Chapter 4

ECOLOGICAL RESTORATION IN DEGRADED DRYLANDS: THE NEED TO IMPROVE THE SEEDLING QUALITY AND SITE CONDITIONS IN THE FIELD

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ABSTRACT

Ecological restoration represents an important tool for combating land degradation and increasing ecosystem resistance and resilience to disturbance, thus favoring the recovery of functions and services. Degraded drylands constitute very harsh conditions for the natural regeneration and rangeland restoration of the ecosystems. Scarcity of rainfall after planting, inappropriate seedling quality and unfavorable hydro-physic and chemical characteristics of the soil often affect the success of ecological restoration projects. Therefore, there is a need to improve ecological restoration techniques in degraded drylands. In this paper we analyze innovative nursery and field techniques oriented to reduce outplanting stress on the basis of the researcher experience of the CEAM Foundation’s Forest Restoration Programme¹ and the Ecosystems Management and Biodiversity group in the University of Alicante’s Department of Ecology² though several RTD projects funded by the Valencia Regional Government, the Government of Spain and the European Commission. In the nursery, the main research lines are directed

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towards improving seedling quality, especially its resistance to water stress, by means of the use of containers gauged to the different root growth patterns of the species, the use of hydrogel to improve the water holding capacity of the substrate and reduce post-planting stress, the use of drought preconditioning to induce mechanisms for drought resistance, the use of fertilization according to field conditions and target seedlings for restoration projects and the use of growth regulators to control the biomass distribution within the seedlings. Other research lines are focused on ameliorating site conditions in the field, particularly soil and microclimatic conditions, by using: microcatchments to improve runoff harvesting and soil water availability to seedlings, deeper planting holes according to species growth patterns, treeshelters to reduce environmental stress, hydrogels to improve soil water-holding capacity, organic amendments like biosolids to improve soil fertility, and biotic interactions to facilitate seedling establishment. Then, we present the demonstration project on the restoration and management of semi-arid areas affected by desertification in Albatera (Spain) as an example of the implementation of these innovative techniques. This project has shown that increased technological investment in forest restoration ensures acceptable results in seedling survival and growth, and gradual ecosystem recovery. Finally, the challenges and opportunities for ecological restoration in dryland are discussed on the basis of the results shown and future climate projections.

**RECENT HISTORY OF AFFORESTATION PROGRAMS IN SPAIN**

The history of mankind is closely related to the use of forests. Wars, wood and fuel gathering, forest fires, grazing and agricultural practices have dramatically reduced the extension and quality of the world’s forests. In drylands (arid, semiarid and dry sub-humid areas), besides these negative anthropic effects, forest degradation has been further exacerbated by climatic conditions characterized by extreme drought periods, which are unfavorable to the natural recovery of plant communities/ecosystems and landscapes.

These causes of forest degradation also apply to Spain. Forest management policies have been conditioned by different factors. Previous studies have summarized the historical evolution of forests and afforestations in Spain (Martinez Hermosilla, 1990; Pemán and Navarro, 1998). In the middle of the 20th century, after the Spanish Civil War, the lack of forest resources made necessary the implementation of a large afforestation program. Although ecological and technical considerations were taken into account, the main objective of this program was to alleviate the harsh economic situation of the rural communities after the war by offering a seasonal job. Sometimes up to 5000 seedlings/ha were planted. This program peaked at 100000 afforested hectares per year in its most productive moments (Pemán and Navarro, 1998). In those years, forest management played an important social role (Ortuño Medina, 1990). The results of old afforestations have provided an information background for subsequent decades. Plantation failures were frequent but the main target was to afforest the most extensive area possible and little funds were allocated for research purposes. In the mid-80s, the restored democratic regime led to a regional decentralization of the government. On the one hand, the regional governments assumed the environmental policies and actions in their area, including afforestation tasks. On the other hand, the central government could then undertake some basic research on the morphological and
physiological quality of Mediterranean seedlings, and some research centers were created, such as The National Center for Forest Improvement "El Serranillo" in 1985, with the aim of adapting the technology implemented in other countries, mainly from Central Europe.

In the early 90s, the afforestation efforts were renovated through a European-funded program to reclaim abandoned agricultural lands. In 1997, 51% of the surface area of Spain was classified as forest, of which 53% was represented by conifers, hardwood and mixed forest (Pemán and Navarro, 1998). In those years, private owners were stimulated to undertake afforestations, and ecological issues (species diversity, low planting densities, low ecological impact) were taken into account for granting funds. Many private forest nurseries were created, and the number of research groups was increased in universities and research centers. One example is the Mediterranean Center for Environmental Studies (CEAM), established in 1991, which has been involved in numerous research projects related to seedling quality, nursery production of Mediterranean species and ecological restoration, funded by the Valencia Regional Government, the Spanish Government and the European Commission.

The techniques of seedling nursery production have also evolved. Up to the 60s, the traditional afforestation system consisted of the plantation of a high amount of bare-root seedlings produced in temporal nurseries close to the plantation sites. In this decade, an important advance was introduced due to the constraints imposed by seasonal drought. In Spain, Southern France, Italy and most Mediterranean-climate countries, bare-root production was substituted with polyethylene bag production to reduce post-planting shock (Figure 1). Survival was greatly improved with this change in cultivation method (Peñuelas and Ocaña, 1996). However, the technological change was not associated with any kind of organized research, and nurseries continued to be managed according to the previous experience of the managers. Diseases like damping-off were frequent, mechanization was impossible and some nursery-production factors (watering, fertilization) were not controlled. Moreover, the bagged seedlings showed serious deficiencies that impaired their survival and growth in the short and long term. The developing roots tended to curl along the internal surface of the bag, especially at its bottom. In the short term, these root deformations reduced the capacity of the root system to explore deeper soil layers after being planted. In the middle and long term, they could provoke the strangulation of the root system or the instability of the trees (Kinghorn, 1978).

In the mid 80s, the implementation of new techniques in other countries changed nursery production. This new phase was based in the control of nursery production and the mechanization of the productive process (Figure 2). The control of nursery production centered on the use of small containers designed to prevent root spiraling, the use of organic substrates with high aeration and water holding capacity, and the control of seedling density, watering, fertilization, culture time, shading and other culture variables. In general, this technological change improved seedling quality with respect to the traditionally bagged seedling (Peñuelas and Ocaña, 1996).

Site preparation techniques evolved from the 60s. Previous to this period, seedlings were planted in hand-dug holes, in accordance with the main afforestation objective during those years: to provide jobs. In the 60s, coinciding with an economic upsurge that reduced the social pressure, some alternatives to traditional soil preparation procedures were explored. Heavy machinery and techniques like mechanical terracing or ripping were introduced.
Figure 1. *Pinus pinea* seedlings cultivated in a nursery by means of polyethylene bag and soil substrate. National Center for Forest Improvement "El Serranillo" (Photo by J.L. Peñuelas).

Figure 2. Environmentally controlled nursery production. Seedlings cultivated in forest trays with organic substrate, in GENFORSA Greenhouse (Cuenca, Spain, photo by J.L. Peñuelas).
In this period forest engineering improved greatly, but a lack of knowledge into the biological component of the afforestation process was observed. In the last decades site preparation methods have continued to evolve and are well described in the contemporary literature (Pemán and Navarro, 1998; Bainbridge, 2007). In the current framework of ecological restoration, site preparation technologies focus on reducing the ecological and visual impact of machinery works, and improving soil fertility, planting hole quality and runoff harvesting, among other alternatives.

Throughout the 20th century, afforestation in Spain has involved around 2.5 million hectares, which corresponds to 5% of its total surface area (Vallejo, 1996). In recent years, notable advances in nursery production and site preparation have been observed. This process has been favored by the evolution in the concepts of ecological restoration and Mediterranean seedling quality, and, in general, by changes in the social situation in Spain and Southern Europe in general. As a result, the efforts of researchers and nursery managers, regional Forest Services and forestry companies have been translated into better results in restoration projects. Although in recent decades several books summarizing the scientific developments on these issues have been published (Peñuelas and Ocaña, 1996; Pemán and Navarro, 1998; Cortina et al., 2006a), our contribution offers a synthesis of the latest results on the use of innovative techniques to improve both seedling quality in nursery cultures and site conditions for planting in drylands areas, in the framework of ecological restoration.

2. ECOLOGICAL RESTORATION IN THE CONTEXT OF FOREST MANAGEMENT IN DEGRADED DRYLANDS

Desertification is defined as “land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities” (UNCCD, 1994). The drivers of desertification operate at a wide range of spatial and temporal scales. It has been suggested that a limited suite of ‘slow’ variables are critical determinants of human-ecological system dynamics. In this sense, the thresholds in key slow variables define different states of these systems (Stafford-Smith and Reynolds, 2002). As we shall see in this section, the identification of ‘slow’ and ‘fast’ variables is of major importance to design feasible methods to combat desertification, including ecological restoration. Examples worldwide testify to the enormous potential of ecological restoration to revert dryland degradation (UNEP, 1999).

Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SERI, 2004). There are two major outcomes of this definition. On the one hand, ecological restoration requires some sort of intervention. Thus, the term ‘passive restoration’ is an oxymoron to be abandoned. On the other hand, ecological restoration involves the identification of target or reference ecosystems, as particular combinations of species and functions that society considers worth recovering after disturbance. But can we identify and characterize reference ecosystems in drylands areas? In other words, which should be the objectives of ecological restoration in these areas?

The identification of a reference ecosystem, as other aspects of ecological restoration, is strongly conditioned by the social and cultural context. Ecosystems are intrinsically dynamic, and thus decisions on the reference ecosystem are heavily dependent on the temporal and
spatial scale considered. Drylands regions have supported humans for millennia, and they are particularly sensitive to climatic changes (Carrión et al. 2001; Reynolds et al., 2007). Anthropogenic activity has shaped, and sometimes degraded, ecosystems for a long time, and thus it is not obvious that historical records, when available, can be used to target reference ecosystems. Extrapolation from refuges is not straightforward, as their conservation is frequently associated with particular soil and microclimatic conditions, as well as unique land use histories, which can hardly be generalized. Finally, restoration must plan for decades ahead, when climatic conditions and disturbance regimes will likely differ from the current ones (Williams et al., 2007). How can we cope with 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.

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 community, are likely to result from a disturbance under a given combination of soil and climatic conditions. These dynamics are well described by state and transition models (Westoby et al., 1989). 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). In addition, states can be characterized in terms of structure (both biotic and abiotic), function and services, allowing management decisions to be made in quantitative terms (Cortina et al., 2006c). In this context, 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 to disturbance and stress should receive highest priority in drylands areas. This can be achieved by ensuring a certain amount of protective plant cover, and improving the quality of such cover.

Degradative trajectories in drylands are commonly non-linear. Relatively stable phases may be followed by abrupt changes when ecosystem functions decay at a higher rate (Whisenant, 1999). The so-called degradation threshold may be caused by the disappearance of a particular species or functional groups. Thornes and Brandt (1994) showed that in erosion-prone ecosystems, at least 30% of plant cover was needed to foster self-organization. This figure can be taken as a target for ecological restoration in dryland areas. On the other hand, the spatial pattern of plant cover affects runoff and sediment yield (Maestre and Cortina, 2004a; Bautista et al., 2007). But the relationship between the spatial arrangement of vegetation and ecosystem function is not simple (see, for example, Huxman et al., 2005). As a precautionary measure, a distribution leaving no large empty patches is probably preferable (Maestre and Cortina, 2004a; Kefi et al., 2007).

Once a protective plant cover is guaranteed, priority must be given to species capable of withstanding unfavorable conditions -mainly drought- and recovering quickly after disturbances such as fire, clearing or grazing. Both obligate seeders and resprouters may be fitted for this purpose, but the latter are commonly faster in achieving high cover after disturbance than the former; in addition, seeders may colonize the area spontaneously if seed sources are available (e.g., from the canopy or soil seed banks), with no extra help from
restoration practitioners. Thus, the reintroduction of resprouters may be a first choice when restoring degraded drylands.

Other criteria can be used to select suitable species for restoration. Keystone species have been defined as species whose impact on ecosystem function (i.e., their importance) is higher than their abundance (Hulbert, 1997). Solé and Montoya (2001) suggested that keystone species can be identified by their degree of connectivity to other species in the community, as highly connected species play a major role in maintaining community integrity. Both definitions of ‘keystoneness’ are related and relevant for restoration. Species that independent of their abundance are capable of positively affecting whole ecosystem behavior interact with other species and favor their arrival and establishment, should be prioritized.

It has been commonly assumed that increasing plant cover may have a positive effect on ecosystem capacity to sequester carbon, produce usable water and regulate water flows. Afforestation of drylands has the potential to accumulate carbon in vegetation and soils. But the accumulation rate may be too low to offset the carbon costs of planting. As the carbon sequestration rate is low, the importance of the afforestation of drylands in the global carbon balance is strongly dependent on the surface area available.

In general, increasing plant cover results in higher transpiration losses and less water available for runoff and deep seepage (Chirino, 2003; Richardson and van Wilgen, 2004; Brown et al., 2005; Farley et al., 2005). But restoring plant cover in dryland areas affects the water balance in various complex ways, and the net effect of these interacting factors may depend on climatic conditions and the amount and type of plant cover (Chirino, 2003; Huxman et al., 2005). In fact, afforestation with a pine stratum produces less runoff and improves the stand’s vertical structure resulting in pluri-stratified communities, but it reduces the species richness and plant diversity in the understorey (Chirino et al., 2006). In contrast, in areas with high atmospheric moisture content, afforestation may contribute to intercept moisture and increase water availability (Estrela et al., 2008). Increased evaporation resulting from large-scale afforestation may contribute to increase water inputs (Millán et al., 2005), although the magnitude of the afforestation program needed to alter atmospheric dynamics may compromise its feasibility. The role of plant cover in controlling floods has recently been questioned (CIFOR-FAO, 2005; Calder and Aylward, 2006); on a large scale, it may account on average for about 14% of the variability in flooding frequency and duration when extreme events are excluded from the analysis (Bradshaw et al., 2007).

A simplified Clementsian view of ecosystem dynamics prevailed during most of the 20th century. Linear successional trajectories, facilitation and climax communities were assumed to be the norm. Thus, emphasis was given to establishing pioneer species, as a first step towards the restoration of climax communities. In the Mediterranean basin, restoration programs concentrated their efforts almost exclusively on conifers, mostly pines. But pines have failed to establish in some areas, and their role in large scale restoration has been questioned (Maestre and Cortina, 2004b). Later, attention shifted towards the establishment of keystone species. In the last 20 years, substantial progress has been made towards designing optimum management practices and developing successful technology for the establishment of keystone species in semiarid lands (Whisenant, 1999; Cortina et al., 2004; Bainbridge, 2007). In this context, we created a graphical model on the state and transition model of ecosystem dynamics, based on ecosystem composition, function and services (Figure 3).
ECOSYSTEM GOODS AND SERVICES
ECOSYSTEM FUNCTION
ECOSYSTEM COMPOSITION

Figure 3. State and transition model of ecosystem dynamics based on ecosystem composition, function and services. Each ecosystem state is described by a different color, its size corresponding to its natural range of variability. Transitions between states are shown by solid lines (high probability, fast process) and dotted lines (low probability, slow process). Only unidirectional arrows are shown for clarity.

The integration of three variables defines the initial state of the ecosystem and enables possible successional trajectories to be predicted according to the changes promoted by the ecological restoration. Each ecosystem state is identified by a different color, its size corresponding to its natural range of variability. The research developed by Cortina et al. (2006c) provides further details on the theoretical model and an example of its application.

Ecological restoration is a complex process; in this sense, we propose four steps to dryland restoration which we hope will be useful for developing ecological restoration projects. Below, these steps are listed:

1) **Diagnosis and prognosis.** Evaluate the current state of the ecosystem as well as the changes expected under no action. Identify the main drivers of degradation and evaluate the possibilities for controlling them.

2) **Locate the target.** Identify a target or reference ecosystem based on the three sets of attributes shown in figure 3 and define the trajectories leading to it. Especially in this step, work in close collaboration with stakeholders.

3) **Identify best practices.** Identify suitable techniques that could foster changes. Consider environmental and socio-economic variability (changes in land use, climate, etc.). For drylands, the priorities could be: (a) to ensure a protective plant cover, (b) to increase ecosystem resistance and resilience and (c) to facilitate the establishment of keystone species.
4) Be adaptive. Save resources and implement a program to evaluate the success of restoration practices and monitor changes. Modify your plan according to the outcomes of your actions and changing conditions.

3. INNOVATIVE TECHNOLOGIES IN NURSERY CULTURE TO IMPROVE SEEDLING QUALITY

Ecological restoration is a process that covers various fields of activity, such as species selection, nursery culture and soil preparation in planting areas, among others. Under a Mediterranean climate, soil water availability represents one of the main environmental constraints (Di Castri, 1973). Drought stress leads to water deficits in the leaf tissue, and these affect plant physiological processes with ultimate consequences for plant survival (Hsiao, 1973). Climatic conditions are one of the main limiting factors in seedling establishment (Alloza and Vallejo, 1999). Plantations in drylands frequently show poor results, especially when species other than pines are used. Planted seedlings often show high mortality rates, particularly when significant rainfall events are absent for more than 3 months (Alloza and Vallejo 1999). During the last decades of the 20th century, climatic conditions in the Mediterranean basin have been particularly adverse, with record high global temperatures (Castro et al., 2005). Hence, drought spells may have been major drivers in the large-scale plant mortality observed. Adverse climatic conditions are likely to persist in the next future (Millán et al. 2005), thus emphasizing the need to improve restoration techniques to make them more efficient against future climatic scenarios. In addition, there is a large body of evidence indicating that a key obstacle to plantation success is transplant shock, which is the intense short-term stress experimented by seedlings as they are transferred from favorable nursery conditions to the adverse field environment (Burdett, 1990). Seedling establishment in forest plantations depends on the morphological and physiological traits of the seedlings and the environmental conditions of the planting site (Burdett, 1990). Planting containerized seedlings represents a suitable option for promoting the reintroduction of woody species in dry and semi-arid areas. However, seedling plantations often show poor results in dry and semi-arid areas (Cortina et al., 2004) and may be helped by improving seedling quality (Burdett, 1990).

Thus, current approaches to ecological restoration stress the importance of seedling quality and, consequently, of nursery culture technology. Nevertheless, several studies have demonstrated that planting seedlings in drylands and degraded soils are often discouraging because of high mortality rates and poor growth (Vilagrosa et al., 1997; Cortina et al., 2004). In fact, in drylands, seedling field performance has been strongly related to the water deficit, the degree of soil degradation and the anthropic disturbance regime. Despite the fact that we usually cultivate species that are drought resistant or adapted to drylands areas, the scarce water availability for the seedlings constitutes one of the main limiting factors in the success of afforestation actions at the establishment stage.

In this context, the technology used in the nursery culture will determine seedling quality and lead to a better field performance. However, at present, no clearly defined nutrition plan exists for the nursery culture of seedlings designated for establishment in semiarid conditions. There are several trends in the programme of nutrition used for these cases, and they depend
on the type of seedlings to be produced and the site conditions for planting; in fact, discussion
is still under way as to the advisability of producing tall or short seedlings, with high or low
nutrient concentrations, for planting in semiarid areas. Moreover, in nursery culture the
selection of substrates and containers is often more influenced by economic factors than by
consideration of the different growth patterns of species; hence, in some cases, seedlings are
not well preconditioned to drought. Although at present there are certain advances in
production technology in nursery plants, it is necessary to revise the traditional cultivation
techniques (Vilagrosa et al., 1997; 2001). Considering that most of the literature on this topic
comes from mesic systems, which often took precedence in terms of productive aspects
(Cortina et al., 2006b), we believe it is now necessary to make an effort to introduce new
technologies in nursery cultures under semi-arid conditions to improve the morphological and
physiological quality of the forest plant produced, focusing on aspects that enhance the water
holding capacity of the substrate, the use of adequate containers to obtain seedlings with an
optimum biomass distribution, programming plant nutrition according to the characteristics of
the species, its growth patterns and target seedlings, and promoting mechanisms for drought
resistance. Summing up, the goal should be to produce seedlings adapted to current stress
conditions and future climate scenarios, capable of optimizing their potential for
establishment in harsh field conditions. These topics will be discussed in the following
sections.

3.1. Using Deep Containers for Species that Rapidly Develop a Long Tap Root

The container is included among the main factors considered to determine the production
of a quality forest plant. In fact, the container design determines the morphological and
physiological characteristics of the seedling, particularly its root system development (Landis,
1990; Aphalo and Rikala, 2003; Domínguez-Lerena et al., 2006) as well as seedling survival
after outplanting (Domínguez et al., 2000). However, container characteristics have often
been the same for plant species with very different growth strategies. In fact, there is
sometimes no distinction made between containers for herbaceous plants, shrubs or trees.
Nevertheless, the selection of a container must be in accordance with the morpho-functional
characteristics of the species, its development patterns and the environmental conditions
where it will be planted. In degraded drylands with strong water restrictions, a poorly
developed seedling root system will lead to high mortality in plantations. As a consequence, it
is necessary to produce seedlings with an appropriate biomass distribution, an optimum
root/shoot ratio and a root system capable of reaching more quickly the deeper horizons
where some soil moisture could be available during the dry summer.

The stress conditions due to water deficit, high temperatures and global radiation in these
ecosystems have limited natural revegetation, which on occasion is also affected by forest
fires. Moreover, direct seeding is generally not successful due to water limitations and animal
predation of seeds and seedlings (Leyva and Fernandez-Alés, 1998; Merouani et al., 2001;
Bladé and Vallejo, 2008). Thus, the use of seedlings produced in containers or forest trays is
the most common technique for introducing native species in dry and semiarid ecosystems
(Cortina et al., 2004). Currently, there is a wide variety of containers on the market.
Figure 4. Initial differences of root plug position in the plantation hole and evolution dynamic of root system growth towards deeper horizons where soil moisture is more stable throughout the year. Hypothetical time scale: A – at planting, B – 3 months after planting and C – before the first summer ($\Delta d$: differences in depth, WC: water content).
Figure 5. *Quercus suber* seedlings grown in a paperpot container at two depths: 18 and 30 cm. Detail of the length of the taproot in each container type (Photo by A. Vilagrosa).

Figure 6. New root biomass (dry weight) by depth. A: Excavation of *Quercus suber* seedlings 3 months after outplanting. B: Excavation of *Q. ilex* seedlings 18 months after outplanting. Significant differences: * p<0.05 and ** p<0.01.
They are defined in terms of their material, shape, size, depth, shallow opening and bottom cells, seedling density and design of vertical ribs to prevent root spiraling. New advances in container design have been implemented in the last decades; they are mainly related to lateral air root pruning and chemical root pruning; but not to container depth. This last factor has been the aim of our latest research.

In general the containers and forest trays most commonly used in afforestation programs in semiarid, dry and subhumid Mediterranean ecosystems have cell volumes between 250 to 400 cm$^3$, and a maximum depth of 18 cm (Peñuelas and Ocaña, 1996). This container depth is relatively shallow for species that rely on the early development of a long tap root to escape drought, such as those of the *Quercus* genus, which might need to be cultivated in deeper containers. The depth of the container determines the length of the taproot and thus the root system positioning depth in the soil (Peñuelas and Ocaña, 1996); greater depths improve the vertical stability of seedlings and their access to deeper horizons where soil moisture is more stable (Chirino, 2003). Previous studies have demonstrated that shallow and low volume containers can restrict water and nutrient availability and impose physical limitations on root system growth (Aphalo and Rikala, 2003; Domínguez-Lerena et al., 2006). In this context, we consider that when the seedlings of species that develop a long taproot are cultivated in deep containers they will reach a deeper taproot tip position in the planting hole (Figure 4.A), begin colonization of the deep horizons faster (Figure 4.B), and reach the deepest layers with higher soil moisture before the dry summer period (Figure 4.C).

Several experiments carried out by our research group have supported these results. A comparative study in three Mediterranean oak species (*Quercus coccifera*, *Quercus ilex* and *Quercus suber*) cultivated in two paperpot container types (a shallow container with a depth of 18 cm and a volume of 353 cm$^3$, and a deep container with a depth of 30 cm and a volume of 589 cm$^3$), confirmed that the seedlings cultivated in deep containers showed: a) a longer taproot (Figure 5), b) deeper soil colonization, and c) a higher number of new roots and root biomass in deeper layers, than the seedlings cultivated in shallow containers (Figure 6; Chirino et al., 2005). Despite the advantages observed, paperpot container showed limited development of fine roots and poor distribution along the container (Serrada and Serrada 2001). In addition, the wrapping paper favored high water loss by evaporation from the substrate and facilitated secondary root intersections among seedlings producing difficulties in separating the seedlings and mechanical damage during handling (Domínguez et al., 1997; Chirino et al., 2005). These aspects discourage the use of paperpot containers for culture nursery.

In this context, the CEAM Foundation, in collaboration with CETAP Antonio Matos Lda. (Forestry Container Manufacturer Company, Espinho, Portugal), has designed and developed a prototype deep container made of high-density polyethylene (HDPE); it both corrects the disadvantages observed in the paperpot container and improves other characteristics (Chirino et al., 2008). This prototype deep container was recently evaluated in *Q. suber*. The results indicated that the seedlings produced in the deep container showed improved morpho-functional attributes and plant quality expressed by means of the Dickson Quality Index (DQI). We can thus confirm that deep containers produce seedlings with a longer taproot, which reaches the deeper soil horizons quickly due to higher growth in the number and biomass of new roots (root growth capacity test).
Figure 7. Comparison between seedlings cultivated in a shallow (18 cm deep) or a deep (30 cm deep) high-density polyethylene (HDPE) container. Seedlings of *Quercus coccifera* (left) and *Quercus ilex* (right) at three months old (Photo by E. Chirino).

These morpho-functional advantages from deep container promote a higher root water transport capacity in the root system (root hydraulic conductance measures), leading to improved water status under drought stress conditions, verified by means of an imposed drought period (Chirino et al., 2008). Our research has concluded that deep containers could also be used in other Mediterranean oaks that develop taproot when planted in dry conditions; in fact, we are currently studying the effects of our prototype deep container in *Q. coccifera* and *Q. ilex* (Figure 7).

### 3.2. Improving the Water Holding Capacity of the Culture Substrate

The substrate, besides being the growing medium of the plant, must permit the optimum oxygenation of the plant’s root system (Tsakaldimi, 2006) and provide the plant with adequate water availability to reduce water stress conditions in outplanting (Aloys et. al., 1999). In the last decades, different substrates have appeared on the market. Often, mixtures of two or more materials, such as peat, coco-peat, vermiculite, perlite, sand, clay and pine bark, are used to elaborate the substrates (Tsakaldimi, 2006). This involves the manipulation of the substrate’s physical and hydro-physical characteristics. Research of this type is aimed at formulating substrates that: (1) show increased water holding capacity and water availability, (2) reduce the post-transplant shock and (3) obtain a better water status for seedlings during the first months after outplanting. In this context, the recent introduction of hydrogel use should be mentioned. Hydrogels are hydro-absorbent polymers with the ability to absorb and deliver water with different speeds according to the degree of polymerization of the constituent monomer. These products are able to absorb 200 to 5300 times their dry weight in water (Figure 8), although the retention may be lower when applied to soils (Chatzoudis and Rigas, 1999).
Hydrogels have been used more frequently as amendments to loamy (Viero et al., 2000; Al-Humaid and Moflah, 2007), sandy loam (Akhter et al., 2004) and sandy clay loam soils (Viero et al., 2002). Previous studies have indicated that the use of hydrogels significantly reduces soil water loss, thus promoting seedling field performance (Viero et al., 2002; Arbona et al., 2005; Al-Humaid and Moflah, 2007). However, the use of hydrogels mixed with the peat-based substrate employed in the nursery culture of forest species has been very rarely studied, and this is the novelty of our research.
Post-transplant shock is one of the main risks for the survival of seedlings in plantations. After being transplanted, plants grown in nurseries under optimum watering conditions or subjected to a drought-preconditioning treatment will find conditions where water availability will depend on rainfall. Thus, the use of the best substrate for cultivation acquires more importance because it can contribute to increasing the xylem water potential and improving the seedling water status. Moreover, access to water and the regulation of losses by transpiration affect species survival and growth, especially in the establishment phase in the field. It is therefore not surprising that seedling mortality is usually highest during the first year after outplanting (Vilagrosa et al., 1997; Vallejo and Alloza, 1998). Thus, the technological developments being implemented in ecological restoration projects, and particularly in the protocols for nursery cultivation, should facilitate seedling establishment in the field by improving micro-environmental conditions in the field and consequently reducing post-transplant shock.

Based on these assumptions, our research group has developed several experiments aimed at manipulating the hydro-physical properties of substrates through mixtures with absorbent materials. The objectives were: i) increase the water holding capacity of the substrate culture and its gradual release to the root system, ii) reduce the effects of post-transplant shock and iii) improve seedling water status in the first months after outplanting. The experiments carried out with *Pistacia lentiscus* (a Mediterranean shrub) showed that the substrates used did not affect the biomass of the morphological fractions (stem, leaves and roots). However, the seedlings cultivated on control substrate mixed with a Stockosorb hydrogel of medium particle size (0.7% w/w) showed higher root/shoot ratio and root biomass/seedling biomass than the seedlings cultivated on either the control substrate (peat + coconut peat, 1:1 v/v) or the control substrate mixed with vermiculite (20% v/v). Moreover, we observed a tendency toward higher field survival in seedlings cultivated on substrate mixed with hydrogel (83.7%), followed by the control substrate (77.6%) and the vermiculite substrate (66.7%); this could be an indicator of the positive effect of hydrogel on seedling establishment. Based on the above results, in the framework of the CREOAK European project we carried out a second experiment in another Mediterranean keystone species (*Quercus suber*) with similar objectives, but utilizing other absorbent materials to mix with the substrate to check whether they could improve the results of the previous test. On this occasion, we used the same control substrate (peat + coconut peat, 1:1 v/v) and we elaborated 10 substrate types by adding hydrogel (Bures and Stockosorb, both of medium particle size), pine bark and clay (Sepiolite and Attapulgite) in different proportions (Table 1).

Previous studies indicated that soil water retention increases with increasing hydrogel concentrations. Hüttermann et al. (1999) reported an exponential increase in water retention with increasing hydrogel (0.04 to 0.40%) in sandy soil. Akhter et al. (2004) reported that the addition of 0.1, 0.2 and 0.3% of hydrogel in sandy loam and loam soil increased the moisture retention at field capacity linearly and thus significantly increased plant water availability in both soil types as compared with untreated soils. Arbona et al. (2005), in a substrate composed of sphagnum peat and perlite (80:20), observed that the addition of 0.4% hydrogel increased the water content by about 128%. In experiments with mixtures of 0.1-0.6% hydrogel in sandy soil, Al-Humaid and Moflah (2007) found that the highest concentration of hydrogel prolonged the time it took for water to be lost from the soil by about 66% with respect to the control soil.
Table 1. Substrate types used in the experiment with Quercus suber seedlings (V: volume, W: weight, C: coarse size, M: medium size, F: fine size)

<table>
<thead>
<tr>
<th>Nº</th>
<th>Substrate types</th>
<th>Label</th>
<th>Mixture (%)</th>
<th>Units of measurement</th>
<th>Particle size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control substrate</td>
<td>CECS</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Pine bark</td>
<td>PineB</td>
<td>25</td>
<td>v/v</td>
<td>M</td>
</tr>
<tr>
<td>3</td>
<td>Hydrogel Stockosorb</td>
<td>HS-0.7</td>
<td>0.7</td>
<td>w/w</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>Hydrogel Stockosorb</td>
<td>HS-1.5</td>
<td>1.5</td>
<td>w/w</td>
<td>M</td>
</tr>
<tr>
<td>5</td>
<td>Hydrogel Bures</td>
<td>HB-0.7</td>
<td>0.7</td>
<td>w/w</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>Hydrogel Bures</td>
<td>HB-1.5</td>
<td>1.5</td>
<td>w/w</td>
<td>M</td>
</tr>
<tr>
<td>7</td>
<td>Attapulgite 4/20 (clay)</td>
<td>AAG-10</td>
<td>10</td>
<td>v/v</td>
<td>C</td>
</tr>
<tr>
<td>8</td>
<td>Attapulgite 20/70 (clay)</td>
<td>AAF-10</td>
<td>10</td>
<td>v/v</td>
<td>F</td>
</tr>
<tr>
<td>9</td>
<td>Attapulgite 20/70 (clay)</td>
<td>AAF-20</td>
<td>20</td>
<td>v/v</td>
<td>F</td>
</tr>
<tr>
<td>10</td>
<td>Sepiolite 4/35 (clay)</td>
<td>ASG-10</td>
<td>10</td>
<td>v/v</td>
<td>C</td>
</tr>
<tr>
<td>11</td>
<td>Sepiolite 4/35 (clay)</td>
<td>ASG-20</td>
<td>20</td>
<td>v/v</td>
<td>C</td>
</tr>
</tbody>
</table>

Figure 9. Relationship between substrate water content and predawn water potential at end of drought period. For abbreviations of substrate types see table 1. Solid line: exponential regression; dashed line: substrate that showed highest water holding capacity (expressed by water content) and highest seedling water status (expressed by predawn water potential). Significant R²: ** p<0.01.
In this context, our results indicated that the seedlings cultivated in substrates mixed with clay (ASG-10) and hydrogel (HB-0.7, HB-1.5 and HS-1.5) and subjected to an imposed drought period (7 days without watering and seedlings placed in full sunlight) showed a higher water holding capacity (expressed by gravimetric humidity of the substrate) and a higher seedling water status (expressed by predawn water potential) than the seedlings cultivated in the control substrate (Figure 9).

Field results ratified the beneficial effects of the use of hydrogels mixed with the substrate on seedlings performance. Despite the fact that the spring of 2005 after outplanting was extremely dry with respect to average years, seedlings cultivated in Bures hydrogel (1.5%) showed better water status than those cultivated in control substrate, verified by means of their higher stomata conductance in outplanting (Chirino and Vilagrosa, 2006, unpublished CREOAK project final report). In the same line, 13 months after outplanting, Q. suber seedlings cultivated in the substrate mixed with Stockosorb hydrogel also tended to show higher survival with respect to seedlings cultivated in the control substrate (Figure 10): 85%, 83% and 65% in HS-1.5, HS-0.7 and control respectively. The other substrate types showed less difference (ASG = 73%, HB-0.7% = 68%, HB-1.5% = 77%). In this context, Hüttermann et al. (1999) and Viero et al. (2002) also observed higher survival when using soil-amended hydrogel in Pinus halepensis and Eucalyptus grandis clone seedlings respectively. Arbona et al. (2005) concluded that the hydrogel substrate amendment reduced the damaging effect of drought stress in citrus plants, improved the physiological parameters and prolonged seedling survival.

![Graph Showing Survival of Q. suber Seedlings](image_url)
Another line of research aimed at seeking alternative substrates in nursery cultivation through the use of compost from sewage sludge. The high demand for substrates for the production of ornamental and forest plants in nurseries, and the economic and ecological problems related to the protection of peat as a resource, suggest the need to produce substrates from surplus and low-value materials such as dry sludge from urban waste water mixed with other agricultural or urban wastes (Ingelmo et al., 1998). In this context, Mupondi et al (2006) indicated the positive effects of pine bark-sewage sludge compost on cabbage seedling growth. The studies carried out by Ostos et al. (2008) with respect to the effect of the partial substitution of peat for compost on the growth and nutrition of the native shrub Pistacia lentiscus L. showed that the plants cultivated in compost-based substrates presented better growth and nutrition, especially those in sewage sludge-based compost. These conclusions agree with the previous results obtained by Ingelmo et al. (2002) in collaboration with our group’s research. They reported better hydro-physical and chemical characteristics in the substrate based in a mixture of dry sewage sludge and grape marc (1:2 v/v) than in the peat-based substrate, and they showed the effects on the morphological characteristics of Pinus halepensis Mill. and Quercus ilex L. However, this substrate type presented some disadvantages regarding its handling in the nursery (i.e., it is very heavy).

3.3. Applying Drought Preconditioning to Induce Mechanisms for Drought Resistance

Nursery techniques to avoid transplant shock focus on manipulating the watering regime so as to favor the acclimation of seedlings to unfavorable field conditions (Duryea and McClain, 1984). Drought preconditioning, i.e., the prior exposure of seedlings to drought stress in the nursery, is one of the main techniques used to induce drought-resistance mechanisms in seedlings. According to Landis et al. (1998), drought preconditioning has four main objectives: 1) to manipulate seedling morphology and to induce dormancy, 2) to acclimate seedlings to the natural environment, 3) to develop stress resistance mechanisms, and 4) to improve seedling survival and growth after outplanting. As a general procedure, drought preconditioning should be carried out during the last months of nursery culture (before outplanting), which are considered to be the period during the nursery culture in which several mechanisms related to resistance to stress are promoted (Brissette et al., 1991; Johnson and Cline, 1991).

Drought preconditioning consists of reducing the watering regime by submitting the seedlings to progressive drought conditions. The intensity of the drought conditions in the nursery should be adjusted to the plant species and the seedling characteristics, particularly their stress resistance. During the application of the drought period it is important to avoid intense drought conditions that can damage the seedlings irreversibly (i.e., loss of xylem conductivity due to cavitation processes). In fact, several studies have observed that mild or moderate drought levels perform better than very intense drought conditions (Villar-Salvador et al., 1999; 2004). These results could be a consequence of surpassing certain limits of stress resistance during the process of desiccation (Vilagrosa et al., 2003a). In the same way, the functional characteristics of each species can determine the relative effect of preconditioning. For example, in the framework of the REDMED project we found that drought conditions of about -1 MPa produced a reduction of about 80% in stomatal conductance in mastic tree
(Pistacia lentiscus) whilst the same level of stress produced a reduction of only 45% in kermes oak (Quercus coccifera) (Vilagrosa et al, 2003b). Therefore, the levels of stress applied should be considered species-specific. On the other hand, the length of the drought preconditioning period can also influence the results obtained. In general, it has been observed that long periods of about 3 to 6 months produce better results than short periods. For example, a preconditioning period of three months in Pistacia lentiscus reported better response after outplanting than previous experience with the same species but with periods of preconditioning of about one month (Fonseca, 1999; Rubio et al., 2001). However, this fact could depend on the species involved. Villar-Salvador et al. (2004) did not find any differences when comparing preconditioning periods of 2.5 or 3.5 months in Quercus ilex. Finally, we have observed that long preconditioning periods of about six months produce significant morpho-functional acclimation changes in Quercus suber with respect to its biomass allocation patterns and water transport capacity by roots (Chirino et al., 2003; Chirino and Vilagrosa, 2006, unpublished CREOAK final report). In this sense, Albouchi et al. (1997) found increases in drought tolerance in Acacia cyanophylla when the preconditioning period was longer than three months.

Table 2. Species Treated And Number Of Studies Carried Out With This Mediterranean Species

<table>
<thead>
<tr>
<th>Species</th>
<th>Nº of works</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinus halepensis</td>
<td>5</td>
<td>Tognetti et al., 1997; Villar-Salvador et al., 1999. Royo et al., 2001; Calamassi et al., 2003; Puértolas, 2003</td>
</tr>
<tr>
<td>Pistacia lentiscus</td>
<td>3</td>
<td>Fonseca, 1999; Rubio et al., 2001; Vilagrosa et al., 2003b</td>
</tr>
<tr>
<td>Quercus ilex</td>
<td>2</td>
<td>Rubio et al., 2001; Villar-Salvador et al., 2004</td>
</tr>
<tr>
<td>Quercus coccifera</td>
<td>2</td>
<td>Fonseca, 1999; Vilagrosa et al., 2003b</td>
</tr>
<tr>
<td>Pinus nigra</td>
<td>2</td>
<td>Guehl et al., 1993; Kaushal &amp; Aussenac, 1989</td>
</tr>
<tr>
<td>Olea europaea</td>
<td>2</td>
<td>Larcher et al, 1981; Dichio et al., 2003</td>
</tr>
<tr>
<td>Juniperus oxycedrus</td>
<td>2</td>
<td>Fonseca, 1999; Vilagrosa et al., 2003b</td>
</tr>
<tr>
<td>Lotus creticus cytisoides</td>
<td>2</td>
<td>Franco et al., 2001; Franco et al., 2002</td>
</tr>
<tr>
<td>Pinus pinaster</td>
<td>1</td>
<td>Fernández et al., 1999</td>
</tr>
<tr>
<td>Pinus pinea</td>
<td>1</td>
<td>Villar-Salvador et al., 2000</td>
</tr>
<tr>
<td>Quercus suber</td>
<td>1</td>
<td>Chirino et al., 2003</td>
</tr>
<tr>
<td>Rhamnus alaternus</td>
<td>1</td>
<td>Bañón et al., 2003</td>
</tr>
<tr>
<td>Nerium oleander</td>
<td>1</td>
<td>Bañón et al., 2005</td>
</tr>
<tr>
<td>Rosmarinus officinalis</td>
<td>1</td>
<td>Sánchez-Blanco et al., 2004</td>
</tr>
</tbody>
</table>
In the literature there are many works analyzing the responses of different forest woody species to drought preconditioning. It is notable that most of these studies are from boreal habitats and humid-temperate areas (see, for example: van den Driessche, 1991; van den Driessche, 1992; Stewart and Lieffers, 1993, among others). In contrast, few studies have been developed for Mediterranean species, in spite of the fact that in these environments water availability is the predominant selective force for the survival of plant species (Table 2).

Table 3. Physiological features studied in drought preconditioning experiments.

<table>
<thead>
<tr>
<th>Adaptations</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>Accumulation of carbohydrates</td>
<td>Aussenac &amp; El Nour, 1986</td>
</tr>
<tr>
<td></td>
<td>Nielsen &amp; Orcutt, 1996</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Van den Driessche, 1992</td>
</tr>
<tr>
<td>Root growth capacity</td>
<td>Rook, 1972</td>
</tr>
<tr>
<td>Root-shoot ratio</td>
<td>Ali Abod &amp; Sandi, 1983</td>
</tr>
<tr>
<td></td>
<td>Aussenac &amp; El Nour, 1986</td>
</tr>
<tr>
<td></td>
<td>Van den Driessche, 1992</td>
</tr>
<tr>
<td></td>
<td>Stewart &amp; Lieffers, 1993</td>
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<tr>
<td></td>
<td>Rubio et al., 2000</td>
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<td></td>
<td>Fonseca, 1999</td>
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<td>Villar-Salvador et al., 1999</td>
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<td>Villar-Salvador et al., 2000</td>
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<td></td>
<td>Villar-Salvador et al., 2004</td>
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<tr>
<td></td>
<td>Franco et al., 2002</td>
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<td></td>
<td>Chirino et al., 2003</td>
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<td></td>
<td>Villar-Salvador et al., 2004</td>
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<tr>
<td></td>
<td>Sánchez-Blanco et al., 2004</td>
</tr>
<tr>
<td>Osmotic adjustment</td>
<td>Stewart &amp; Lieffers, 1993</td>
</tr>
<tr>
<td>Cell wall elasticity</td>
<td>Ruiz Sánchez et al., 1997</td>
</tr>
<tr>
<td></td>
<td>Fernández et al., 1999</td>
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<tr>
<td></td>
<td>Rubio et al., 2000</td>
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<tr>
<td></td>
<td>Larcher et al., 1981</td>
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<tr>
<td></td>
<td>Dichio et al., 2003</td>
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<tr>
<td></td>
<td>Vilagrosa et al., 2003</td>
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<td></td>
<td>Villar-Salvador et al., 1999</td>
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<td></td>
<td>Villar-Salvador et al., 2000</td>
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<td></td>
<td>Calamassi et al., 2001</td>
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<tr>
<td></td>
<td>Puértolas, 2003</td>
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<tr>
<td></td>
<td>Royo et al., 2001</td>
</tr>
<tr>
<td></td>
<td>Tognetti et al., 1997</td>
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<tr>
<td></td>
<td>Fernández et al., 1999</td>
</tr>
<tr>
<td></td>
<td>Sánchez-Blanco et al., 2004</td>
</tr>
<tr>
<td>Apoplastic water</td>
<td>Blake &amp; Bevilacqua., 1991</td>
</tr>
<tr>
<td></td>
<td>Albouchi et al., 1997</td>
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<tr>
<td></td>
<td>Villar-Salvador et al., 1999</td>
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<tr>
<td></td>
<td>Vilagrosa et al., 2003b</td>
</tr>
<tr>
<td>Synthesis and activity of ABA</td>
<td>Ali Abod &amp; Sandi, 1983</td>
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<td></td>
<td>Zwiazek &amp; Blake, 1989</td>
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<td></td>
<td>Edwards &amp; Dixon, 1995</td>
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<tr>
<td>Gas exchange</td>
<td>Rubio et al., 2000</td>
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<tr>
<td>Chlorophyll fluorescence</td>
<td>Stewart et al., 1995</td>
</tr>
<tr>
<td></td>
<td>Van den Driessche, 1991</td>
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<td></td>
<td>Vilagrosa et al., 2003</td>
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<td></td>
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<td></td>
<td>Sánchez-Blanco et al., 2004</td>
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<tr>
<td>Cuticular transpiration</td>
<td>Villar-Salvador et al., 1999</td>
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<td></td>
<td>Vilagrosa et al., 2003</td>
</tr>
<tr>
<td>Water status</td>
<td>Rook, 1972</td>
</tr>
<tr>
<td></td>
<td>Vilagrosa et al., 2003</td>
</tr>
</tbody>
</table>

There are a number of studies on the different physiological and morphological changes driven by drought preconditioning (Table 3). Usually, the reported adaptations were tested
under nursery or relatively controlled conditions but very few were tested under field conditions. In general, mild water stress is known to reduce growth to a higher extent than carbon fixation, resulting in an accumulation of carbohydrates and nutrients (van den Driessche, 1992; Nielsen and Orcutt, 1996). Drought preconditioning may also promote root growth by increasing the root to shoot ratio of seedlings in the nursery or the root growth capacity of seedlings after outplanting in the field (Stewart and Lieffers, 1993; Fonseca, 1999). At the physiological level, preconditioning promotes changes in cell wall elasticity associated with mechanisms of avoidance or tolerance to water stress, osmotic adjustment or increases in water capacitance at leaf level (Blake and Bevilacqua, 1991; Fernández and Pardos, 1999; Vilagrosa et al., 2003b). The changes in physiological attributes caused by drought preconditioning are also related to better stomatal control under drought conditions, higher stomatal conductance when plants are again under water deficits or decreases in cuticular conductance (Edwards and Dixon, 1995; Stewart et al., 1995; Villar-Salvador et al., 1999; Vilagrosa et al., 2003b).

In a recent review of the effects of drought preconditioning techniques in fifteen Mediterranean plant species, it was observed that preconditioning increased the drought stress resistance of seedlings but that the magnitude of the effects was low, with the results showing diffuse patterns of response (Vilagrosa et al., 2006). In general, they observed a higher response in relation to drought stress avoidance mechanisms and a lower response of the tolerance mechanisms. Reductions in the gas exchange variables (cuticular transpiration and/or stomatal conductance) were reported in Pinus halepensis (Villar-Salvador et al., 1999) P. pinea (Villar-Salvador et al., 2000), Quercus ilex (Villar-Salvador et al., 2004), Pistacia lentiscus (Vilagrosa et al., 2003), Rhamnus alaternus (Bañon et al., 2003), Nerium oleander (Bañon et al., 2005) and Rosmarinus officinalis (Sánchez-Blanco et al., 2004). Other drought avoidance mechanisms like root growth showed contrasting results. Root growth decreased in preconditioned seedlings when they were subjected to good conditions, i.e., tested under irrigated conditions (Fonseca, 1999; Villar-Salvador et al., 1999, 2000, 2004); however, root growth increased in field conditions under low water availability (Rubio et al., 2001; Franco et al., 2001, 2002; Chirino et al., 2003). These results suggest that testing root growth capacity under watered conditions cannot represent the response of seedlings under field conditions when water has lower availability (Simpson and Ritchie, 1997). The different responses observed seem to be related to the drought resistance strategy developed in each species (Vilagrosa et al., 2003a). In this sense, species like Pinus halepensis or Pistacia lentiscus, with a predominant drought avoidance strategy, mainly developed responses related to avoidance mechanisms (decreased stomatal conductance, increased root:shoot ratios) whilst tolerant species like Q. ilex or Olea europaea ssp sylvestris developed mechanisms to increase their tolerance to drought such as cell membrane stability and osmotic adjustment (Dichio et al., 2003; Villar-Salvador, 2004).

As the ultimate goal of these nursery techniques for improving plant stock quality is the survival and growth of seedlings under field conditions, the latter must be evaluated to determine the success of the reforestation efforts. In this regard, drought preconditioning techniques have reported few effects on the survival of seedlings (Figure 11). Analyzing fifteen papers which carried out field plantations in Mediterranean conditions, Vilagrosa et al (2006) reported that 60% of them found no effect on seedling survival. Negative effects (lower survival in preconditioned seedlings) were observed in 20% and the rest (the other 20%) showed a positive effect. On analyzing several species with plantations in Spain,
Portugal and Greece in the framework of the REDMED European project (Cortina, 2001), we observed few effects of the preconditioning techniques applied; however, we did detect a tendency towards improvement in the survival and growth of the seedlings. Preconditioned *Ceratonia siliqua* seedlings showed higher survival rates, shoot height and root collar diameter than control seedlings in the field (Cortina, 2001). In general, seedling growth in the field is not improved by preconditioning (Vilagrosa et al., 2006), which in some cases results in a higher allocation to root systems. In fact, Rubio et al. (2001) observed that preconditioned seedlings of *Pistacia lentiscus* and *Quercus rotundifolia* developed both more and deeper roots in the soil than seedlings not subjected to preconditioning (Figure 12). The same authors observed that non-preconditioned seedlings suffered higher drought stress than preconditioned seedlings during the first year, manifested in an intense defoliation (Figure 13).

The apparent lack of effect of preconditioning techniques on survival seems to be in contradiction with the evident physiological adaptations observed in most studies. Many of these adaptations can produce moderate effects when seedlings are transferred to wet soils. When seedlings are bare-root cultured, preconditioning can be essential to withstand the intense transplant shock. However, transplant shock is much more limited when planting containerized seedlings during the wet season, which is the common practice in Mediterranean areas. Therefore, when the dry season begins several months after planting, the physiological features will be very different from those induced by preconditioning, and seedlings can naturally adapt to water stress. Only when the onset of the dry period is close to the planting date, as occurs in the most arid areas of the Mediterranean basin, is it more likely to observe a significant effect of some physiological adaptations on the survival of certain species. Rubio et al. (2001) observed that preconditioned seedlings of *Pistacia lentiscus* showed higher water potential at turgor loss point than control seedlings and that they also presented other signs of acclimation to drought (e.g., lower bulk modulus of elasticity and higher symplast water content). Sánchez-Blanco et al. (2004) observed sustained osmotic adjustment in water-conditioned *Rosmarinus officinalis* seedlings subjected to drought by withholding water one month after planting. This adaptation led to higher survival rates. These morphological adaptations can easily persist until the dry period. Increased root to shoot and sapwood area to leaf area ratios may enhance water saving and leaf-specific hydraulic conductance, improving water availability in the planting hole and water transport respectively. Many of the observed enhanced survival rates are probably linked to morphological adaptations.

In conclusion, the response of seedling morphology and physiology to the treatments applied depended very much on the species considered. Drought preconditioning affected some of the morphological and physiological traits of the seedlings studied, but the magnitude of the changes was rather moderate as compared to that observed in other temperate and boreal species. Trends are related to reduce aboveground biomass, higher root growth and better physiological acclimation to drought in the field for preconditioned seedlings.
3.4. Selecting the Fertilization Geared to Target Seedlings

It has been known for a long time (Wakely, 1948) that mineral nutrition is just one of a number of physiological characteristics that contribute to a healthy seedling.

Figure 11. Cork oak (*Quercus suber*) seedling survival after outplanting in experimental plots with standard watering (dashed line and white squares) and drought preconditioning (solid line and black squares) Drought preconditioning treatment did not affect survival in our experiment although the drought-preconditioned seedlings consistently presented higher values than the control seedlings throughout the 32 months of observation.

Figure 12. Biomass of new roots colonizing the planting hole of *Q. rotundifolia* seedlings excavated after one year in the field (Mean ± SE, N = 5; C: Control seedlings; DP: Drought-preconditioned seedlings; From Rubio et al., 2001).
Figure 13. Shoot height of control (triangles, dashed line) and preconditioned (squares, solid line) *Quercus rotundifolia* seedlings after outplanting in the field (Mean ± SE; N = 5; significant differences: * p<0.05 and ** p<0.01; From Rubio et al., 2001).

A balanced nutrient status provides a reserve of mineral elements for the growth of new tissues until the seedling can be established in the field (Landis, 1985). Thus, all the essential nutrients are indispensable to structure the maintenance and functionality of plants. In fact, nitrogen (N), phosphorus (P) and potassium (K) form 75% of the nutrient concentrations in plant tissues, and thus are the most important nutrients in nursery culture techniques. Nitrogen is the main nutrient because it is a component of chlorophyll, amino-acids and proteins and plays an important role in photosynthetic carbon reduction processes (Margolis and Brand, 1990). It is also related to the post-planting recovery of photosynthesis processes, which are more efficient in leaves with a high nitrogen concentration (Folk et al., 1996). However, nitrogen can have negative effects, such as reducing stress resistance or provoking dilution effects of other nutrients (Grossnickle, 2000), which produce nutrition unbalance. Phosphorous is another crucial nutrient in ATP, starch and other carbohydrate formation; it encourages root rather than aerial growth (Salisbury and Ross, 1994). Potassium is implicated in osmotic regulation and enhances water stress resistance and low temperature resistance (Salisbury and Ross, 1994). Therefore, changes in nutrients will promote changes in seedling physiology and morphology.

The effects of complete NPK vs. single-element fertilization are currently under discussion. Very rapid decrease in leaf growth and higher allocation of carbon and nutrient resources to the roots were observed when nitrogen or phosphorus were excluded or were added to the culture solution at a reduced relative rate (Ericsson and Ingestad, 1988; Jovanovic et al., 2004); thus, fertilization could modify shoot:root ratios. On the other hand, an increased shoot:root ratio has at times been reported as negative for water stress avoidance and survival (Thomson, 1985; Haase and Rose, 1993); nevertheless, a low shoot:root ratio is not an advantage per se for containerized seedlings planted on dry sites (Bernier et al., 1995;
Diverse studies have indicated that fertilization may increase drought tolerance for several reasons. For example, N and P availability increases root growth potential and root hydraulic conductance (Singh and Sale 2000; Trubat et al. 2006); thus, the ability to capture soil water may be enhanced in fertilized seedlings (Reinbott and Blevins 1999). This can be crucial in degraded areas where nutrients may be limiting (Valdecantos et al. 2006). Nevertheless, it is common for seedlings with deficient N and P fertilization to show changes in their biomass accumulation and allocation patterns (Poorter and Nagel 2000) that may result in a decreased demand for water and a higher ability to endure drought. Moreover, nutrient deficiency may also enhance the accumulation of non-structural carbohydrates (Oliet et al. 2006), which may act as energy reserves allowing seedlings to withstand transplant shock (Burdett 1990). Obviously, each species has its own nutritional requirements for optimum growth and vigor; these requirements are not constant, however, and they change according to seedling growth (Birchler et al., 1998).

Also being debated are the best procedures for characterizing seedling quality (Mattson, 1997). Different fertilization regimes have been widely used to manipulate seedling size and reserves. Fertilization can accelerate the shoot and root growth of plants, modify tissue nutrient contents and hence the amount of available reserves, and improves post-transplant rooting by promoting a higher growth capacity in new roots as well as increased resistance to water stress (van den Driessche, 1984; Landis, 1985; Malik and Timmer, 1998; Grossnickle, 2000). In this sense, fertilization can be particularly relevant in Mediterranean areas, since nutrients influence seedling resistance to drought (Trubat et al., 2008, Luis, 2006). However, gearing this fertilization to target seedlings is an issue not yet resolved. Some studies suggest that, in semiarid areas, smaller seedlings may show better field performance and survival (Seva et al., 2000; Trubat et al., 2006); however, the opposite has been observed in Pinus canariensis (Luis, 2006).

Our results contribute to this debate. On the one hand, we raise the hypothesis that in semiarid areas fertilization improves the physiological status of seedlings during the establishment phase and accordingly favors root growth and increases survival. In this line, a comparative study was carried out by Luis (2006). Seedlings of containerized Pinus canariensis were cultured under two different regimes: Non-fertilized seedlings (cultured in natural soil: N-F) and fertilized ones (in fertilized peat: F). This study concluded that the fertilization treatment produced more developed seedlings (higher shoot height, root collar diameter, seedling biomass, shoot:root ratio and N content; Table 4) with lower mortality in the field during the first 17 months after outplanting: less than 10% in fertilized seedlings and 40% in non-fertilized seedlings (Figure 14). Previous studies pointed out a negative effect of higher shoot:root ratios on water stress avoidance (Thomson, 1985; Haase and Rose, 1993); this was not observed in our case. After three years of outplanting, the fertilized seedlings maintained higher shoot:root ratio, better physiological status and higher survival. A higher biomass allocation to roots post-planting seems possible, thereby enhancing water stress avoidance. This may be a specific behavior of Pinus canariensis, which is known to have a high biomass allocation to roots in the seedling phase (Climent et al., 2008).

Nutritional hardening, i.e., reducing the nutrient supply (particularly nitrogen) to promote stress-resistance mechanisms, has received less attention than water stress preconditionning. We propose that traits associated with nutritional stress, such as reduced aboveground biomass allocation and changes in root morphology and architecture may promote seedling drought resistance and enhance field performance.
Table 4. Morphological traits and foliar nutrient concentration (mg g\textsuperscript{-1}) of: Pinus canariensis seedlings grown under fertilized (F) and non-fertilized (N-F) conditions and seedlings of Pistacia lentiscus, Rhamnus alaternus, Rhamnus lycioides, Quercus coccifera and Tetaclinis articulata grown under standard nutritional conditions (C) and under late-season N deprivation (NH). Abbreviation: Fert., Fertilization treatment; H, Shoot height; D, Root collar diameter; SDW, Shoot dry weight; RDW, Root dry weight; S:R, Shoot:Root ratio; N, leaf nitrogen content. Data are means ± S.E (N=10 plants).

Different letters for a given species indicate significance differences at p < 0.05.

<table>
<thead>
<tr>
<th>Species</th>
<th>Fert.</th>
<th>H (cm)</th>
<th>D (mm)</th>
<th>SDW (g)</th>
<th>RDW (g)</th>
<th>S:R</th>
<th>N (mg g\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pinus canariensis</td>
<td>N-F</td>
<td>8.10± 0.16a</td>
<td>23.40 ± 0.03a</td>
<td>0.57 ± 0.02a</td>
<td>0.52 ± 0.01a</td>
<td>1.10 ± 0.04a</td>
<td>10.00 ± 0.11a</td>
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<tr>
<td></td>
<td>F</td>
<td>20.10± 0.34b</td>
<td>40.40 ± 0.03b</td>
<td>3.22 ± 0.32b</td>
<td>1.28 ± 0.13b</td>
<td>2.53 ± 0.11b</td>
<td>21.50± 0.13b</td>
</tr>
<tr>
<td>Pistacia lentiscus</td>
<td>C</td>
<td>9.00 ± 0.50a</td>
<td>2.00 ± 0.10a</td>
<td>0.90 ± 0.04a</td>
<td>1.10 ± 0.01</td>
<td>1.39 ± 0.14</td>
<td>10.50 ± 0.60a</td>
</tr>
<tr>
<td></td>
<td>NH</td>
<td>19.50± 1.30b</td>
<td>4.20 ± 0.30b</td>
<td>1.90 ± 0.02b</td>
<td>1.10 ± 0.02</td>
<td>1.59 ± 0.21</td>
<td>13.30± 0.40b</td>
</tr>
<tr>
<td>Rhamnus alaternus</td>
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<td>9.10 ± 0.70a</td>
<td>2.70 ± 0.10a</td>
<td>0.63 ± 0.03a</td>
<td>0.59 ± 0.04a</td>
<td>1.39 ± 0.31</td>
<td>15.10 ± 1.26a</td>
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<td></td>
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<td>1.88±0.24</td>
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<tr>
<td>Rhamnus lycioides</td>
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<td>2.00 ± 0.10a</td>
<td>0.63 ± 0.03a</td>
<td>0.59 ± 0.04a</td>
<td>0.96 ± 0.04a</td>
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</tr>
<tr>
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<td>0.90 ± 0.03b</td>
<td>2.01 ± 0.19b</td>
<td>21.10±1.10b</td>
</tr>
<tr>
<td>Quercus coccifera</td>
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<td>16.10 ± 1.40</td>
<td>3.70±0.20a</td>
<td>1.20 ± 0.02</td>
<td>4.70 ± 0.11</td>
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<tr>
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<tr>
<td>Tetraclinis articulata</td>
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<td>0.30±0.01</td>
<td>1.71±0.15</td>
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</tbody>
</table>

Figure 14. Temporal changes in the field mortality of Pinus canariensis seedlings during the first 17 months after outplanting (black bars: fertilized seedlings; grey bars: not fertilized seedlings).
To test this hypothesis, Trubat et al. (2008) evaluated the effects of nutritional hardening (by means of late-season N deprivation) on the morphology, growth and field survival of five Mediterranean woody species: *Pistacia lentiscus* L., *Rhamnus alaternus* L., *Rhamnus lycioides* L., *Quercus coccifera* L., and *Tetraclinis articulata* L. The results showed that nitrogen hardening reduced shoot size, root collar diameter, leaf area, specific leaf area (SLA), and root growth potential. Moreover, reduced nitrogen availability had a strong effect on foliar nutrient concentration, but the effect differed among species (Table 4). Seedlings deprived of N had a lower mortality range than those with standard fertilization three months after planting and six months later (Figure 15). Short-term field survival was highly dependent on the species and the nutritional conditions. The reduction in N supply resulted in smaller seedlings in 3 out of 5 of the species tested. Reduced growth rates are common in plants living in low-resource environments, including those characterized by drought (Chapin, 1991). *Q. coccifera*, *T. articulata*, and *R. alaternus* showed a significant reduction in SLA (data not shown) with N deprivation. These may reflect different proportions of new leaves in control and N-deprived seedlings. This study concluded that the short-term reduction of N availability prior to planting could be a promising technique to improve the establishment of woody species in semi-arid environments.

Figure 15. Temporal changes in the seedling field mortality of four Mediterranean woody species during the first 9 months after outplanting (black bars: standard nutritional conditions in the nursery; grey bars: late season N deprivation).
The two studies on this topic carried out by our research group have shown different results. Both methods of fertilization: on the one hand, optimum nutrition and, on the other hand, nutritional hardening, have shown positive results in the field. In this topic, the bibliography also shows contrasting results. Thus, we conclude that the effects of different N fertilization regimes are highly dependent on the specific behavior of each species, and that other factors must also be considered. It is obvious that more research needs to be undertaken in the areas of seedling quality enhancement and gearing the fertilization to the attributes of the target seedlings and the characteristics of the planting sites.

3.5. Applying Plants Growth Regulators (PGRs)

Growth regulators (PGRs) are synthetic chemical compounds that induce hormone-like responses in plants, promoting, inhibiting or modifying plant behavior and imitating the structure of the natural phyto-hormones (Kamara Keita, 2003). For this reason, synthetic PGRs have been acquiring increasing importance in improving the yield of agricultural crops and in ornamental plant production (Petracek et al., 2003). The use of PGR as a chemical tool to regulate the development of nursery cultures is an important objective in the agro-chemical industry. PGR use should make it possible to regulate the size and development of plants and promote other direct and indirect physiological effects in cultures, like stimulating flower formation, increasing the sturdiness of the stem or increasing photosynthesis and resistance to drought conditions, among many others (Weyers and Paterson, 1991). Nevertheless, the effect of exogenous PGR application on the physiological and morphological properties of woody plants has been studied relatively little. Recently, the use of PGRs has been introduced in forestry practices with the aim of improving plant stock quality and increasing seedling resistance to stress conditions. PGRs have been focused in growth inhibitors or retardants which regulate leaf and stem development and promote higher allocation to root system (Aphalo et al., 1997; Pardos et al., 2005). Thus, several PGRs are frequently used in forestry practices, e.g., Abscisic acid (ABA), Chlormequat chloride (CCC), Paclobutrazol (PBZ) and Ethylene-related compounds.

ABA is a well-known stress-inducible plant hormone and growth inhibitor which seems to play a predominant role in the induction of stress tolerance in plants (Davies and Jones, 1991; Franks and Farquhar, 2001). The diverse physiological effects mediated by ABA indicate that this compound possesses several mechanisms of action. One of the characteristic responses in plants is to increase the ABA content in roots and leaves against drought stress (Davies and Jones, 1991; Davies et al., 2005). It has been verified that the ABA formed in the roots is transported through the xylem to the leaves, where it causes stomatal closure, although no change in the water status of the leaves has taken place. Thus, the ABA contribution from the roots serves as a signal by means of which plants regulate their water status during drought and acclimate their functioning before the stress becomes more intense (Dodd et al., 1996; Davis et al., 2005). ABA has been regarded as a key component in water-deficit-induced responses, including those triggered by drought, salinity and low temperature. ABA not only affects stomatal response but it has also been observed to increase root hydraulic conductivity (Zhang et al., 1995).

PBZ and CCC are also widely used PGRs, which inhibit the biochemical synthesis of gibberellins (Rademarcher, 2000). This suppression of the biosynthesis of gibberellins occurs
in the apical meristems of plants. The consequent reduction in the levels of gibberellins diminishes the rate of cellular division and expansion (Rademarcher, 2000). CCC inhibiting actions take place in a previous phase to those of PBZ (Weyers and Paterson, 2001). The direct consequence on seedling morphology is a reduction in vegetative growth which leads to the indirect effect of altering the pattern of resources consumption within the plant. This effect implies an increased and improved distribution of the assimilates in the photosynthesis towards reproductive growth, formation of floral yolks, formation and growth of fruits (Chand and Lembi, 1994) or increased root biomass (Watson, 2004; Gandía, 2005). PBZ can be absorbed by stem, leaves or roots, thus it can be applied by spraying or as a treatment in the growing medium. CCC and PBZ have been reported as effective growth inhibitors of aboveground development. Aphalo et al. (1997) observed reductions in the stem length and aboveground biomass in *Betula pendula* after the application of CCC. In a comparative study, Williams et al. (1999) observed that PBZ is more efficient at reducing growth than CCC.

In general, PGRs should not affect the development of the root system. On the contrary, the reduction in aboveground biomass would increase the root to shoot ratio of seedlings. However, if the doses applied are too high it is possible to observe some negative effects on the root development (Aphalo et al., 1997). Some effects, such as a higher density of fine roots, have been related to an improved absorption of iron (Watson and Himelick, 2004) while other works have associated chlorosis effects in the leaves with the application of PBZ (Swietlik and Miller, 1985). In this context, an experimental study with PBZ, CCC and Ethephon in *Quercus suber* was carried out by our group. We observed that low doses of PBZ were more efficient at increasing the ratio of fine roots to total biomass than higher doses (Gandía, 2005). In the same study, PBZ was also found to be more efficient at regulating seedling growth than either CCC or Ethephon (Figure 16). Moreover, PBZ decreased seedling biomass, although the aboveground biomass was more reduced than the root biomass, and thus, the root to shoot ratio increased. In this sense, Pardos (2005) observed that the biomass reductions followed a quadratic trend with increasing doses of PBZ. Other papers have reported better responses against stress conditions, mainly in relation to more efficient stomatal control (Marshall et al., 2000; Scagel and Linderman, 2001), but also to higher antioxidant activity in leaves and roots (Pinhero et al., 1997). However, not all species responded in the same way. Treatment responses probably depend on the species involved, the doses applied and the mode of application. Comparing the effect of applying PBZ, CCC and Ethephon in *Quercus suber* seedlings, the authors observed changes in growth and in biomass allocation patterns which were not paralleled by changes in gas exchange, PSII photochemical efficiency or hydraulic conductivity of stems and root systems (Gandía, 2005; Pérez-Reverte, 2008).

Few studies have analyzed the effect of PGRs on survival and growth after outplanting. Marshall et al. (1991) compared the survival of Pinus banksiana seedlings treated with PBZ against that of control seedlings and reported that the treated seedlings were able to reach a survival of 89% in contrast with 0% survival in the control seedlings. The comparative study of three PGRs (PBZ, CCC and Ethephon) carried out by our group indicated that the survival and growth of seedlings under field conditions was not enhanced by PGR treatments (Figure 17). In contrast, PBZ treated seedlings had both lower development in the field and lower survival rates than the other treatments. These results call into question whether the efficiency of the treatments evaluated under controlled conditions will report good results under field conditions for forestry applications.
Figure 16. Effect of several PGRs on stem length in Cork oak (*Quercus suber* L.) seedlings during the nursery period. PGRs were applied with irrigation when seedling size was close to optimum values according to recommended sizes for this species. The PRGs chosen were paclobutrazol (PBZ), ethephon (ETF) and chlormequat chloride (CCC) at three different doses: PBZ (1, 5 and 25 mg/seedling); ETF (100 and 500 mg/seedling); and CCC (5, 15 and 30 mg/seedling). Doses were determined according to previous studies with other forestry species and manufacturer recommendations. *Q. suber* seedlings were grown in 350 cm$^3$ containers filled with limed peat and cocopeat substrate (1:1) in the nursery. Different letters mean significant differences among treatments at P<0.05 level. (From Gandía, 2005).

Figure 17. Survival in experimental plots of *Quercus suber* seedlings treated with PGRs. Period of observation: 17 months. Control seedlings (white circle), Chlormequat chloride -15 mg/seedling (white square), Ethephon – 100 mg/seedling (black triangle) and Paclobutrazol – 5 mg/seedling (black circle). From Vilagrosa & Chirino, unpublished Data CREOAK project Final Report.
In conclusion, the effect of PGRs to regulate growth and to improve drought tolerance in plants has been widely described and studied. However, their application within forestry practices has to date been scarce. The results being obtained in different research studies are promising in relation to modulating seedling growth, biomass allocation patterns and resistance to stress conditions, but it is necessary to contrast these results with research in the field.

4. TECHNOLOGIES TO IMPROVE SITE CONDITIONS IN THE FIELD

As mentioned above, water is the main limiting factor in Mediterranean countries, but it is probably not the only one. Degraded areas are less capable of retaining resources like water, which makes them particularly sensitive to drought (Noy-Meir 1973). On the one hand, their soils are frequently thin, crusted, with a low organic matter content, and thus unable to store sufficient amounts of water (Matson et al. 1997). On the other hand, their degraded plant cover loses its ability to retain water, which is then lost as runoff. Thus, one of the main priorities of restoration in the Mediterranean is to conserve water and soil by means of fluxes regulating water and nutrients and by reducing erosion (Vallejo et al. 2004). Another source of stress in degraded drylands is the incident radiation. Photoinhibition, reduction in photochemical efficiency and high leaf temperature are consequences of direct exposition to intense sunlight (Valladares and Pearcy 1997). Furthermore, elevated radiation enhances the intensity of other sources of stress, particularly drought. Some Mediterranean soils also show low levels of fertility (Vallejo et al. 1998; Díaz-Hernández et al. 2003), to the point that plant performance can be limited by nutrient availability (Carreira et al. 1997; Valdecantos et al. 2006). For example, low amounts of available P in highly calcareous soils constrain seedling performance (Valdecantos et al., 2006).

In this context, restoration programs in Mediterranean degraded drylands should aim to control the sources of stress and promote the capacity of plants to establish under adverse environmental conditions. Various tools and practices have been designed for this purpose. It is interesting to note that environmental technology to foster seedling establishment frequently mimics ecological interactions (Cortina et al., in press). New technologies have significantly improved plantation success by decreasing environmental impacts. Here, we review some of these advances and discuss future challenges in this area.

4.1. Soil Preparation to Improve Soil Water Availability to Seedlings

4.1.1. Runoff Harvesting

In drylands, runoff production is spatially heterogeneous and the distribution of net source and sink areas can be used to improve plantation success. Planting holes with their associated microcatchments, sometimes called negarim (Critchley and Siegert 1991), act as ‘microdams’ allowing runoff capture and a higher water storage capacity. In addition, the surplus water may help to reduce saline stress when soils are rich in soluble salts from natural or anthropogenic origin (Bainbridge 2002). Moreover, the microcatchments reduce runoff erosivity by creating sinks along the slope.
The use of runoff produced upslope ensures higher water availability for the planted seedling with lower economic costs than watering. The success of these techniques depends on various factors, including the amount and distribution of rainfall events, soil properties and topography. Lightweight and simple structures built in the terrain divert runoff water towards the planting holes, significantly decreasing water stress. For instance, Oweis and Hachum (2006) reported that the survival and normal growth of fruit trees planted on arid lands in Jordan (≈ 160 mm annual rainfall) was only feasible when implemented with water harvesting systems. Plant survival and growth can be promoted by digging two 1.5 m long, 0.20 m high ridges forming an oblique angle upslope from the planting hole (Figure 18). This runoff harvesting system has been described by Bocio et al. (2004), Fuentes et al. (2004) and Saquete et al. (2006).

In our own experiments in E Spain, microcatchment increased the survival of *Quercus ilex* seedlings by 15% five years after planting (Figure 19). In contrast, seedling morphology was positively affected after the first summer, but showed no significant response to microcatchments afterwards. In the same plantation, the survival of *Pinus halepensis* seedlings was not affected by microcatchments, but this treatment had a positive effect on stem height and root collar diameter which was still significant after 5 years. The functionality of the ridges was lost after the second year, when the positive relationship between soil moisture in the planting hole and upslope collecting surface vanished. At this stage, roots probably reached deep soil horizons and seedlings were less dependent on the capture of runoff water. This technique is technically feasible and economically affordable, and has been used for centuries in agricultural and agroforestry systems in arid regions worldwide (Juo and Thurow 1998; Prinz and Singh 2000; Mugwe et al. 2001; Blay et al. 2004; Abdelkdair and Schultz 2005). In addition, any overcosts may be balanced by the increase in seedling survival as replacement planting may not be necessary.
4.1.2. Increasing the Planting Hole Depth and the Use of Mulching

Soil preparation improves soil physical properties and enhances deep rooting. Surface soils become dry during seasonal droughts, and only seedlings reaching the deep soil horizons may be capable of withstanding this period (Padilla and Pugnaire, 2007). Alloza (2003) has shown that increasing the depth of the planting hole from 40 to 60 cm may increase seedling performance by 15%. But site preparation also exposes the soil surface to raindrop impact, which may promote soil surface sealing and crusting, thus reducing water infiltration (Ramos et al. 2000; Llovet 2005; Ries and Hirt 2008). Lower infiltration in the planting hole favors overflow, damaging the planting pits and promoting rilling.
Figure 20. Survival of one-year-old seedlings of three Mediterranean species 46 months after planting in a degraded montane shrubland in E Spain with (dark grey) or without (light grey) mulch application (bars are means and standard errors; n=3, significant differences: * p<0.05).

The application of plastic sheets, chopped plant debris and other types of mulch is an effective measure to reduce the kinetic energy of raindrops, avoid soil crusting and promote water infiltration. In addition, mulches reduce evaporation and contribute to controlling plant competition by hampering the establishment of neighboring vegetation (Roberts et al. 2005; Valdecantos et al. 2008). Thus, this technique has been successfully used in areas prone to drought (Jiménez et al. 2007; Valdecantos et al. 2008). In this context, we have studied the effect of clearing slash on the establishment of three Mediterranean woody species in a montane shrubland in E Spain. Quercus ilex and Rhamnus alaternus showed survival rates above 90% in all cases (Figure 20) and no response to mulching. In contrast, the survival of Pistacia lentiscus seedlings did not exceed 50% and was positively affected by mulching. Pistacia lentiscus is a thermophyllous, frost-sensitive species. Protection of the soil surface probably buffered the freezing temperatures occurring during the winter.

4.2. Improving Microclimatic Conditions and Soil Water Holding Capacity

High radiation levels and high evaporative demand characterize Mediterranean environments. Seedling survival is usually higher under the protection of a canopy than in open areas (Espelta, 1996; Vilagrosa, 1997; Broncano et al., 1998; Rey Benayas et al., 2005),...
but exceptions are not uncommon (Vilagrosa et al., 2001). The use of treeshelters or shade-cards may ameliorate the harsh conditions and improve the survival and growth of Mediterranean species. In addition to protecting against herbivores, treeshelters create a greenhouse microclimate for seedlings by increasing the temperature, relative humidity, and carbon dioxide levels (Burger et al., 1992) and reducing the incident radiation and evaporative demand (Adams et al. 1992). In fact, treeshelters protect seedlings from the desiccating effects of wind. Most of the species tested showed a positive response to treeshelters, including some growing under Mediterranean humid conditions, for example, *Quercus douglasii*, *Q. lobata*, *Q. wislizenii* and *Pseudotsuga menziesii* (Costello et al., 1996) and *Prunus avium* (Bergez and Dupraz, 1997; Bergez and Dupraz, 2000). Other researchers have carried out comparative studies on treeshelter types (Bellot et al. 2002; Oliet et al. 2003).

There is considerable evidence indicating that the key obstacles to plantation success are: a) the post-transplant shock experimented by seedlings after outplanting, and b) the intensity and length of summer drought (Burdett, 1990; Haase and Rose, 1992; Vallejo et al., 1999). To reduce the negative effects of both factors, the use of hydrogel as a soil amendment has been introduced in the last decades. In section 3.2, we analyzed the use of hydrogels for increasing the water holding capacity of substrates in nursery culture. In this section, we analyze the use of hydrogels as soil amendments in the field. This technique aimed at reducing water stress by increasing soil water availability to the planted seedlings, at reducing the post-transplant shock and the effect of summer drought.

Between 1996 to 2000, in the framework of the European REDMED project, research was carried out into the effects of hydrogel amendment and plastic treeshelter use on the reintroduction of seven Mediterranean species (*Ceratonia siliqua*, *Medicago arborea*, *Pistacia lentiscus*, *Quercus suber*, *Quercus ilex*, *Quercus macrolepis* and *Quercus coccifera*) in three Mediterranean regions (Algarve, Portugal; Lesvos, Greece and Valencia, Spain). This research indicated that the use of treeshelters improved survival in some species and improved shoot height consistently in all species. In contrast, the effects of the hydrogel treatment were variable and low. Before summer, some alleviation of the transplant shock was observed. But after summer, negative effects were observed due to poor root-soil contact. The combination of both treatments (treeshelters plus hydrogels) carried out in Algarve (Portugal) improved shoot height and root collar diameter in relation to control seedlings, but did not improve these variables substantially in relation to treeshelters alone (Vilagrosa, 2001, unpublished REDMED project Final Report). With respect to our study case (Valencia region), 9 years after planting one-year-old seedlings and seeding, the survival rate was between 60-70% (Figure 21), which is a good result as compared to other studies under similar field conditions (Valdecantos et al. 2006; Fuentes et al. 2007c; see also Figure 19), although was not found significant differences between treatments.

In those studies the use of treeshelters had increased seedling height by more than 60%; however, no differences had been observed with respect to basal diameter. This significant increase in plant height and nil effect on basal diameter due to treeshelters is very common in Mediterranean oaks, at least till the plant reaches the top of the shelter (McCreary and Teckling 2001). In our study, hydrogel use was not seen to significantly affect seedling morphology. A similar result has been reported on *Pinus halepensis* seedlings Barberá et al. (2005).
Figure 21. Seedling survival (above) and morphology (below) of 1-year-old holm oak seedlings nine years after planting (mean and standard error). CS=control seedling, S+TS=seedling with treeshelter, S+HG=seedling with hydrogel. Different letters mean significant differences among treatments at P<0.05 level.
4.3. Promoting Natural Ontogenetic Development

Most *Quercus* species have a pivot root that grows deeply into the soil. Nursery cultivation in forest containers causes root pruning which may hamper the species strategy to colonize deep soil horizons. The direct seeding of acorns could be a suitable technique to avoid root pruning and improve biomass balance and seedling morphology in relation to habitat conditions. However, the scarcity of rainfall events characteristic of Mediterranean drylands and the predation risk make germination a very uncertain technique. Seeding pregerminated acorns (McCreary 1996) may facilitate the germination stage and avoid the unbalanced morphological features of nursery-grown seedlings.

In this line, we carried out an experiment in Holm oak (*Quercus ilex*) by means of a complete factorial design that included two factors: 1) type of planting: direct seeded in the field vs. pregermination of acorns in the nursery and subsequent transfer to the field before the radicle reached the bottom of the container avoiding root pruning; and 2) treeshelter: protected vs. unprotected acorns. The overall survival of the seedlings nine years after the seeding was lower than 45% (Figure 22). These data included both germination success and seedling establishment. Pregerminated acorns, especially when protected by treeshelters, showed 2 to 4 times higher survival than directly seeded acorns. Treeshelters also promoted higher shoot height and basal diameter in pregerminated acorns. But the main positive effect of the treeshelter was the protection it provided against predation by micromammals. Gómez et al. (2003) reported that up to 96% of seeded acorns of Holm oak may be predated by rodents. In one of our experimental plots we recorded an acorn predation rate of 88% in the treatments without treeshelters. The introduction of pregerminated acorns faced several problems: assure seed viability and germination, permit an undisrupted growth of the tap root, and reduce the maintenance cost of the aboveground part by keeping a reduced leaf-to-fine root ratio.

4.4. Creating Islands of Fertility

The application of organic amendments in forest restoration has been receiving increasing attention in Mediterranean areas (Guerrero et al. 2001ab; Valdecantos 2001; Caravaca et al. 2003ab; Barberá et al. 2005; Larcheveque et al. 2005; Larcheveque et al. 2006ab; Fuentes et al. 2007abc; Querejeta et al. 2008). But this technique has rarely been implemented to date at management scale (but see Valdecantos et al. 2001; Bailly et al., 2004; Fuentes et al., 2007c for exceptions). Biosolids are a by-product of waste water treatment plants and show high contents of organic matter, nutrients and other components. Land application of biosolids is generally regulated by their heavy metal content. Nitrogen content must also be taken into account to avoid contamination of groundwater. An European Directive on the use of biosolids in restoration is currently being discussed, as no specific regulation has been approved to date (European Commission, 2000). It must be noted that the application of organic amendments in forest restoration differs substantially from applications in agricultural crops. The main purpose of this practice in forest restoration is to favor establishment and early growth of target species, while minimizing negative impacts on other components of the ecosystem.
Figure 22. Survival (above) and morphology (below) of Holm oak acorns nine years after seeding (mean and standard error). SA=seeded acorn, TS=treeshelter, PGA=pregerminated acorn. Different letters mean significant differences among treatments at P<0.05 level.

Applications should be made once or only a few occasions to avoid excessive load; they should be restricted to the planting holes thus leaving most of the area undisturbed; finally, the amendment cannot be incorporated into the soil by using common agricultural machinery. Exceptions to these constraints are quarries and roadside slopes where the functionality of the original ecosystem has been intensely altered (Figure 23).
Figure 23. Technical constraints for the application of organic amendments in degraded shrublands (above) and limestone quarries (below) are very different. Whereas application must be localized in time and space in the former, amendments can be spread over the whole area and thoroughly incorporated into the soil in the latter (Photo by D. Fuentes).

The application of organic refuses (i.e., biosolids plus municipal solid waste) in restoration generally enhances plant water status and growth (Querejeta et al., 1998; Querejeta et al., 2000; Valdecantos, 2001), turning a refuse into a resource. In contrast, seedling survival usually shows negative or no response to organic amendments. Some negative effects of the application of organic amendments which may partially explain seedling mortality have been identified: i) the forming of cracks and hollows when uncomposted fresh materials dry out; ii) the combination of drought and increased soil salinity in the rhizosphere (Fuentes et al., 2007c); and iii) the increased competition from weeds resulting from the localized increase in soil fertility. Amendments from industrial areas may contain high amounts of heavy metals.
However, the calcareous soils that are common in drylands have a high capacity to immobilize heavy metals, and dryland woody species may not be particularly sensitive to them (Fuentes et al., 2007a). Some of the above-mentioned risks can be avoided by using dewatered sludge, reducing the contact between roots and amendments, and adjusting doses and types of application to species requirements and site conditions. Application rates of composted and air-dried sewage sludge above 30 Mg ha\(^{-1}\) (equivalent to 570-670 kg N ha\(^{-1}\)) increased the mortality of *Pinus halepensis* Mill. seedlings. The synergistic effect of an intense drought and a weak increase in soil salinity during the first summer explained most of the variability in seedling survival, suggesting that these were the main factors of seedling performance. The joint analysis of seedling survival and growth showed that the application of composted biosolid at 30 Mg dry weight ha\(^{-1}\) significantly increases plantation success where average annual rainfall ranges from 350 to 600 mm (Figure 24). Under more stressful conditions optimum application rates may be lower as the impact of increased salinity may be more intense.
4.5. Using Biotic Interactions

Environmental techniques such as shading and fertilization mimic natural processes enhancing seedling establishment. These kinds of positive interactions have been known for a long time and were incorporated into early models of ecological interactions (Callaway, 2007), but it was not until the end of the 20th century that the ecological and evolutionary implications of positive interactions have been recognized. In this sense, interactions with so-called ‘nurse’ plants may significantly increase the performance of seedlings planted in drylands (Maestre et al., 2001; Gómez-Aparicio et al., 2004). However, most evidences are experimental, and few advances have been made in the implementation of these techniques at a management scale. The intrinsic dynamics of ecological interactions, e.g., their dependence on species, site and climatic conditions (Maestre and Cortina, 2004), makes this transfer particularly challenging.

Shrubs often dominate successional stages in areas that are suitable for the establishment of forests (Cabezas and Escudero, 1992; Torres, 2003), causing in some cases a negative effect on the establishment of new species. In this sense, the restoration of forested ecosystems in dense shrub layers may require resetting the succession (Cortina et al., 2006b) by reducing shrub dominance and reintroducing tree species. This alternative method could involve reducing the environmental stress on the new species. In the framework of the CREOAK project, we carried out an experiment with Quercus suber seedlings in the Sierra de Espadán (Spain). We concluded that strip clearing slightly improved seedling survival and notably increased its growth (Figure 25), especially when the seedling was planted in the middle of the strip, avoiding plant competition. Adding other treatments to the clearing one, such as treeshelters or microcatchments, did not improve survival, and only treeshelters produced taller seedlings (Cortina, 2006, unpublished CREOAK project Final Report). On the other hand, in the same experiment, seedling survival was negatively correlated with the abundance of obligate seeders such as Cistus salvifolius, and positively correlated with the abundance of resprouting species such as Erica arborea, suggesting that the interaction between Q. suber seedlings and extant vegetation may be species-dependent (Perez et al., 2007).

5. A Case-Study of Ecological Restoration to Combat Desertification in Semi-arid Ecosystems: The Albatera Demonstration Project (SE Spain)

The previous sections in this chapter have summarized the most recent advances in ecological restoration techniques and approaches. Dissemination and technological transfer to managers is a first step towards management-scale application of these improvements. The Albatera demonstration project has been implemented to put into practice the best available restoration techniques for the restoration of semi-arid ecosystems, to disseminate and transfer this technology to forest managers, to help in disseminating Forest Administration initiatives for combating desertification, and to promote society involvement in such tasks. The project was launched by the General Directorate for Biodiversity (Ministry of Environment, Spain), with the collaboration of the Valencian Regional Ministry of Environment.
Figure 25. Effect of treeshelters on survival rates, stem height and root collar diameter of *Quercus suber* seedlings 30 months after planting (third summer after planting). USTRI and MSTRI correspond to unprotected seedlings planted on the upslope and middle parts of a cleared shrubland strip. USHEL and MSHEL correspond to protected seedlings planted on the same sites. Bars correspond to average and standard errors of n=3 replicated plots.
Project implementation was carried out by the Forest Service of Alicante (Generalitat Valenciana, Spain), with scientific advice from the CEAM Foundation and the Department of Ecology of the University of Alicante.

The Albatera demonstration project was implemented in a small watershed of 25 ha located in the south of the province of Alicante (Spain), in the Albatera-Crevillente range, one of the areas most intensely affected by desertification in Southern Europe. Past grazing and wood gathering, slope terracing for cultivation and failed past reforestation efforts, together with recent forest road and water channeling works, have contributed to produce the deeply altered landscape patterns and soil surface conditions in the Albatera watershed. Land degradation in the Albatera area is worsened by scarce and highly variable rainfall and erosion-prone soils. The Albatera watershed presented three main problems to be addressed: 1) Degradation of ecosystem processes and functions, particularly soil water infiltration and nutrient cycling, linked to the degradation of the vegetation cover and leading to both a net loss in productivity and a loss of resources which are exported outside the watershed. 2) Deep alteration of the landscape characteristics as a result of land use changes. 3) High risk of floods due to intense precipitation events. To mitigate these problems, since the mid-60s, the Albatera catchment has been the object of several restoration efforts, fundamentally by means of plantations of pines (Aleppo pine), which have showed very poor results, with high values of seedling mortality and poor growth.

5.1. Restoration Strategy for the Albatera Project

The ecological restoration of desertification-prone areas is based in increasing the capture and conservation of resources. The main aims of the restoration program in the Albatera watershed were: a) Repair ecosystem functioning by enhancing patches of vegetation that contribute to the regulation of water, materials and nutrients fluxes; b) Increase species diversity in the area, and contribute to improvements in ecosystem stability and resilience against disturbances; and c) Reduce the risk of soil erosion and floods. These objectives led us to define a restoration strategy built on five blocks:

1) **Environmental units.** Define and identify landscape functional units considering the site heterogeneity and design specific actions for each unit.

2) **Improve the plant diversity, species richness and vegetation cover.** According to the potential vegetation in the area, introduce native evergreen trees and shrubs with a high potential for covering the surface, developing a dense canopy, producing litter, and recovering rapidly after disturbances. Avoid clearing the existing natural vegetation and foster the introduction and growth of spontaneous species by using organic amendments

3) **Innovative technologies in culture nursery.** Improve seedling quality, using specific protocols of nursery culture that take into account the morfo-functional development strategy of the seedling and its acclimation to environments with strong water limitations.

4) **Innovative technologies on site preparation.** Improve plantation success by applying recent research results and using the best technology available to improve seedling survival and growth.
5) Monitoring program. Establish a monitoring program to evaluate the performance of the actions and the success of the project.

5.2. Environmental Units

Seven environmental units (EU) of similar characteristics were identified, taking into account: slope aspect, degradation status, vegetation cover, and previous land use (Figure 26). For each environmental unit, specific restoration techniques were designed jointly with the combination of suitable species and plantation densities (Table 5). The environmental units and particular conditions considered were:

Head of the watershed (EU 1). Located in the upper part of the watershed and presenting moderate to high plant cover (grasses with sparsely distributed shrubs). Its degradation status was considered to be low and no restoration actions were applied to this unit (Figure 27).

Old Terraces with pines (EU 2). This unit was covered with old terraces (30-40 years old), afforested with Pinus halepensis. This past afforestation effort was unsuccessful and the area presented a severe degradation status (Figure 28). In this unit, the restoration actions were aimed at reducing the impact of soil loss due to terrace collapses and increase vegetation cover with resprouter shrubs. The restoration approach was based on the creation of soil-retaining vegetation barriers of deep-rooting and high-cover shrubs and trees (Figure 29).

![Figure 26. Landscape Digital Model. Distribution of the environmental units (EU) on the Albatera catchment (SE Spain). Pilot project on ecological restoration.](image-url)
## Table 5. Environmental units (EU), objectives, plant species and management techniques used in Case-study of a pilot project in Albatera (SE Spain)

<table>
<thead>
<tr>
<th>Units</th>
<th>Objective</th>
<th>Plant species</th>
<th>Management techniques</th>
</tr>
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<tbody>
<tr>
<td><strong>EU1</strong> Head of the watershed</td>
<td>No restoration actions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EU2</strong> Old terraces with pines</td>
<td>To reduce the impact of soil loss due to terrace collapses&lt;br&gt;To increase vegetation cover with resprouter shrubs species.</td>
<td>1, 2, 3, 4</td>
<td>Planting holes (60x60x60) and small furrows (300x60x60)&lt;br&gt;Density: variable as a function of pine death.&lt;br&gt;Addition of compost from sewage sludge (4 kg/hole).&lt;br&gt;Seedlings protected with a mesh to avoid predation</td>
</tr>
<tr>
<td><strong>EU3</strong> South facing slopes</td>
<td>To increase vegetation cover with resprouter shrubs species.&lt;br&gt;To improve runoff harvesting and environmental conditions for the introduced seedlings.</td>
<td>2, 3, 4, 5, 6, 7, 8</td>
<td>Planting holes (60x60x60) plus microcatchment&lt;br&gt;Density: 625 holes/ha&lt;br&gt;Addition of compost from sewage sludge (4 kg/hole).&lt;br&gt;Mulch in soil surface&lt;br&gt;Treesheeters (75% of shading)</td>
</tr>
<tr>
<td><strong>EU4</strong> North facing slopes</td>
<td>To increasing vegetation cover, species richness and plants diversity by using resprouter shrubs species.</td>
<td>1, 2, 3, 7, 9, 10, 11, 12, 13, 14</td>
<td>Planting holes (60x60x60)&lt;br&gt;Density: 400 holes/ha&lt;br&gt;Addition of compost from sewage sludge (4 kg/hole).&lt;br&gt;Mulch in soil surface&lt;br&gt;Mesh against predation that provides some shade (25% of light extinction)</td>
</tr>
<tr>
<td><strong>EU5</strong> North facing slopes with pines</td>
<td>To increase the species richness and plants diversity by using resprouter shrubs species.</td>
<td>1, 2, 3, 4, 10, 11, 12, 14</td>
<td>Planting holes (60x60x60)&lt;br&gt;Minimal density: 100 holes/ha&lt;br&gt;Seedlings protected with a mesh to avoid predation</td>
</tr>
<tr>
<td><strong>EU6</strong> River bed</td>
<td>To increase the density, richness and diversity of the riparian communities.&lt;br&gt;Create physical barriers to reduce the erosion and transport of sediments.</td>
<td>13, 15, 16,</td>
<td>Planting holes (60x60x60)&lt;br&gt;Minimal density: 100 holes/ha</td>
</tr>
<tr>
<td><strong>EU7</strong> Water channeling</td>
<td>Construction of small terraces with stone walls&lt;br&gt;To increase vegetation cover by means of a high density plantation&lt;br&gt;To facilitate natural establishment of opportunistic species, mostly grasses.</td>
<td>3, 4, 17, 18, 19</td>
<td>Planting holes (60x60x60) and small furrows (300x60x60)&lt;br&gt;High density: 2500 plants/ha&lt;br&gt;Addition of compost from sewage sludge (4 kg/hole and mixed with soil to allow the natural establishment of opportunistic species (i.e. grasses).&lt;br&gt;Treesheeters (75% of shading)</td>
</tr>
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Figure 27. View of the Head of the watershed environmental unit (EU 1; Photo by E. Chirino).

Figure 28. View of the Old Terraces with pines environmental unit (EU 2; Photo by E. Chirino).
South-facing slopes (EU 3). The fundamental problem of this unit was the low vegetation cover (Figure 30), which was mainly dominated by seeder shrub species. The degradation status of this unit was considered to be moderate. The actions were focused on increasing vegetation cover by using resprouting shrub species. To improve runoff harvesting and environmental conditions for the introduced seedlings, the treatments applied included microcatchments (Figure 19), treeshelters (greenhouse tubes with a minimum of 75% shade), organic amendments to soil (composted sewage sludge), and mulching.

North-facing slopes (EU 4). The degradation status of this unit was relatively low (Figure 31), and therefore the restoration effort in this unit was less intense than on the south-facing slopes. The actions were focused on increasing vegetation cover, species richness and plant diversity by using resprouter shrub species. Treatments included soil organic amendments and a protective mesh against predation that in addition provided some shade (25% light extinction). Micro-catchments and greenhouse tubes were not used.

North-facing slopes with pines (EU 5). Located in the lower part of the Albatera watershed, and covered by an open pine forest (*Pinus halepensis*) from an old reforestation, and with scattered native shrubs (Figure 32) such as Kermes oak (*Quercus coccifera*), juniper (*Juniperus oxycedrus*), Mastic tree (*Pistacia lentiscus*) and *Rhamnus lycioides*. The restoration objective for this unit was to increase the species richness and plant diversity by using resprouter shrub species.
Figure 30. View of the South-facing slopes environmental unit (EU 3; Photo by E. Chirino).

Figure 31. View of the North-facing slopes environmental unit (EU 4; Photo by E. Chirino).
River bed (EU 6). This unit was affected by landslides from adjacent slopes caused by the severe channel incision (Figure 33). The restoration actions in this unit were aimed at increasing the density, richness and diversity of the riparian communities. In the medium and long term, the developments of these communities were expected to create physical barriers to reduce the erosive power of the water and to minimize the transport of sediments.

Water channeling (EU 7). This unit was affected by the construction of an irrigation water conduction that crosses the Albatera watershed from east to west. Due to successive breakages and repairs, the area showed advanced soil erosion processes (Figure 34A). The objective was to stabilize the zone by: a) constructing small terraces with stone walls (Figure 34B), b) increasing vegetation cover in a relatively short time-frame by applying a high density plantation pattern (2500 seedlings/ha) and c) applying organic amendments to both the planting holes and the soil surface to allow the natural establishment of opportunistic species, mostly grasses.

5.2. Plant Species Selection and Nursery Culture

Plant species were chosen according to the potential vegetation of the area (Table 5). Within the wide range of species, we selected evergreen trees and shrubs with high potential cover for soil protection, high capacity to develop a dense canopy and accumulate litter, and fast recovery from disturbances so as to confer increased resilience to the whole ecosystem. Seeds were supplied by the Forest Services (Seed Bank, Regional Forest Service of Valencia) and collected in the same biogeographic area as the restoration project.
Figure 33. View of the River bed environmental unit (EU 6; Photo by E. Chirino).

Figure 34. Initial view of water channeling unit (EU 7) showing advanced soil erosion processes as a consequence of successive breakages and repairs of a water conduction pipe for irrigation (Photo by A. Vilagrosa).
Figure 34B. Final view of water channeling unit (EU 7) showing small terraces with stone walls to reduce or soil erosion and increase the vegetation cover in a relatively short time-frame by applying a high density plantation and others management techniques (Photo by A. Vilagrosa).

Seedlings were grown in high capacity containers (400 cm$^3$) that allow a good development of root system, and filled with a mixture of light peat and coconut fiber (50:50). The containers used had lateral ribs to impede root spiraling and stimulate the development of secondary roots. Seedlings were cultivated in direct sunlight for 9 months in the nursery under the same climate as the restoration area. Watering was adjusted to seedling needs, avoiding excess water. At the end of the nursery culture, we applied several mild drought cycles (“preconditioning phase”) to stimulate mechanisms of drought resistance and to induce dormancy. Fertilization was applied according to seedling growth with basic levels of N-P-K plus micronutrients. We applied a hardening fertilization (4:25:35, N:P:K) fixed to 50 ppm nitrogen during the preconditioning phase. This type of fertilization is recommended during the last phases of culture to inhibit shoot growth and facilitate preconditioning. Prior to outplanting, seedlings were watered to field capacity to assure a good water status. A sample of each species was used to characterize stock quality.

5.3. Short-Term Results

Reforestation actions were carried out during the winters of 2003 and 2004. The monitoring period was January, 2003 to November, 2007. Maximum mortality generally takes place after the first year of plantation. In the case of the Albatera pilot-project, after the first year in plantation, survival varied between the different environmental units. After 4 years, the average survival in the whole Albatera catchment of Albatera has been about 54% (Figure 35).
Figure 35. Averages for seedling survival, stem height and root collar diameter in the different environmental units (EUs) after four years of outplanting. (Albatera Ecological Restoration Project database. Dashed line indicates the average value for the whole Albatera catchment).
Figure 36. Survival, stem height and root collar diameter for the different species in the Albatera project after four years of outplanting (Mean ± standard error). Abbreviations: Qc: Quercus coccifera, Cs: Ceratonia siliqua, Pl: Pistacia lentiscus, Ta: Tetraclinis articulata, Ef: Ephedra fragilis, Rl: Rhamnus lycioides, Oe: Olea europaea sylvestris, Ph: Pinus halepensis, Oq: Osyris quadripaltra, Jo: Juniperus oxycedrus, Sg: Salsola genistoides, No: Nerium oleander, Taf: Tamarix africana. (Albatera Ecological Restoration Project database, with species in outplanting in December 2003. Dashed line indicates the average value for the whole Albatera catchment.)
Figure 37. View of some species after five years of outplanting in three environment units. From left to right: *S. tenacissima* in Water channeling environmental unit; *P. halepensis*, *C. siliqua*, *T. articulata* in North facing environmental unit and *E. fragilis*, *P. lentiscus*, *R. lycioides*, *O. europaea sylvestris* in South-facing environmental unit. The bar of wood with tape reference measured 83 cm to long (Photo by E. Chirino).

Generally, and in comparison with previous experiments by the forestry services of Alicante in the same zone and with other plantations carried out by CEAM in experimental plots, this survival rate in the catchment of Albarra can be regarded as moderately high and the growth reached by some species as remarkable. On the other hand, the rainfall regime during the years after plantation has been particularly dry, with an average of 221 L m$^{-2}$ of annual precipitation, which represents a reduction of about 20% with respect to the historical average for the area (285 L m$^{-2}$). In addition, the various summer periods without rain have been very long, with an average of 147 days without significant precipitations (> 5 L m$^{-2}$).

If we analyze the Environmental Units, EUs 6 and 7 (River bed and Water channeling) reached the highest values in seedling survival (> 83%). EU5 (North aspect with Aleppo pines) and EU3 (South aspect) showed above-average survival, 66% and 56% respectively. However, EU4 (North aspect slopes) showed lower values than EU3, with a survival of 40%. The most unfavorable results were observed in EU2 (Old terraces with pines) with average survival values of 30%. If these survival results are examined by species, it is possible to distinguish 4 species groups (Figure 36). The first group is composed of species with survival values between 92 and 100%, like *Stipa tenacissima*, *Lygeum spartum*, *Salsola oppositifolia*, *Nerium oleander* and *Ephedra fragilis*. The second group, composed of *Olea europea sylvestris*, *Salsola genistoides*, *Juniperus oxycedrus*, *Tetraclinis articulata* and *Tamarix africana*, shows survival values higher than 60%. The third group, with values between 50 to 60%, is formed by *Ceratonia siliqua*, *Pistacia lentiscus* and *Chamaerops humilis*, and the
fourth group, which showed the lowest values of survival (lower than 40%), is made up of *Rhamnus lycioides*, *Pinus halepensis*, *Osyris quadripartita* and *Quercus coccifera*.

In relation to growth, 63% of the species planted in Albartería reached plant height values higher than the global average (46 cm; Figure 36). Of these, *Tamarix africana* with an average height of 172 cm, *Salsola oppositifolia* with 113 cm, *Stipa tenacissima* with 102 cm and *Salsola genistoides* with 86 cm were the species with the highest growth. The species showing the lowest growth were *Tetraclinis articulata*, *Quercus coccifera* and *Ceratonia siliqua* (Figure 36), and they generally coincided with the species presenting the lowest survival rate. The highest root collar diameters (> 15 mm) were observed in *T. africana*, *E. fragilis* and *N. oleander* and the lowest were observed in *O. quadripartita*, *R. lycioides* and *Q. coccifera*, with values of about 4 mm (Figure 36). The root collar diameters of the remaining species were close to the average value. The figure 37 shows the development of some species after five years of outplanting in three environment units.

5.4. Conclusions and Lessons Learned

1) Combining the application of technological improvements with an adequate plant species selection in this ecological restoration project has resulted in an improvement in the reforestation outcome. These innovations have allowed to obtain better results than in previous experiments in the same area.

2) Plant species selection and adequate nursery culture protocols produced high quality seedlings with morpho-functional characteristics adapted to water-limited environments. Nevertheless, the survival and growth between the species was highly variable, as expected. The species with the highest survival rates were also those with the highest growth rates. On the other hand, in spite of the technological innovations applied, some very common species, such as kermes oak (*Quercus coccifera*), continue showing low rates of survival, thus reflecting unsolved problems in the use of this species for restoration. Some of the introduced species have flowered and fructified during the last years, which should contribute to the recovery of the area.

3) Field treatments have improved conditions for the introduced seedlings. In addition, they have made possible the development of an ample variety of opportunistic species which have also colonized the planting hole. Although these results could be detrimental for the introduced seedlings, the fact that vegetation cover and stability have increased represents an advantage for these degraded areas.

4) Several indicators have suggested the existence of an increasing gradient of functionality between the environmental units: north slopes (EU4) > old terraces (EU2) > south slopes (EU3). Nevertheless, a higher functionality did not necessarily correspond to a higher seedling survival rate, although a certain tendency in this respect was observed for some common species. In EU3, the combination of a higher technological investment and an adequate species selection may have compensated for the limitations imposed by the higher degree of soil degradation and higher abiotic stress in this unit.

5) The ecological restoration of degraded lands is a complex task. Low-cost land restoration techniques often fail in these harsh conditions. The limiting conditions prevailing in many degraded areas increase the cost of ecological restoration actions
that apply the best technology available. The introduction of keystone species or the increase in vegetation cover were surrogates for the main goal: restoring ecosystem functioning and allowing self-sustainable system organization.

6) Collaboration at local level among scientists and stakeholders, along with society involvement, has been key milestones towards the successful application of the ecological restoration program in Albatera. Monitoring and database elaboration should be intrinsic components of all restoration projects.

6. CHALLENGES AND OPPORTUNITIES FOR THE ECOLOGICAL RESTORATION OF DEGRADED DRYLANDS

Over the past few decades, substantial advances have been made in developing ecological restoration strategies and technologies for addressing the particular challenges of drylands – notably water scarcity, and severe land degradation associated with overexploitation and frequent disturbances. In the 21st century, however, climate change and the land uses changes, together with increasing human population growth, will force ecological restoration practices to address new challenges as well as having new opportunities.

First, since both the capacity and the resources for ecological restoration are limited, restoration practices must prioritize efforts and identify priority areas where prevention and restoration actions could be most effective. Socio-economic conditions can also impose limitations on the technology and inputs available for conducting restoration actions. However, knowledge on the feasibility and cost-effectiveness of the restoration strategies and available techniques over a wide range of environmental and socio-economic conditions is very scarce. Furthermore, the relationships between restoration potential, environmental stress and the necessary eco-technological inputs are complex and presumably non-linear (Suding et al., 2004; Maestre et al., 2006). More research is needed to help define these relationships, as well as cost-effective thresholds for the various conservation, management, and restoration alternatives.

We must also consider that high levels of natural heterogeneity are common in drylands areas. The spatial structure of semiarid landscapes has to be taken into account in planning and implementing ecological restoration at all spatial scales (Allen et al., 2002). Recent studies have shown that vegetation pattern plays an important role in the functioning of semiarid ecosystems (e.g., Bautista et al. 2007, Kéfi et al., 2007). At the landscape scale, patches are not isolated, and the interactions and transfers of materials between units can play a major role in ecosystem and landscape functioning. The within-site spatial design (Maestre et al., 2003) and the different spatial arrangements in the landscape submitted to restoration actions (Vanacker et al., 2005) may result in very different outcomes, particularly in terms of water fluxes, and should therefore be taken into consideration in dryland restoration programs.

On the other hand, the vulnerability of many communities depends on ecosystem structure and biodiversity. That is why the maintenance of biodiversity requires the full attention of restoration practitioners. We need to improve our understanding of the impact of restoration actions and strategies on biodiversity and sustainable management in drylands areas. In addition, restoration actions should be integrated with those aimed at conserving
biodiversity and mitigating the effects of climate change. This perspective requires the
development of multifunctional mitigation strategies.

Monitoring and evaluation of restoration actions are essential to refine restoration
approaches. Cost-benefit analyses, as well as evaluation of the effect of restoration practices
on major indicators of ecosystem function, composition, and services, can no longer be
relegated to being a minor and dispensable element in restoration programs. The development
of a complementary framework for knowledge sharing and technological transfer is equally
crucial if restoration efforts are to succeed on a large scale. Though there have been some
recent attempts to document, share, and disseminate knowledge on the successes and failures
of restoration actions (see, for example, REACTION Project; Bautista and Alloza, 2008), this
is still a major challenge in improving ecological restoration in semiarid lands. Scientific and
technical advances in restoration practices must be linked to adaptive management,
knowledge sharing, and dissemination of best practices.

Finally, climate change and its accompanying uncertainty pose a challenge to restoration
efforts. There is growing evidence that land degradation in drylands areas will worsen with
climate change (IPCC 2007). The immediate challenge becomes promoting ecosystem health
and resilience under the altered and changing conditions. Proactive restoration programs must
necessarily be built on projections of future scenarios. On the other hand, restoration is
accepted both as an effective means to mitigate the negative ecological effects of human
activities, and as one of many tools that can help to mitigate climate change. Though there is
still some debate about their efficacy in drylands areas, afforestation and reforestation
activities would contribute to carbon sequestration, thus reducing a major driver of climate
change. In the coming years, the societal demand for ecological restoration is expected to
increase as part of a comprehensive global strategy for mitigating climate change and its
effects.

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