New Forests (2012) 43:561–579
DOI 10.1007/s11056-012-9325-9

Perspectives in dryland restoration: approaches for climate change adaptation

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Received: 5 December 2011 / Accepted: 3 April 2012 / Published online: 20 April 2012

Abstract Reforestation efforts in dryland ecosystems frequently encounter drought and limited soil productivity, although both factors usually interact synergistically to worsen water stress for outplanted seedlings. Land degradation in drylands (e.g. desertification) usually reduces soil productivity and, especially, soil water availability. In dry sub-humid regions, forest fires constitute a major disturbance affecting ecosystem dynamics and reforestation planning. Climate change projections indicate an increase of drought and more severe fire regime in many dryland regions of the world. In this context, the main target of plantation technology development is to overcome transplant shock and likely adverse periods, and in drylands this is mostly related to water limitations. In this paper, we discuss some selected steps that we consider critical for improving success in outplanting woody plants, both under current and projected climate change conditions including: (1) Plant species selection, (2) Improved nursery techniques, and (3) Improved planting techniques. The number of plant species used in reforestation is increasing rapidly, moving from a reduced set of well-known, easy-to-grow, widely used species, to a large variety of promising native species. Available technologies allow for reintroducing native plants and recovering critical ecosystem functions for many degraded drylands. However, climate change projections introduce large uncertainties about the sustainability of current reforestation practices. To cope with these uncertainties, adaptive restoration approaches are suggested, on the basis of improved plant quality, improved techniques for optimizing rain use efficiency in plantations, and exploring native plant species, including provenances and genotypes, for their resilience to fire and water use efficiency.

Keywords Mediterranean ecosystems · Nursery cultivation · Reforestation · Species selection · Water harvesting

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Introduction

Drylands occupy approximately 40 % of the continental earth surface (White and Nackoney 2003), and may be classified as dry sub-humid, semi-arid and arid according to the ratio of mean annual precipitation to potential evapotranspiration (between 0.05 and 0.65), the FAO-UNESCO aridity index as adopted by the UN Convention to Combat Desertification (UNCCD, http://www.unccd.int). Productivity of drylands is mostly limited by water scarcity, and this scarcity is aggravated by desertification processes. Adult plants may survive drought owing to their growth plasticity and morphological and physiological adaptations. However, natural seedling recruitment and seedlings introduced through planting are extremely sensitive to drought, until the seedling root system is well-established in the soil. Therefore, the main challenge in dryland restoration using outplanting is overcoming drought at the seedling stage (Oliet et al. 2002).

In the moister range of aridity under the broad concept of drylands defined above, dry sub-humid regions are subjected to the impacts of semi-natural wildfires. Wildfires are natural in these and other regions of the world, but their occurrence and regime have been altered by human activities, especially during the last century (Pausas and Vallejo 1999). In the Mediterranean European countries, wildfires have dramatically increased during the last few decades in response to land abandonment and subsequent increased fuel load and continuity in rural areas (Vallejo and Alloza 1998). Wildfire has become a major objective of forest management in these fire-prone regions, and should be considered in reforestation planning. Forest plant species may be highly diverse in their flammability and in their fire vulnerability in a given region; therefore, reforestation planning has to take these features into consideration.

According to the IPCC projections, many dryland regions in the world, including the Mediterranean basin, will experience increased drought intensity, and potentially altered fire regimes (IPCC 2007), with a longer and more severe fire season as a result of increased drought and extreme meteorological events (e.g. heat waves). In SE Spain for example, a reduction of the total amount of rainfall is expected as well as a higher concentration in fewer events, resulting in high intensity storms. This new regime will generate a different inter- and intra-annual pattern of water availability for seedlings. As a consequence, semi-arid environments in this area will face potentially more severe and longer water shortages during summer, but also longer droughts within rainy-season periods. Therefore, to accommodate climate change projections, reforestation strategies and techniques in drylands have to be adapted to increased drought stress alone or in combination with increased fire occurrence in some dry sub-humid areas. This paper reviews the current and future limitations and alternatives in dryland restoration, using results from reforestation experiences in the Mediterranean basin where extensive plantations have been created over the past century or more (Vallejo 2009). Climate conditions range from dry sub-humid to semi-arid, and the land has been largely over-exploited, including deforestation, over millennia (Vallejo et al. 2006).

Limiting factors to reforestation: drought length and soil characteristics

Different biotic and abiotic factors constrain the success of reforestation projects in dry and semi-arid degraded areas. Low amounts of rainfall, uneven spatial and temporal rain distribution, and high evapotranspiration rates represent the main abiotic limitations. In particular, summer drought determines seedling mortality. For example, Alloza and

Vallejo (1999) reported that woody plant seedling establishment in Mediterranean environments is significantly reduced if there is a rainless period longer than 90 days during the first year. Navarro et al. (2006) observed that the establishment of forest seedlings under Mediterranean conditions is negatively correlated with the cumulated evapotranspiration of the site between planting (usually in autumn or winter) and June, and positively correlated with summer rainfall. In Mediterranean environments of California, Tyler et al. (2008) found that rainfall in the first year after planting was the main determinant of seedling survival for two oak species in California oak savannah.

In this context, an important strategy for Mediterranean woody species to cope with water limitation is the ability of seedlings to quickly reach relatively deep and moist enough soil layers to withstand the first drought period. Two direct factors determine whether these deep moist layers of the soil are reached before drought occurrence: soil depth and the length of the vegetative period from planting time to drought occurrence (Navarro et al. 2006). Therefore, soil depth is one of the soil properties that most influence seedling performance during the first year after planting (Alloza 2003; Bonfills 1978). High positive relationships between soil depth, soil moisture, and seedling survival have been observed (Padilla and Pugnaire 2007). Therefore, facilitating deep rooting of planted seedlings may be more important than increasing the volume of altered soil (Grantz et al. 1998; Padilla and Pugnaire 2007). Several authors have suggested a minimum threshold of 30 cm of soil depth before bedrock is reached to carry out reforestation actions (Bonfills 1978; Kosmas et al. 1999; Navarro et al. 2006), 40 cm according to our experience in Eastern Spain.

The effect of soils on seedling performance can not be explained solely by soil depth. Rather, other factors related to available water holding capacity, such as texture and stoniness, may be crucial in the success of reforestation. In general, fine textures have higher water retention capacity but lower percolation, aeration and organic matter mineralization rates than coarse soils. Reduced water availability in fine textured soils during drought has a strong influence on seedling survival (Valdecantos et al. 2006).

Degraded soils in drylands often show high rock content in hilly areas. Selective surface erosion of fine particles may give way to a superficial gravel pavement on top of the soil, e.g. in limestone uplands. Moderate rock contents positively affect the moisture regime and soil temperature. The presence of rock fragments in the soil can act as preferential water pathways (Van Wesemael et al. 1995). A soil surface stone layer can also act as mulch by reducing soil temperature and evapotranspiration, thereby leading to increased water availability, and protect the soil against compaction, runoff, and desiccation (Casals et al. 2000; Katra et al. 2008; Maestre et al. 2003). The role of these surface rock fragments can vary according to their relative position in the soil (Maestre et al. 2003; Poesen and Ingelmo-Sanchez 1992; Poesen and Lavee 1994), probably due to the temporal dynamics of fine-sediment entrapment and crusting. Above an optimal range of stoniness that can vary between 10 and 30 % (Poesen and Bunte 1996), the abundance of stones starts to negatively affect plant productivity, reducing resource availability to the seedling roots.

Species selection: functional traits and water-use strategies in water-limited ecosystems

Criteria for species selection in reforestation have been discussed for a long time beginning with the earlier extensive forest plantings more than a century ago, where the focus was largely on productivity and a few conifer species were used as pioneer species in ecosystem recovery. More recently reforestations are carried out using a larger number of native tree and shrub species, taking into account objectives other than simply productivity, i.e. plant biodiversity and functionality, soil conservation, climate change mitigation, among others (FAO 1989; Hernández et al. 2010; Vallejo 2009; van Andel 1998). The re-introduction of plants into degraded drylands in the Mediterranean will involve planning for several limiting factors related to a combination of high water stress and post-planting disturbances (e.g. recurrent wildfires and grazing) (Vallejo 2009). Apart from the old-identified limitations to re-introduce native species, climate change will likely have considerable influence and, should therefore play an important role in species selection. In this sense, mitigation and adaptation to climate change is of paramount importance in current and future restoration plans (Harris et al. 2006).

The use of native flora has been considered a priority in afforestation (FAO 1989; van Andel 1998), but their wide use has been hampered by seed availability and technical considerations during nursery period, especially for late-successional species. These species may have higher resource requirements, showing limited success in reforestation programmes due to high mortality and low growth rates after outplanting on degraded sites (Vallejo et al. 2006; Villar-Salvador et al. 2004a, b). This may be, in part, consequence of the poor knowledge of the autoecology and plant requirements of these species. In addition, until recently, the scarcity of native plant material available from nurseries or seed suppliers was a barrier to diversify species in plantations. Recent advances in the autoecology, ecophysiology, and plant functional traits of native flora are facilitating a larger number of available species in the nurseries and thus improved field results for restoration of degraded areas (Cortina et al. 2006; Chirino et al. 2009a; Puértolas et al. 2003).

In Mediterranean ecosystems, the main limitation for the successful introduction of plants is drought stress during summer months (Cortina et al. 2004; Vallejo et al. 2006), which is also likely extensive to other dry sub-humid semi-arid and arid regions of the world. Broadly speaking, plant species selection and breeding has focused on several characteristics regarding water use efficiency (i.e. higher carbon fixation per unit of water consumed), promotion of traits related to higher drought tolerance (i.e. antioxidant systems, vulnerability to cavitation), and root system characteristics required to optimize water uptake. In recent times, a large number of papers have focused on the study of combinations of plant functional traits observed in water limited ecosystems (Ackerly 2004; Hernández et al. 2010; Paula and Pausas 2006) and several studies have focused on species comparison and plant quality for reforestation (Chirino et al. 2008; Hernández et al. 2009; Trubat et al. 2011; Villar-Salvador et al. 2004b).

Further aspects to be considered in species selection in the face of climate change relate to the relationships between functional characteristics and species lineage ("phylogenetic relatedness"; Hernández et al. 2011; Paula and Pausas 2011; Pratt et al. 2010). From an evolutionary point of view, some species in Mediterranean areas of the world have evolved from Tertiary lineages (pre-Mediterranean), whilst others evolved during the Quaternary when Mediterranean climates emerged (Herrera 1992). Pre-Mediterranean species correspond to Pre-Pliocene taxa, which evolved under a tropical-like climate and later survived in current Mediterranean areas but retain traits from their earlier heritage (Quézel 1995; Thompson 2005). These taxa show similarities among themselves including sclerophyllous leaves, wind pollinated flowers, and endozoochorus seeds. They include plant species of the genera *Quercus*, *Rhamnus*, *Pistacia*, *Phyllirea*, among others; however, these convergent traits were not shaped by a Mediterranean climate (Thompson 2005; Verdú et al. 2003). Other traits of pre-Mediterranean and Mediterranean species are related to regeneration after disturbances and rooting habit. Root system characteristics are another suite of plant traits showing phylogenetically relatedness (Paula and Pausas 2011; Verdaguer and Ojeda 2002). The main regeneration characteristic in Pre-Mediterranean species is by means of resprouting after disturbance from underground buds (Verdú et al. 2003). Although some Quaternary species can also present this trait, most are obligate early seeders or facultative resprouters with less well developed root systems. It has been observed that roots of resprouter species have characteristics associated to a deeper penetration in the soil than those found in seeder species (Canadell and Zedler 1995) and, in addition, roots in resprouters also may function as storage organs (Verdaguer and Ojeda 2002).

Resprouter species are considered more suitable for reforestation plans in fire-prone areas. These species have the capacity to quickly regenerate after disturbances, thus promoting ecosystem resilience (Ferran et al. 1992; Vallejo and Alloza 1998). The capacity of responding via regeneration after aboveground biomass removal is mediated by an extensive root system which allows access to deep water reserves in the soil (Canadell and Zedler 1995; Jacobsen et al. 2007). By contrast, non-resprouter individuals die in canopy fires and their regeneration solely relies on early seed germination, depending on seed traits and seedling functional characteristics (Moreira et al. 2010; Paula and Pausas 2006). In addition, obligate seeders frequently accumulate high quantities of dead biomass in the short-term which may facilitate wildfires (Baeza et al. 2002, 2005; Schwilk and Ackerly 2001). In relation to water stress tolerance at the physiological level, seeder and resprouter species are found to be two functional plant groups (Hernández et al. 2011). Seeders, in a broad sense, are frequently shallow rooted species and present some specific functional characteristics related to response to drought conditions (Hernández et al. 2011; Pratt et al. 2010). They show higher rates of gas exchange, associated with an efficient photosynthetic machinery (i.e. high rates of carbon fixation), but also high rates of water consumption. By contrast, resprouter species have a more conservative water use strategy with high water use efficiency (Hernández et al. 2010, 2011). In addition, seeders are found to be more drought tolerant with morphological traits adapted to resist high xylem tension and low vulnerability to cavitation (Hernández 2010; Pratt et al. 2010). This array of traits probably makes seeders more competitive in water limited ecosystems than their counterparts (Groeneveld et al. 2002). However, their capacity to survive with low (fuel) moisture content makes these species more flammable and vulnerable to fire mortality. Although both functional groups coexist for a long time and often in quite similar proportions in a site (Pausas 2004), changing conditions in the future may influence decisions about which group to emphasize. In some intense degraded areas of southeast of Spain, the use of summer-deciduous drought avoiding species may be recommended due to their morpho-functional characteristics like leaf shedding during unfavourable summer conditions, and a competitive strategy of high rates of photosynthesis during periods of high water availability (García-Forner 2010). In areas where higher fire frequencies are expected, resprouter species may be advantageous because of their ability to survive repeated burning without relying on seed set to replenish depleted seed banks and their lower fine and dead fuel accumulation rate.

Some guidelines for species selection can be summarized as follows:

- Original species and community composition: Analyze what native species are suitable for the habitat to be restored from field observations or reference studies on area phytosociology.
- Identification of critical site characteristics in degraded lands: soil limitations, microclimate conditions. Assess whether conditions for plant establishment can be readily modified (e.g. through soil amendment or use of nurse plants).

- Restoration objectives: From the set of suitable species to the habitat to be restored, select those that best fit to the management objectives proposed.
- Species autoecology: Morphological and functional characteristics will determine species suitability according to their capacity for acquisition of resources, drought tolerance, plant competitiveness, and acclimation capacity, among the most relevant characteristics.
- Technical constraints. The introduction of species in a restoration project requires the technical knowledge of the species cultivation requirements, planting techniques (including planting windows), and its plasticity in tolerating fluctuating environmental conditions.

Nursery techniques to improve seedling quality

Nursery culture has an impact on seedling quality and, consequently, survival in the field (Del Campo et al. 2010; Oliet et al. 2009). Morphological and physiological traits of seedlings in relation to water stress play an important role in predicting their survival and field performance. In this context, and in addition to conventional good quality seedling production standards, seedling stock quality should focus on enhancing the growth of the root system by improving the water holding capacity of the substrate of the root plug, by using adequate containers, and by promoting mechanisms for drought resistance and high water use efficiency (Chirino et al. 2009a).

Increase the water holding capacity of the substrate of the root plug

An increase of water holding capacity of the growing media used in the nursery could provide an extra water supply in the critical early post-plantation period. Several studies have indicated the importance of the growing media in the quality of the plant produced (Marfà et al. 2002; Owen et al. 2008). Currently, a wide variety of organic and inorganic materials are available for producing the different types of growing media used in nursery cultures, e.g., sphagnum peat moss, coconut peat, vermiculite, perlite, sand, clay, and composting of forest waste, cattle manure and sewage sludge, etc. Our team has used a standard substrate (i.e. a mixture of limed sphagnum peat moss and coconut peat 1:1 v/v) with satisfactory results. This growing medium uses lightweight materials, showing low bulk density (BD = 0.90 g cm^{-3}), high values of total porosity (EPT = 94 %), high aeration capacity (AC = 35 %), adequate value of easily available water (EAW = 22 %) and moderately low water reserve (BC = 6 %).

Hydrogel has been successfully used in agriculture and forest restoration as soil amendment (Al-Humaid and Moftah 2007; Hüttermann et al. 1999), increasing soil water content (Akhter et al. 2004). Moreover, hydrogel increases water-holding capacity of the peat-based growing media (Arbona et al. 2005). We have observed higher water content in a peat-based growing media mixed with hydrogel (HS, granulometry: 0.2–0.8 mm) at 2.0 %, w/w (HS-2 %) than control growing media (CS) and hydrogel mixed at 1.0 % during a drought period (G-$G' < 0.001$; Fig. 1). This higher water availability of the root plug, as a consequence of a higher water holding capacity in the substrate, can increase shoot growth in height but not in the root collar diameter (Akhter et al. 2004; Chirino et al. 2011; Hüttermann et al. 1999). In some cases, the hydrogel produces a significant increase in aboveground biomass (Frantz et al. 2005; Ochoa et al. 2009), although this effect was

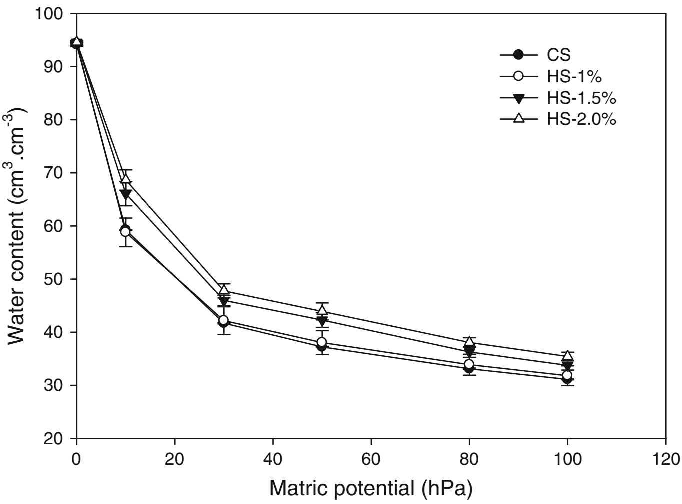

Fig. 1 Water release curve of growing media used in nursery culture of *Quercus suber* seedlings (Mean ± SD, N = 3). Treatments: Control substrate (CS, a mixture of limed peat and coconut peat, 1:1 v/v); CS with hydrogel mixed at 1 % (HS-1 %), at 1.5 % (HS-1.5 %) and at 2.0% (HS-2.0 %). *Symbols* per treatment: CS = *black circle*, HS-1 % = *white circle*, HS-1.5 % = *inverted black triangle*, HS-2 % = *white triangle* (Modified from Chirino et al. 2009b)

not observed in our experiments (Chirino et al. 2011). On the other hand, several field results have indicated the beneficial effect of hydrogel on seedling survival, both as a soil amendment (Al-Humaid and Moftah 2007; Hüttermann et al. 1999) and mixed with a peat-based growing medium (Arbona et al. 2005). We observed that hydrogel added to the culture substrate at 1.5 %: (1) increased the water holding capacity of the root plug (high volumetric water content), (2) improved seedling water status (higher predawn leaf water potential and stomatal conductance in a controlled drought period in the nursery and lower carbon isotopic composition in outplanting), and (3) enhanced seedling survival in the field (Chirino et al. 2011). Nevertheless, some studies warn that a large dose of hydrogel can produce negative effects (Sarvaš et al. 2007). In this sense, a test of mortality in greenhouse conditions with *Pistacia lentiscus* and *Quercus ilex* showed that a peat-based growing medium mixed with hydrogel at 2.0 % produced an early mortality respect to control substrate not mixed with hydrogel (Fig. 2). Hydrogels can absorb a volume of water 400 times their own weight (Bouranis et al. 1995), which greatly increases their volume. Therefore, a peat based growing media mixed with high proportions of hydrogel can create lumps of hydrated hydrogel grains in the root plug. These wet expanded lumps will generate large air-filled macropores when drying, which may interrupt the continuum of the water column in the substrate and the contact of the root with the substrate after outplanting, reducing water uptake by roots in the plug.

Using deep containers to develop a deep root system

A deep root system may be an advantage to forest plant survival. It allows access to water from deep soil horizons where some water is available even in the driest seasons, avoiding the summer drought stress (Gibbens and Lenz 2001) and the indirect water stress derived from plant competition (Pinto et al. 2012). Nursery containers modify the morphological

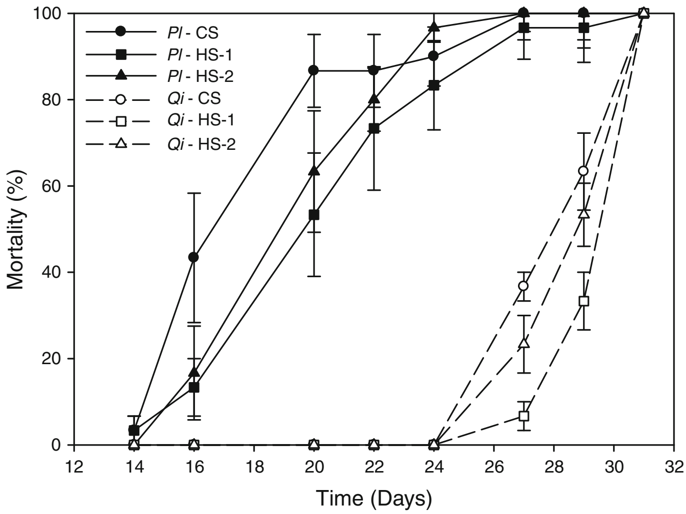

Fig. 2 An imposed drought period under greenhouse conditions tests the 100 % mortality threshold of *Pistacia lentiscus* (*Pl*) and *Quercus ilex* (*Qi*) seedlings under various hydrogel treatments. Each point is the mean accumulated mortality of 30 seedlings distributed in 6 blocks. Treatments: Control substrate (CS, a mixture of limed peat and coconut peat, 1:1 v/v), CS with hydrogel at 1 % (HS-1) and at 2 % (HS-2). Symbols per treatment and specie: *Pl*-CS = *solid line* and *black circle*, *Pl*-HS-1 = *solid line* and *black square*, *Pl*-HS-2 = *solid line* and *black triangle*, *Qi*-CS = *dash line* and *white circle*, *Qi* -HS-1 = *dash line* and *white square*, *Qi* -HS-2 = *dash line* and *white triangle*

and physiological characteristics of seedling root systems (Domínguez-Lerena et al. 2006; Tsakaldimi et al. 2005). The use of a deep container in species developing a main tap root during the nursery culture period, such as *Quercus* species, can favour the growth of a deep root system in the field. Our experience using deep container (paperpot type, depth: 30 cm, diameter: 5 cm) in *Quercus coccifera*, *Q. ilex,* and *Q. suber* produced seedlings with a longer tap root and deeper root system in the planting hole. We have recently experimented the use of a prototype of deep container made of high-density polyethylene (denominated CCL-30), with a depth of 30 cm, a diameter of 5 cm, a volume of 589 cm^3 and a plant density of 318 seedlings/m^2 (Chirino et al. 2008). Using this prototype, *Q. suber* produced seedlings with a longer tap root and higher rooting depth, which allowed the roots to quickly reach the deeper soil horizons by means of higher growth in the number and biomass of new roots. These morpho-functional advantages from deep container CCL-30 promoted a higher root water transport capacity in the root system (root hydraulic conductance measures), leading to improved water status under drought stress conditions (stomatal conductance measures), verified by means of an imposed drought period (Fig. 3; Chirino et al. 2008). Similar results have been reported by Pemán et al. (2006) and South et al. (2005).

Applying drought preconditioning to develop mechanisms of drought resistance

Nursery culture can include hardening techniques to prepare seedlings for different stress types once they leave the nursery (Landis et al. 1998). Drought preconditioning is one of the hardening techniques used to induce drought-resistance mechanisms in seedlings and

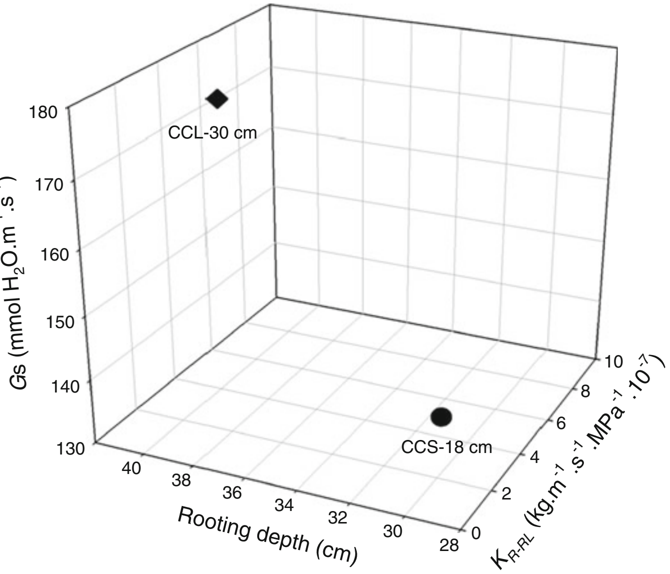

Fig. 3 3D figure using three variables: rooting depth (cm), horizontal x-axis; stomatal conductance (*Gs*), vertical y-axis; and root hydraulic conductance ($K_{R\text{-}RL}$), horizontal z-axis. *Black diamond*: deep container, CCL-30 cm and *black circle*: container of standard depth, CCS-18 cm. Deep container shows higher rooting depth, root hydraulic conductance and stomatal conductance (Modified from Chirino et al. 2011)

consists of exposing seedlings to controlled drought stress in the nursery. As a general procedure, drought preconditioning should be carried out during the last months of nursery culture, which is right before outplanting. In this technique, it is necessary to consider intensity and duration of drought preconditioning. The levels of stress applied should be considered species-specific. In this sense, several studies have observed different response of species to the same drought conditions (Cregg 1994; Vilagrosa et al. 2003), and that treatments with very intense drought conditions show poorer results than mild or moderate drought levels (Villar-Salvador et al. 2004a). On the other hand, the length of the drought preconditioning period can also influence seedling performance (Villar-Salvador et al. 2004b). Chirino et al. (2003) indicated that long preconditioning periods (e.g. 6 months) produce significant morpho-functional acclimation changes in *Quercus suber* with respect to its biomass allocation patterns, showing lower shoot biomass, lower root biomass, and higher root:shoot ratio (Chirino et al. 2003) and higher water transport capacity by roots (Chirino et al. 2009a). However, in the field, although the drought-preconditioned seedlings showed certain tendency to higher survival values than the control seedlings; drought preconditioning did not affect plant survival (Chirino et al. 2009a).

In general, plant response will depend on species and the degree of stress applied (Chirino et al. 2009a; Vilagrosa et al. 2006). In spite of the results observed, drought preconditioning continues to be a controversial technique between the specialists and nursery technicians. However, our results showed that, for the species tested, some degree of preconditioning improves acclimation of seedlings to field conditions. In this sense, we recommend a suboptimum watering from the rapid growth phase to the end of nursery culture, with the aim of favouring the acclimation of seedlings to field conditions.

Field techniques to improve water availability

As previously mentioned, climate change projections indicate a reduction of precipitation will occur across the Mediterranean basin. The ecological restoration of semi-arid and dry-subhumid degraded lands involving woody seedling plantations should develop field techniques to maximize water availability for introduced seedlings, especially during the first post-planting period. Techniques should be effective to enhance growth of seedling root systems beyond the planting hole. In this context, our group has tested some of these techniques aimed at maximizing water collection and minimizing water loss in the restoration of semiarid degraded areas in SE Spain by planting seedlings of wild olive tree (*Olea europaea* ssp. *sylvestris*), a key shrub species of Mediterranean semi-arid ecosystems.

Runoff harvesting

Capturing runoff water (runoff harvesting), promoting infiltration, enhancing water holding capacity, and reducing evaporation are complementary actions that may result in higher water availability to seedlings and therefore may increase plantation success (Fig. 4). Runoff production responds to vegetation distribution pattern, presenting high spatial heterogeneity because of geomorphological, edaphic and vegetation features (Martínez-Mena et al. 1998; Puigdefábregas 2005). This results in sink and source areas depending on the balance between resource retention and export. Microcatchments are simple structures designed to increase the surface of land (*source*) that supply runoff water to the planting hole (*sink*) by shaping small channels at both sides of the hole that direct collect runoff to it (Shachak et al. 1998; Whisenant 1999). This technique is very efficient and less expensive than other watering systems that has been applied from centuries in agriculture and agroforestry systems in arid regions all around the world (Abdelkdair and Schultz 2005; Tubeileh et al. 2009), and does not imply much overcost from a traditional plantation. In arid to semiarid setting reforestations, microcatchments increase soil moisture and seedling survival and growth with respect to conventional planting holes (Edwards et al. 2000;

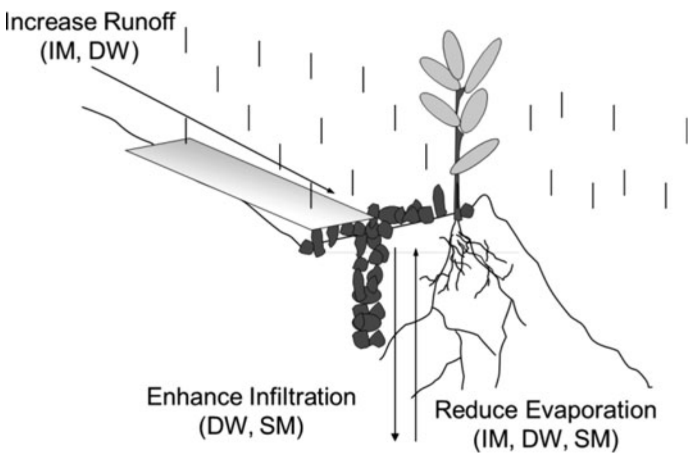

Fig. 4 Planting field techniques and water-related processes aimed at optimizing water availability to planted seedlings. *IM* improved microcatchment, *DW* dry well, *SM* stone mulch (see text for descriptions)

Fuentes et al. 2004). Some of the experiments carried out by our group under semi-arid conditions did not show positive effects on seedling performance in the short term, but other authors found them over the long term (Saquete et al. 2006) and under abandoned farmland conditions (Bocio et al. 2004). Microcatchments usually have positive relations between growth of the planted seedling and microcatchment dimensions (Li et al. 2006a) but other natural site factors such as plant cover, rain intensity, slope, and soil properties will determine the direction and magnitude of the effects (Bainbridge 2007). The effectiveness of this technique is of course restricted to rainfall events generating surface runoff.

Little attention has been paid to the use of inexpensive agricultural techniques in aridland restoration, such as plastic mulches. The implementation of plastic sheets upstream the planting hole has been selected among other water harvesting techniques (Li et al. 2006b) as it reduces the interception of runoff by microtopography (stones and plants) and generate runoff even for very light rain events (Li 2000; Li et al. 2008; Wang et al. 2005). Rainfall events lower than 10 mm are the most frequent (up to 90 % of total events, Mayor et al. 2011) under semiarid conditions in SE Spain, also in summer. Therefore, and considering that plant ecophysiological responses depend on both the volume and duration of the water pulses (Schwinning and Sala 2004), these events might be considered as non exploitable by vegetation (Domingo et al. 1999). Plastic sheets may convert unprofitable light rain events into natural emergency water pulses, improving the limited efficiency of the traditional microcatchments. Using microcatchments implemented with a 300 cm^2 plastic sheet upstream the planting hole (*Improved Microcatchment*) in the restoration of semi-arid areas, we observed an improvement in the amount and durability of these water pulses in relation to traditional planting benches, even in late spring and summer months when water stress is exacerbated (Valdecantos et al. 2009, Fig. 5).

It is known that rock fragments embedded in the soil surface affect hydrological processes of semi-arid soils (Katra et al. 2008; Kosmas et al. 1998). As well, the presence of

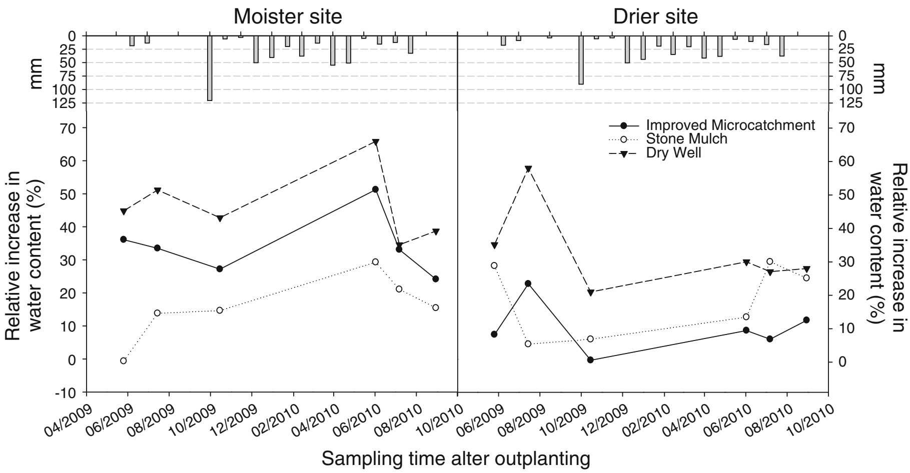

Fig. 5 Relative effect of the three different experimental treatments on soil volumetric water content (0–25 cm depth) as compared to traditional planting holes [$y = ((T_1 - T_0)/T_0) * 100$, where T is the mean of the variable of $n = 10$ measurements, T_1 represents the treatment and T_0 the traditional control holes] in two experimental reforestation sites under Mediterranean semi-arid conditions. Plots and treatments were established in February 2009. *Bars* on the *top* represent monthly rainfall recorded at each experimental site (adapted from Valdecantos et al. 2009)

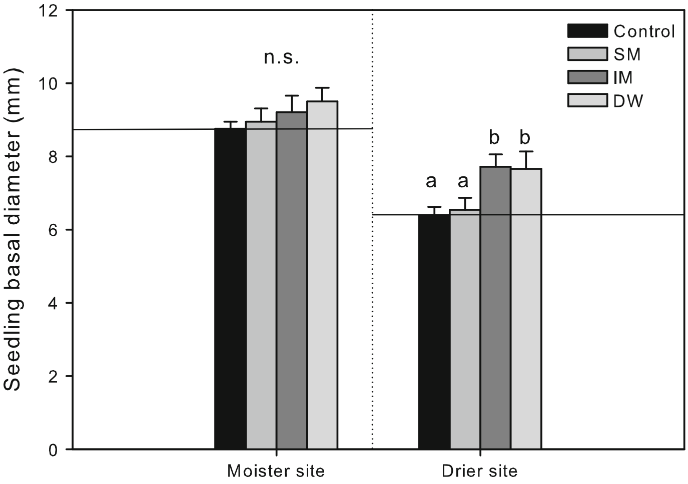

Fig. 6 Seedling basal diameter of *Olea europaea* ssp. *sylvestris* individuals 2 years after planting under Mediterranean semi-arid conditions as affected by water optimization treatments. *Different letters* denote significant differences between treatments ($P < 0.05$). *Horizontal lines* mark data of control seedlings as reference. Treatments (see text) *SM* stone mulch, *IM* improved microcatchment, *DW* dry well (adapted from Fuentes et al. 2009)

rock fragments in the soil profile may also facilitate the penetration of the wetting front down the soil profile by decreasing the density of fine earth and increasing macropores (Van Wesemael et al. 1995); this may also reduce evaporation losses and enhance ground water recharge (Li 2003). A dry well filled with stones (*Dry Well*), 20–25 cm deep and close to the planted seedling promotes infiltration around the root system before collected water evaporates (Bainbridge 2007). As a consequence, planted seedlings may have higher water availability for longer periods and remain less affected by high evaporation rates (Gupta 1994). We have observed that wild olive seedlings planted with dry wells under semiarid field conditions increased survival and growth (basal diameter) in the first post-planting seasons as compared to conventional planting techniques (Fuentes et al. 2009, Fig. 6). Therefore, seedlings may be sensitive to the more favorable conditions in the planting holes (Fig. 5), but some other physical (soil depth, texture) and/or biotic (extant vegetation type and cover) properties of the sites can restrict the plant response (Smanis et al. 2011). Our experience shows that these techniques were more effective as stress increased (driest site, in Fig. 6) where productivity was markedly lower. Moreover, the implementation of a single technique had less effect on soil moisture or seedling survival, suggesting the relevance of simultaneously promoting infiltration and reducing evaporation.

Mulching the soil surface with gravel (*Stone Mulch*), plant refuses, or plastic materials may also reduce loss of water by soil evaporation. Using gravel for these techniques (stone mulch) is a cheap and sustainable option as this material is usually available and often abundant in many restoration sites in drylands.

Fog harvesting

Fog represents an important input of water for certain ecosystems all around the world. For instance, in California redwoods, fog interception by needles of *Sequoia sempervirens* trees represents up to 34 % of the total input of water during a whole hydrological year (Dawson 1998). In Canary Island laurel forests, water from fog may account for 20–45 % of conventional precipitation (Ritter et al. 2008). In a dry inland area of the Valencia region (E Spain), captured fog water measured 1,200 l m^{-2} (referred to m^2 collector), while direct rainfall measured only 500 l m^{-2} (Estrela et al. 2009). Although mountain ranges of southern areas of the Valencia region do not meet ideal physiographic conditions for fog collection, we installed two experimental planting plots (Benidorm and Crevillente sites) of *Olea europaea* seedlings under semi-arid conditions and deployed in each planted seedling a small individual collector with pipes to carry captured water directly to the seedling (Fig. 7). A subset of seedlings was planted without fog collectors to act as controls and treatments were randomly distributed within each plot. We planted 50 seedlings per treatment and site.

During the year 2010, daily volume of collected fog water was 0.6 and 1.7 l m^{-2} day^{-1}, while the average rain volumes were 0.6 and 0.8 l m^{-2} day^{-1} in Benidorm and

Fig. 7 *Top*: General view of the experimental fog collection plot established in Crevillente (SE Spain). *Bottom*: details of the channel (*left*) and micropipe (*right*) to carry the collected water towards the seedling root zone

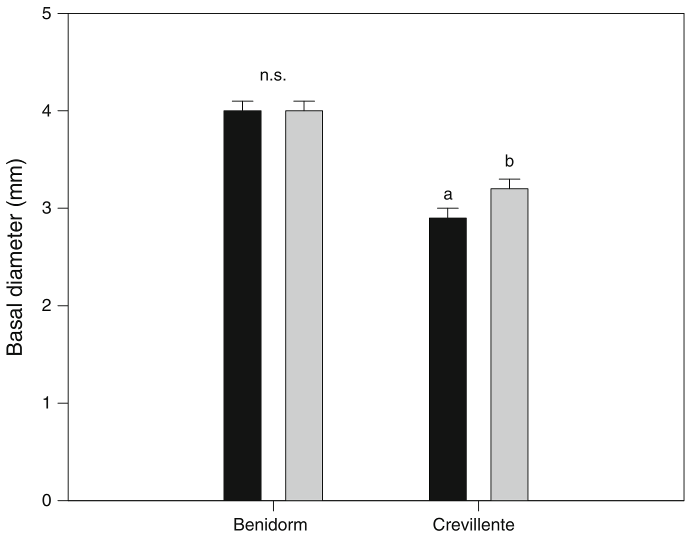

Fig. 8 Effect of fog harvesting devices on seedling basal diameter in the two experimental sites under semi-arid Mediterranean conditions. *Grey bars* represent seedlings planted with a small individual collector *while black bars* are control seedlings. *Different letters* indicate significant effect ($P < 0.05$)

Crevillente, respectively. Fog and rain values are not directly comparable because they refer to different surface dimensions in space (vertical vs. horizontal surface collections). However, these results suggest that fog may represent, if collected, a significant water input for the ecosystem.

First year survival of *Olea europaea* seedlings planted in these two experimental sites was close to 100 % due to the benign weather conditions of the year. Seedling basal diameter was different in the two experimental sites and fog collection devices had significant effect only in Crevillente, where basal diameter was 10 % bigger in seedlings under the fog harvesting treatment (Fig. 8). In this site seedlings were smaller than in Benidorm suggesting stronger site limitations.

Conclusions

Currently available technologies allow for reintroducing native plants into many degraded drylands. However, higher technological inputs (e.g. combination of techniques) are required for highly degraded ecosystems because of higher environmental stress for establishing plants thus resulting in higher reforestation costs (Vallejo et al. 2012). Thus, to ensure sustainable and cost-effective revegetation of these habitats, we need greater understanding of the biophysical thresholds for species establishment.

Climate change projections indicate both an increase of drought and more severe fire regime in several dryland regions of the world. Species selection and techniques for re-establishing woody species should optimize use of rainwater as well as resilience of the species and hence ecosystems to fire (in fire-prone areas). Woody resprouters are recommended for the reforestation of fire-prone areas, and a combination of seeders and resprouters for semi-arid areas where fires are less frequent. To specifically improve seedling quality under high water stress, the use of hydrogels in the nursery substrate, the use of deep containers for species with tap root, and the application of mild drought preconditioning are promising techniques for improving plant establishment. In addition, improved water harvesting techniques have been demonstrated to provide higher water availability for the seedling soon after planting. Finally, fog provide additional water input for seedling establishment in some dryland areas. These techniques, combined with others also oriented to improve water availability for the seedling or reduce transpiration (e.g. tree shelters), offer technical options to alleviate what are expected to be more severe droughts. Nevertheless, there are large uncertainties in climate change projections, and on the species responses to the projected new combination of water stress and fire regime, complicated with the uncertainties on social changes that will affect land use. To cope with these global change uncertainties, we recommend using the precautionary principle of making use of the wide array of available native species in reforestation, including different provenances and genotypes, and exploring their acclimation potential through nursery culture techniques.

Acknowledgments This paper summarizes some of the outputs generated from research projects funded by the European Commission (*FUME* - GA243888, and *CREOAK* - QLRT-2001-01594), by the Spanish Ministries of Science and Innovation (*GRACCIE*-CSD2007-00067, CONSOLIDER-INGENIO 2010 Program, *LORAIN*-AGL2008-05532-C02-02, *SURVIVE*-CGL-2011-30531-CO2-02) and Environment (*RECUVES* - 077/RN08/04.1; *ESTRES*, 063/SGTB/2007/7.1), and by the Regional Government of Valencia (*APLITEC*, GV 05/208; *INNOVA*, GVPRE/2008/085; *FEEDBACKS*-PROMETEO/2009/006). Special thanks to the Forest Service in Alicante (Consellería de Medi Ambient, Aigua, Urbanisme i Habitatge, Regional Government of Valencia) for the support given to research. We sincerely thank Carla D'Antonio for her comments and suggestions on the manuscript and the revision of the English version. Fundación CEAM is supported by Generalitat Valenciana and Fundación Bancaja.

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