et al. 2005). Shade provided by treeshelters enhance photoprotection and reduce photoinhibition. It is not clear to what extent seedlings acclimation to the relatively mild conditions inside treeshelters may hinder their capacity to withstand drought once shelters are overgrown or removed. For example, a reduction in the amount of belowground biomass in protected seedlings has frequently been observed, which may cause an unbalance between absorbing and transpiring tissues.

Piled branches attached to the soil can be an affordable alternative to provide shade and create a suitable microhabitat for seedling establishment (Ludwig and Tongway, 1996). Although they may not be so efficient in capturing radiation than artificial treeshelters, they have some advantages. A heterogeneous radiative environment and sunflecks may resemble natural conditions and allow gradual acclimation to full sunlight. In intimate contact with the surface soil, branches may retain resources transported by runoff and wind. Finally, branches contribute to improve soil fertility as they decompose.

Interaction with other organisms

The use of interspecific interactions is one of the fastest developing areas of dryland restoration. The recognition of the importance of extant communities and remaining functions in degraded ecosystems and the interest in conserving them, fostered studies on the use of biotic interactions in restoration. This trend has been supported by an increasing knowledge on positive ecological interactions (Azcón and Barea, 1997; Callaway, 2003; Maestre et al., 2001; Gómez-Aparicio et al., 2004). It is worth mentioning that facilitative interactions were well incorporated in traditional knowledge. For example, in early 20th century cereal crop lines, grasses and branches were used to shadow seedlings in E Spain (Mira-Botella, 1929).

It is not clear that facilitative interactions are more common in drylands than in mesic areas (Maestre et al., 2005). But sometimes the performance of seedlings planted in the vicinity of nurse plants in areas experimenting seasonal drought can increase dramatically (see for example Maestre et al., 2001 and Gómez-Aparicio et al., 2004). Studies by Valiente-Banuet et al. (2006) show that this type of interaction represents an essential part of plant's strategy to withstand stress.

In parallel with the study of plant-plant interactions, there has been increased interest in using other types of interactions to improve plant establishment in drylands. The use of mycorrhizal fungi is probably the more widely tested and developed. Mycorrhization with selected species and strains often improves seedling performance, including seedling capacity to withstand drought (Querejeta et al., 2003; Querejeta et al., 2007), and it may be of interest when seedlings are planted in areas where fungal propagules are absent (**Fig. 4**). Variability and uncertainty of the effects of controlled mycorrhizal inoculation and the difficulty in implementing efficient and reliable nursery protocols for inoculation at a management level suggest that this technique should be improved further before being incorporated into commercial nursery production.

Animals play a key role in community dynamics and ecosystem functioning in drylands. Some studies suggest that interactions with animals can be used to foster restoration. These include the use of artificial perches to encourage the visit of seed-dispersing birds (Zanini and Ganade, 2005), the introduction of soil fauna and organic amendments to improve soil properties (Roose et al., 1999), and the application of cyanobacteria, watering and compost to foster the development of biological soil crusts (Maestre et al., 2006).

Despite claims on the need to incorporate positive interactions in restoration at a management scale, most information on this topic comes from experiments. The shift from experiments to management is not straightforward. First, studies on facilitation between plant species commonly compare survival and growth rates of seedlings planted in open areas and in the vicinity of presumed nurse species. Soil preparation is minimum, to keep the resource island effect undisturbed. But minimum soil preparation may compromise seedling ability to reach deep soil horizons before the onset of summer drought, and can not be recommended as a regular practice. Second, some species – e.g., rockroses (*Cistus* sp.), have consistently negative effects on the establishment of other plants (Gómez-Aparicio et al., 2004; Pérez-Devesa et al., 2008). Thus, practitioners should be formed on the identification of these species and take time to avoid them in the field, thus increasing plantation costs. Third, mechanization becomes more difficult, which may also increase costs in some countries. Fourth, nurse species are not always present. Finally, drivers of positive interactions, such as shadow and increased soil fertility, can be mimicked by technological tools such as treeshelters, organic amendments and mulches which may be more affordable and operational. There is a great potential for improvement in the use of species interactions. A deeper knowledge on the outcomes and drivers of these interactions, and on the ways to incorporate them into management programs will contribute to improve restoration success in drylands.

Beyond individuals

The establishment of plant cover affects community composition and ecosystem function. In general, the increase in plant cover promotes transpiration losses and thus may generate less runoff and deep seepage water. But the significance of this effect is heavily dependent on the type of cover. In a modelling exercise, Huxman et al. (2005) suggest that the effect of woody vegetation colonizing grasslands depends on average precipitation. South African shrublands provide dramatic examples of the effect of tree colonization on the water balance of native shrublands (Le Maitre et al., 2002). It also emphasizes the importance of species selection, unexpected outcomes and adaptive management in restoration programs.

The spatial distribution of plant cover may also play a relevant role in restored watershed function. Unfortunately, available information on this topic is scarce. Recent studies have shown that the magnitude of open spaces –i.e., where resource flow originates, is directly related to slope scale runoff and erosion (A. García-Mayor, University of Alicante, unpubl. data). Kéfi et al. (2007) suggested that size classes of vegetated patches in undisturbed semiarid ecosystems follow a power law distribution, and departures from this distribution are associated with overuse.

Effects of restoration actions on community composition and ecosystem function can not be directly extrapolated from lower levels of organization (Ludwig et al., 2000). Larger scales incorporate new factors and emergent properties, generating non-linear responses as size is increased.

Watershed scale patterns and processes have major implications on restoration objectives and planning. Hopefully, as their importance is emphasized, they will gradually be incorporated into restoration programs.

4. Concluding remarks

Ecological restoration has the potential to increase natural capital in drylands and contribute to combat desertification. The theory and practice of ecological restoration have substantially improved in the last decades, and this improvement has been responsible for the increased success of restoration actions. Despite the uncertainty of future conditions, including changes in climate and land use, ecological restoration can help to make drylands less vulnerable to unfavorable events. Future challenges in this area include a better understanding of community dynamics and large scale processes, and higher permeability between ecological and human systems. In this context, ecological restoration should play a key role in water management and policy.

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Table 1. Plant morpho-functional traits contributing to specific restoration objectives. Items 1 to 4 are directly related to water production and quality. Modified from Cortina et al. (2006).

RESTORATION OBJECTIVE	**PLANT TRAITS**
1. Hydrological control	High cover, water use efficiency, high infiltration
2. Soil protection	High growth rate, horizontal growth, early and high reproductive output, vegetative reproduction
3. Genetic diversity, phenotypic plasticity, avoid inbreeding depression	Diversity of genotypes, provenances
4. Resistance to adverse current and future stress	Phenotypic plasticity, morpho-functional traits associated with resistance and resilience against drought, freezing, contamination
5. Ecosystem resistance and resilience against disturbances	Sprouting capacity, high relative water content, serotiny, persistent seed bank, defense against pests
6. Sustain herbivore populations	High palatability, tolerance to browsing
8. Sustain populations of fruit and seed-eaters	Prolonged production of high quantities of high-quality seeds and fruits production
9. Improve soil fertility	High productivity, nitrogen fixation, fibrous rooting systems, deep rooting systems
10. Ecosystem engineering, niche construction	Traits associated with changes in the flow of water, radiation and nutrients, structural complexity
11. Production of forest goods	High growth rate, low taper, straight trunks, low ramosity, high quality wood, production of resin, turpentine, melliferous species and varieties
12. Aesthetics	High/low growth rate, shape, chromatic changes, production of flowers and fruits

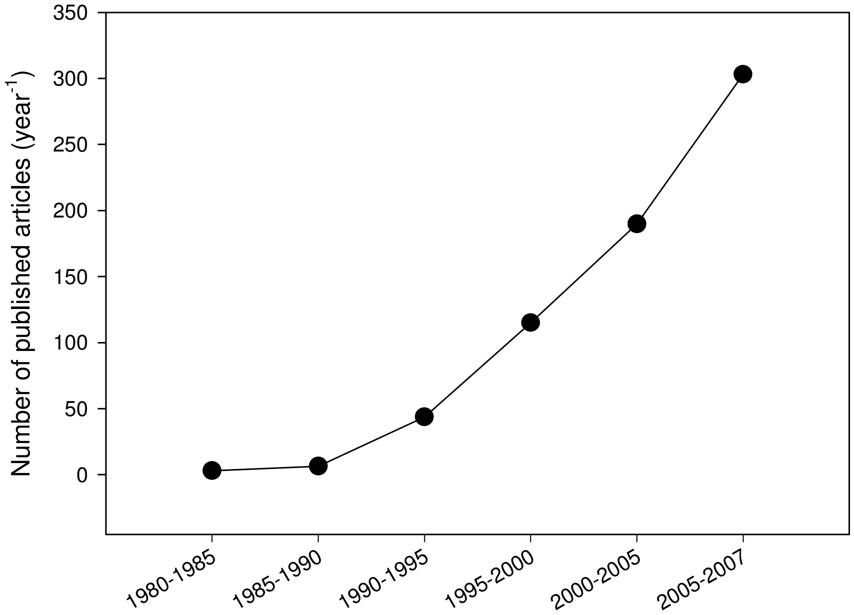

Figure 1. Number of published articles containing the terms 'restoration ecology' or 'reforestation' in the title (From ISI Web of Knowledge - Science Citation Index accessed on January 09 2008; modified from Cortina et al., 2008).

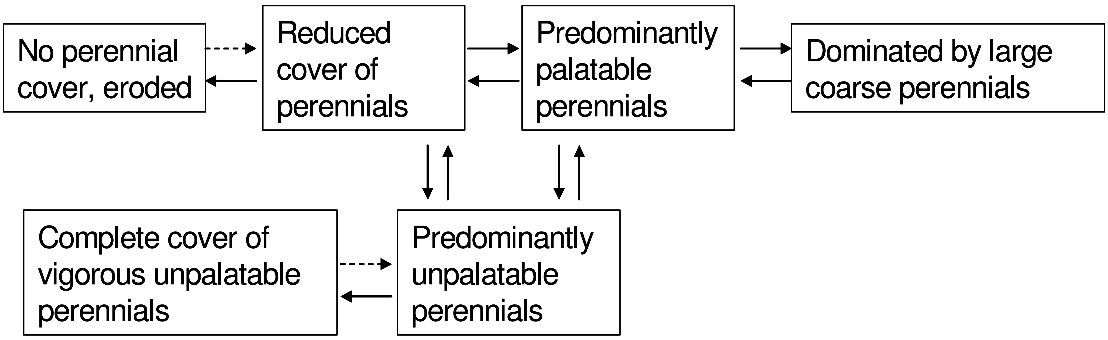

Figure 2. State and transition model from a tall *grassveld* in South Africa. Dashed arrows indicate slow and unfeasible transitions where intervention (disturbance, reseeding) may be needed (from Westoby et al., 1989).

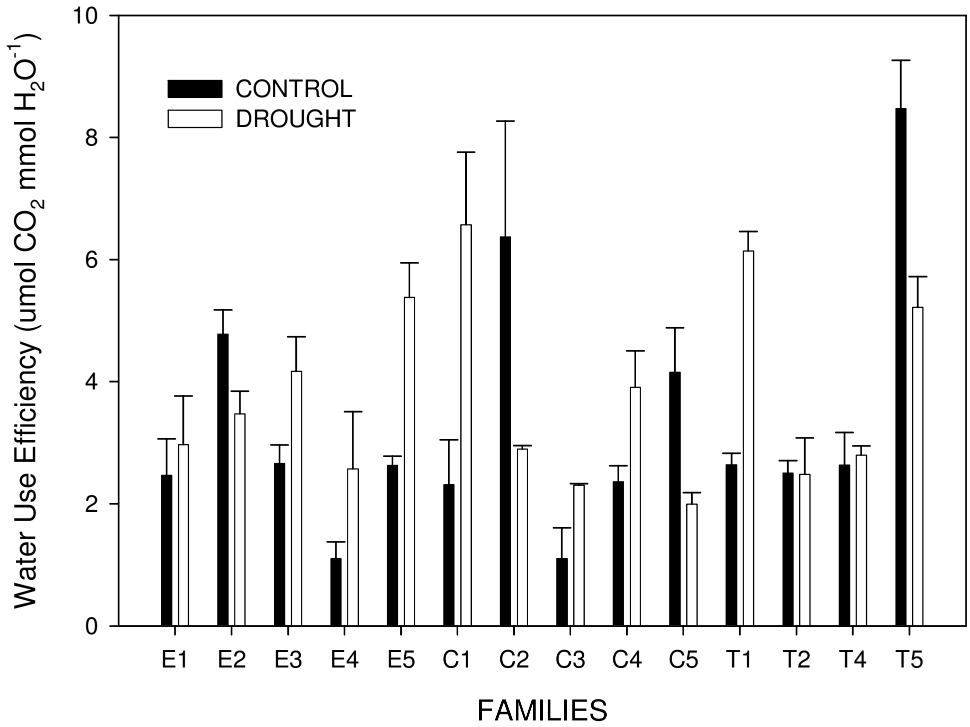

Figure 3. Effect of drought on the instantaneous water use efficiency of *Quercus suber* seedlings from 14 half-sib families from three Iberian provenances. E: Espadà, C: Calderona, T: Toledo (T. Bitinas, University of Alicante, unpubl. data).

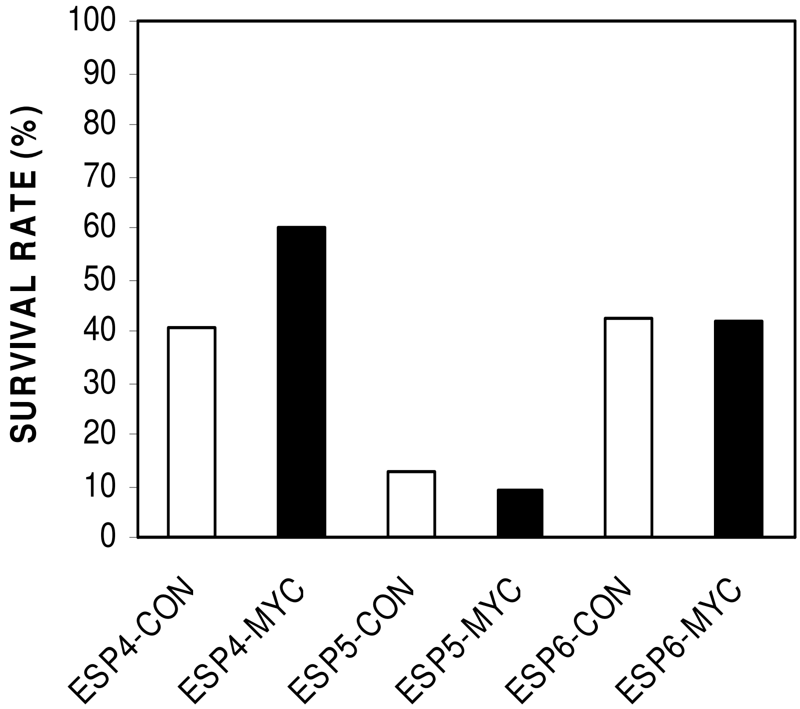

Figure 4. First year survival of *Quercus suber* seedlings inoculated (MYC; black bars) and non-inoculated (CON; white bars) with *Pisolithus arrhizus* v. F33. ESP4 to ESP6 correspond to 3 abandoned old-fields located in Serra d'Espadà (Castelló, E Spain; M. Pérez-Devesa, Fundación CEAM, unpubl.).