Ecological Engineering 61 (2013) 133–144

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Ecotechnology as a tool for restoring degraded drylands: A meta-analysis of field experiments

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ARTICLE INFO

Article history:
Received 19 May 2013
Received in revised form 23 August 2013
Accepted 20 September 2013

Keywords:
Ecotechnology
Restoration
Drylands
Seedling survival
Seedling growth
Mycorrhization
Treeshelters
Organic amendments
Hydrogels

ABSTRACT

Land degradation and desertification are widespread in drylands, highlighting the need to restore them to reverse their negative effects. The restoration of degraded drylands is commonly initiated by restoring the vegetation using plantations of tree/shrub seedlings. We conducted a meta-analysis of published field experiments in drylands to analyze and compare the effects of different ecotechnological techniques (nursery mycorrhization, treeshelters, organic amendments, hydrogels and the combined use of mycorrhization and organic amendments) on the survival and growth of seedlings of woody species used during restoration activities. We also evaluated how these effects were influenced by the planting method used, and by the duration of the experiments. We gathered results from 1207 case studies from 88 studies conducted in 14 countries. Our analyses indicate that the inoculation with mycorrhizal fungi (mycorrhization) in the nursery (alone, or in combination with organic amendments) and the use of treeshelters were the most effective treatments for enhancing both the survival and growth of the planted seedlings. The use of organic amendments by themselves did not increase seedling survival. The combined use of mycorrhization and organic amendments in the field improved the results when compared to the use of organic amendments alone. The analysis of hydrophilic gels and organic amendments revealed evidence of publication bias, so more studies are needed before any generalization on their effects on seedling establishment can be made. The planting method influenced the effects of some of the treatments evaluated, though this response varied depending on the seedling performance variable considered. The length of the study was negatively related to growth variables in treatments including organic amendments. Our results provide general trends and guidelines for researchers and practitioners involved in dryland restoration, which can be used to maximize the benefits provided by the ecotechnological techniques evaluated.

1. Introduction

Over 10–20% of arid, semi-arid and dry-subhumid areas (hearafter drylands) show severe levels of degradation, which impairs their ability to provide ecosystem services (Reynolds, 2013). Land degradation and subsequent desertification have been estimated to affect over 250 million people in drylands worldwide (Reynolds et al., 2007), a process that has important socio-ecological consequences (e.g. biodiversity losses, reductions in productivity, and socio-cultural capital; Reynolds et al., 2007; Maestre et al., 2012). The extent of the area and the number of people affected by land degradation highlights the need to restore degraded drylands to reverse its negative effects and improve the provision of ecosystem services (Whisenant, 2002; Van Andel and Aronson, 2006; Rey Benayas et al., 2009).

The restoration of degraded drylands throughout the world is commonly initiated through actions designed to restore their vegetation such as plantings of tree/shrub seedlings (Gao et al., 2002; Walker, 2003; Ouahmane et al., 2009; Cortina et al., 2011). The aim of these activities is to modify those factors limiting the natural recovery of vegetation, and to foster the natural regeneration and the resilience of ecosystems (Whisenant, 2002; Cortina et al., 2011). Because of the reduced success of restoration actions carried out using seeds (Rey & Alcántara, 2000; Pausas et al., 2004; Cortina et al., 2011), the most popular revegetation method consists of the introduction of one- or two-year old saplings (e.g., Dupponois et al., 2005; Palacios et al., 2009; Fuentes et al., 2010; Ruthrof et al., 2010). Similar to what happens under natural recruitment processes, the establishment and growth of plantations is affected by environmental conditions, particularly during the first year after planting

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http://dx.doi.org/10.1016/j.ecoleng.2013.09.066

(Vallejo et al., 2012), and by small-scale heterogeneity in the distribution of soil resources (Maestre et al., 2003; Cao et al., 2011). Many strategies have been suggested to optimize the results of field plantations (see Pausas et al., 2004; Oliet & Jacobs, 2012; Vallejo et al., 2012 for reviews), and the type of application is dependent upon the state of degradation of the area to be restored (Cortina et al., 2006). Under light or low levels of degradation, the generally accepted process is to use "resource islands" and positive biotic interactions that generally develop under the canopies of existing vegetation patches (Maestre et al., 2001; King, 2008; Hafidi et al., 2013). In those degraded areas unable to retain and use resources such as water and nutrients (*sensu* Tongway & Hindley, 2004), the reintroduction of vegetation requires the physical modification of the environment (Whisenant, 2002; Cortina et al., 2011) using ecotechnology-based tools. Typically, the restoration of degraded drylands commences with the mechanical preparation of the area to be planted. This aims to establish woody seedlings, increase the volume of useful soil, and thereby promote the capture and retention of water (Li et al., 2000; Palacios et al., 2009; Villar-Salvador et al., 2011). These specific site preparation activities are often followed by the application of complementary ecotechnological techniques (e.g. use of treeshelters, addition of fertilizers and hydrogels) that are designed to assist seedlings overcome environmental and management constrains such as drought and herbivory, and thereby further facilitate their establishment and growth (Maestre et al., 2003; Löf et al., 2012; Vallejo et al., 2012; Hafidi et al., 2013).

Ecotechnological approaches are used because they mimic some of the natural processes provided by existing vegetation such as the formation of "resource islands" or improved microclimatic conditions (Pausas et al., 2004; Cortina et al., 2011; Löf et al., 2012). These approaches also minimize the damage to remaining vegetation, and ensure the maintenance of appropriate levels of critical ecosystem functions (Cortina et al., 2011). Ecotechnological tools developed to enhance the revegetation of drylands have focused mainly on (i) improving the ability of introduced plants to withstand stressful environmental conditions, (ii) reducing seed and seedling predation, and (iii) improving microsite conditions and the availability of resources for planted individuals (Pausas et al., 2004; Cortina et al., 2011; Oliet & Jacobs, 2012). The addition of organic amendments (Valdecantos et al., 2006; Larchevêque et al., 2006), treeshelters (Leroy & Caraglio, 2003; Padilla et al., 2011), the pre-conditioning of seedlings in nurseries (including fertilization, mycorrhization and/or nutrient and water hardening treatments; Requena et al., 1997; Barea et al., 2011; Trubat et al., 2011), the use of structures such as microcatchments (Saquete et al., 2006) built during site preparation works, and materials that increase the retention of rain water (e.g., mulches or hydrogels; Chirino et al., 2011; Oliveira et al., 2011) are among the most widely employed ecotechnological tools for restoring degraded drylands. In the last 20 years, the interest in the use of ecotechnological techniques has risen considerably, and there has been an increase in research to evaluate their effectiveness at enhancing seedling establishment under field conditions (Pausas et al., 2004; Cortina et al., 2011; Oliet & Jacobs, 2012; Vallejo et al., 2012). While the scientific evidence available is growing exponentially, observed results are, on occasions, contradictory (e.g. see Requena et al., 1997 and Maestre et al., 2002 for contrasted results on the effects of inoculation with mycorrhizal fungi). This lack of certainly stifles our ability to make decisive management decisions based on the literature (Pullin et al., 2004).

Different authors have stressed the need to evaluate the efficiency of ecotechnological techniques and their practical applicability (Cortina et al., 2011). However, and to our knowledge, no previous study has conducted an exhaustive and quantitative synthesis on the effects of different ecotechnological tools on the establishment of seedlings employed in dryland restoration. We aimed to do so by conducting a systematic review of existing literature and a meta-analysis of the effects of the application of organic amendments, treeshelters, hydrogels and mycorrhizal fungi, and their combined use with organic amendments, on the survival and growth of seedlings of woody species used during dryland restoration. Such a synthesis would be highly relevant for scientists and managers alike, as it would allow us to evaluate the suitability of the main ecotechnological techniques proposed so far, and to provide management recommendations based on rigorous and defensible science. Meta-analysis is a systematic revision that synthesizes in a quantitative way the evidence obtained from independent studies (Stewart et al., 2005; Borenstein et al., 2009). This synthesis adheres to a strict methodological and statistical protocol, bringing to its results transparency, objectivity and statistical strength (Stewart et al., 2005; Borenstein et al., 2009; Pullin & Knight, 2009). Meta-analyses are also considered to be an important and effective way of transferring knowledge between researchers and managers, and their use may be an important step forward for facilitating the adoption of management practices based on the best available science (Pullin et al., 2004; Stewart et al., 2005). Our specific objectives were to: (1) analyze and compare the effects of different ecotechnological techniques on the survival and growth of seedlings of woody species used during dryland restoration, (2) explore the potential reasons for the variation found in the effects of these techniques, and (3) provide recommendations for the restoration of degraded drylands based on the results obtained.

2. Material and methods

2.1. Database building

For building our database, we searched for studies that quantitatively evaluated the response of planted seedlings to the following ecotechnological techniques: nursery mycorrhization, treeshelters, organic amendments (organic fertilizers added to the seedlings at the moment of planting, such as sewage sludge, the organic fraction of municipal solid waste, and residues from animal and plant production), hydrogels and the combined use of nursery mycorrhization and organic amendments in the field. We selected them because they are among the ecotechnological treatments most widely recommended and used in dryland restoration (Pausas et al., 2004; Cortina et al., 2011), and because the number of studies using them is large enough to synthesize them using meta-analysis. We included the combined use of nursery mycorrhization and organic amendments in the field because mycorrhizal improvements on plant nutrient uptake (Caravaca et al., 2003a) could be complementary to increases in nutrient availability provided by such amendments (Larchevêque et al., 2006), and because both ecotechnological techniques are commonly used together. This also allowed us to explore differences in treatments individually and when used in combination. On the other hand, as water availability is the main constraint for plantation establishment in drylands (Vallejo et al., 2012; Pausas et al., 2004; Whisenant, 2002), we also decided to evaluate the effects of hydrogels because of their high capacity to absorb, retain and slowly release water (Liang et al., 2010; Oliveira et al., 2011), which could help planted seedlings to overcome summer drought. We acknowledge that there are more ecotechnological techniques that are being used, but we did not include them either because their effects have been recently synthesized using meta-analysis (e.g. the use of nurse plants in restoration; Gómez-Aparicio, 2009), or because there are too few case studies to conduct a quantitative synthesis.

Since studies using the same ecotechnological tool employed different site preparation techniques (e.g. planting using subsoiling or mechanically/manually dig holes), we investigated whether such site preparation techniques affected the outcome of our analyses (see Section 2.2 below).

We searched for relevant studies published between January 1980 and December 2011 using the ISI Web of Knowledge®, searching for the terms "*restoration*", "*plantation*", "*desertification*" and "*afforestation*", which were combined with "*mycorrhizae*" "*Glomus*", "*AM fungi*", *"tree shelter" "tube shelter", "Tubex", "compost", "sludge", "mulch", "organic residue", "hydrogel*" and *"hydrophilic polymer*". This search was completed with additional searches of databases of scientific journals published in Spanish, such as Dialnet (www.dialnet.unirioja.es) and the database of the Spanish Society of Forest Sciences (www.secforestales.org), and with an exhaustive research of unpublished documents, reports and other articles included in the reference list of the different studies found. Such thorough searches using multiple information sources are commonly recommended when conducting meta-analyses (e.g. Maestre et al., 2005; Gómez-Aparicio, 2009; Harrison, 2011). Our searches led to a large number of articles that were then examined, but were only included in our quantitative synthesis if they met the following criteria:

1. The study was conducted in drylands, regions with aridity index (precipitation/potential evapotranspiration) values lower than 0.65. When climatic data provided in the original article/report did not allow us to discern whether the study could be placed within drylands, we consulted the FAO global map of aridity (www.fao.org/geonetwork/srv/en/metadatashow).
2. The study reported results of experiments conducted in the field under natural conditions. Those studies carried out in a nursery, greenhouse or the laboratory were not included.
3. The study evaluated the effect of the presence and absence (control) of one or several of the treatments indicated on the survival and growth of woody species. The indicators (variable responses) chosen to evaluate seedling growth were: height, diameter, shoot biomass and root biomass. When the size of the seedlings studied differed between the treatment/s and the control at the beginning of the experiment, their growth was estimated using the relative growth rate (RGR) as $(\ln Xt_2 - \ln Xt_1)/(t_2 - t_1)$, where X is the variable of interest at the beginning (t_1) and end (t_2) of the experiment. If the same treatment presented several levels (e.g. compost doses, types of treeshelters or hydrogels) or the experiment was conducted with multiple species, each treatment level/species was considered as an independent unit for the analysis. Therefore, the same study could contain several case studies. While results from different species/sites within each study are not certainly independent, we retained each combination of control/ecotechnological treatment and species as a separate case study to ensure that the results of our analyses were as general as possible. Although this approach tends to reduce the overall heterogeneity when estimating effect sizes (see below), excluding multiple results from one data source can underestimate such sizes (Gurevitch & Hedges, 1999; Karst et al., 2008). Furthermore, our approach has been successfully applied in many previous ecological meta-analyses (e.g., Liao et al., 2008; Rey Benayas et al., 2009; Eldridge et al., 2011; Vilà et al., 2011). In those studies where other treatments (e.g. clearing of competing vegetation and fertilization) were also applied, we considered those combinations of treatments where the only variation was due to the presence/absence of the ecotechnological treatment/s of interest.
4. The study presented sufficient quantitative results to be used in a meta-analysis. When the information contained in the study did not allow us to conduct the analysis, the authors were contacted to obtain the information needed (e.g., number of replicates or standard deviation). Survival data were organized as the number of living and dead seedlings in both the treatment and the control. For growth data, we obtained the mean, the standard deviation (SD) and the number of replicates. When the same study contained survival and growth results, and it did not specify the number of replicates used to calculate growth data, the number of live seedlings was used to estimate effect sizes for such data. In those experiments reporting data for multiple points in time, only the results from the end of the experiment were selected. If several studies presented results in the same experimental plots, only the results of the most recent study were used. When the results were presented as graphics, the data were extracted using Datathief (www.datathief.org).

In addition, the following additional information was obtained from each study (when available): (1) length of the experiment, (2) precipitation in the study area during the first year of the study, (3) the age and functional type (shrub or tree) of the seedlings planted, (4) plantation method and previous site preparation, and (5) country where the study took place. The information gathered on the site preparation techniques allowed us to establish three different planting methods (depending on the technique, not all these methods were available for all the treatments/response variables): subsoiling (linear, mechanized and high-depth, usually up to 80 cm), hole digging (puncturing, or digging with a mechanical or manual auger to depth of about 40 cm), and mechanically-built terraces, characterized by having a depth higher than 80 cm and a complete alteration of the soil layer. When a study reported no information on the technique used, those data were not included in our analyses.

All the data gathered were stored in different databases according to the treatment and the variable response evaluated (available in the Supplementary Electronic Materials http://dx.doi.org/10.1016/j.ecoleng.2013.09.066). Thus, five and twenty-five databases were created for survival (in relation to each treatment under study), and growth (the result of the combination of each treatment and variable response), respectively.

2.2. Statistical procedure

Independent meta-analyses were carried out for each combination of treatment and variable response that had at least ten case studies. We first analyzed the data grouping results from all the planting methods employed. Survival data were summarized in 2×2 contingency tables as in Maestre et al. (2005). An odds metric was obtained for each case study, calculated as the ratio of the odds of survival with the ecotechnological treatment to the odds of survival without it (control; Rosenberg et al., 2000). In some studies, all the individuals of the target species died or survived, and thus we added 1 to the number of individuals in each study case to avoid values that would require division by 0 (Maestre et al., 2005; Gómez-Aparicio, 2009). To retain the symmetry of the analysis (Borenstein et al., 2009), meta-analyses were conducted with the natural logarithm of the odds ratio, so values higher and lower than 0 indicate that the odds of surviving were higher or lower, respectively, when the ecotechnological treatment was applied.

To estimate TE for growth data, we used the response ratio (ln RR), obtained as (Hedges et al., 1999):

$$\ln \ \mathrm{RR} = \ln\left(\frac{X_t}{X_c}\right) \qquad (1)$$

the variance of this ratio is calculated according to:

$$V_{\ln RR} = \frac{D_t^2}{N_t \cdot [X_t^2]} + \frac{D_c^2}{N_c \cdot [X_c^2]} \quad (2)$$

where X_t and X_c are the means of the treatment and control, respectively, N_t and N_c are the number of replicates of the treatment and the control, respectively, and D_t and D_c are the standard deviations of the treatment and the control, respectively. We selected the ln RR for our meta-analyses because this metric also allows estimating TE in those cases were some information was missing (e.g., number of replicates [n] or standard deviation [SD]), or where the data were obtained as relative growth rates. ln RR values above 0 show a positive effect of the treatment on the growth variables.

In the cases were all the information could be retrieved (mean, n and SD for growth data, number of alive and dead seedlings for survival data) we used a random effects model to calculate the cumulative TE. This model was used to estimate mean effect sizes because the fixed-effects model assumption that all observed variation is due to sampling error is very difficult to meet when using a broad range of studies such as that employed here (Gurevitch & Hedges, 1999). In addition, the total heterogeneity of each meta-analysis, Q_T, was also calculated as described in Rosenberg et al. (2000). Q_T is tested against a χ^2 distribution with $n-1$ degrees of freedom. A significant value of this statistic indicates that the variance among effect sizes is greater than expected by sampling error (Rosenberg et al., 2000), suggesting that other factors should be evaluated (Higgins & Thompson, 2002). Because the cumulative TE of each treatment could be segregated in groups determined by site preparation procedures, we also conducted the analysis by calculating cumulative TE values for each planting method (terraces, subsoiling and hole digging) within the different treatments evaluated. For categorical data, heterogeneity analyses allow partitioning Q_T into Q_M (between-groups heterogeneity or heterogeneity explained by the model) and Q_E (within-group heterogeneity or residual heterogeneity). Q_M and Q_E can be tested against a χ^2 distribution with $m-1$ degrees of freedom, where m is the number of groups, and $n-m$ degrees of freedom, respectively (for details see Rosenberg et al., 2000). A significant Q_M implies that there were differences among cumulative TE for the different planting methods employed, while a significant Q_E implies that there was heterogeneity among TE not explained by them (Rosenberg et al., 2000; Borenstein et al., 2009). This analytical procedure is also called a mixed effects model. When a particular planting method contained less than two study cases, it was not included in the mixed effects model. Thus, we decided to present results from the random effects model when analyzing mean TE and total heterogeneity values, while results from a mixed effects model were presented to compare the effects of different site preparation techniques within each ecotechnological treatment. We also conducted similar analyses using the functional type of the seedlings planted (shrub or tree) as a grouping variable. Considering these functional types did not modify any of the results of the random effects model (data not shown), and thus we do not present the results from these analyses here. We also evaluated the relationships between TE and the length of the experiment using lineal regressions. The statistical significance of cumulative TE from each meta-analysis was tested through the calculation of 95% confidence intervals, generated using bootstraping procedures (Rosenberg et al., 2000).

We tested for publication bias in our databases, i.e. the greater probability of publishing significant results, by checking weighted histograms, funnel plots and normal quantile plots (Rosenberg et al., 2000). A weighted histogram (where weight is the inverse of the variance of the effect size in each study) showing a distribution depressed around 0 suggests that such a bias exists. In funnel plots, the resulting plot is shaped like a funnel, with the large opening at the smallest sample sizes, if there are no biases. With publication bias, normal quantile plots are non-linear or contain unusual gaps in the data (Rosenberg et al., 2000). We conducted Spearman's rank-correlation tests examining the relationship between the standardised effect size and the sample size across studies (Begg & Mazumdar, 1994); significant correlation indicates that larger effect sizes in either direction are more likely to be published than smaller effect sizes. We also calculated the Rosenthal's fail-safe number, which provides the number of analytical units with a treatment effect equal to zero that should be added to each meta-analysis to nullify its overall results (Rosenberg et al., 2000). A value of this number higher than $5n+10$ is considered to be sufficient to assume the absence of publication bias (Rosenberg et al., 2000).

In addition to the parametric analyses described above, we conducted additional non-parametric analyses of seedling growth data. For these analyses, we obtained ln RR values for all case studies, and used the Wilcoxon Signed Rank tests to examine whether median response ratios were different from zero. With this approach we did not weight effect sizes, i.e. we did not use measured sample variance in a calculation of effect sizes so that studies with more replication are counted more heavily. While such weighting is always preferable when conducting meta-analyses (Gurevitch & Hedges, 1999; but see Cardinale et al., 2006 and Marvier et al., 2007 for examples of lack of important differences between weighted and unweighted meta-analyses), we conducted these additional analyses to ensure that our analyses accounted for as many case studies and geographical regions as possible. All the parametric meta-analyses were conducted with the program MetaWin version 2.1.4 (Rosenberg et al., 2000). Wilcoxon Signed Rank tests were conducted using the QI Macros for Microsoft Excel (KnowWare International Inc., Denver, CO, USA).

3. Results

A total of 88 studies complied with our selection criteria. They provided 1207 case studies, which included data on a total of 52 woody species that were used in the restoration of degraded drylands from 14 countries.

3.1. Mycorrhizal fungi

A total of 40 studies complied with the selection criteria, providing 121/227 case studies that were included in parametric/non-parametric meta-analyses depending on the evaluated variable (Fig. 1a–e, Table 1). Given the low number of case studies found for root growth ($n < 10$), the effects of mycorrhization on this variable were not statistically evaluated. Overall, nursery mycorrhization had positive and significant effects on seedling survival and growth, regardless of the variable and analytical approach (parametric or non-parametric) used (Fig. 1a–e, Table 1). The total heterogeneity test was marginally significant for the growth in height (Table 2), suggesting the presence of additional factors that co-determine the variation in the TE found for this variable. For any other variable, the variation in TE was found to be within the model assumptions (Table 2). The effects of nursery mycorrhization did not differ significantly among site preparation techniques in any case (Fig. 2a, Table 2). The length of the study was negatively related to the TE for seedling survival and diameter growth, though the r^2 values were below 0.1 in all cases (Table 3). Spearman's correlation tests did not suggest publication bias in any of the seedling

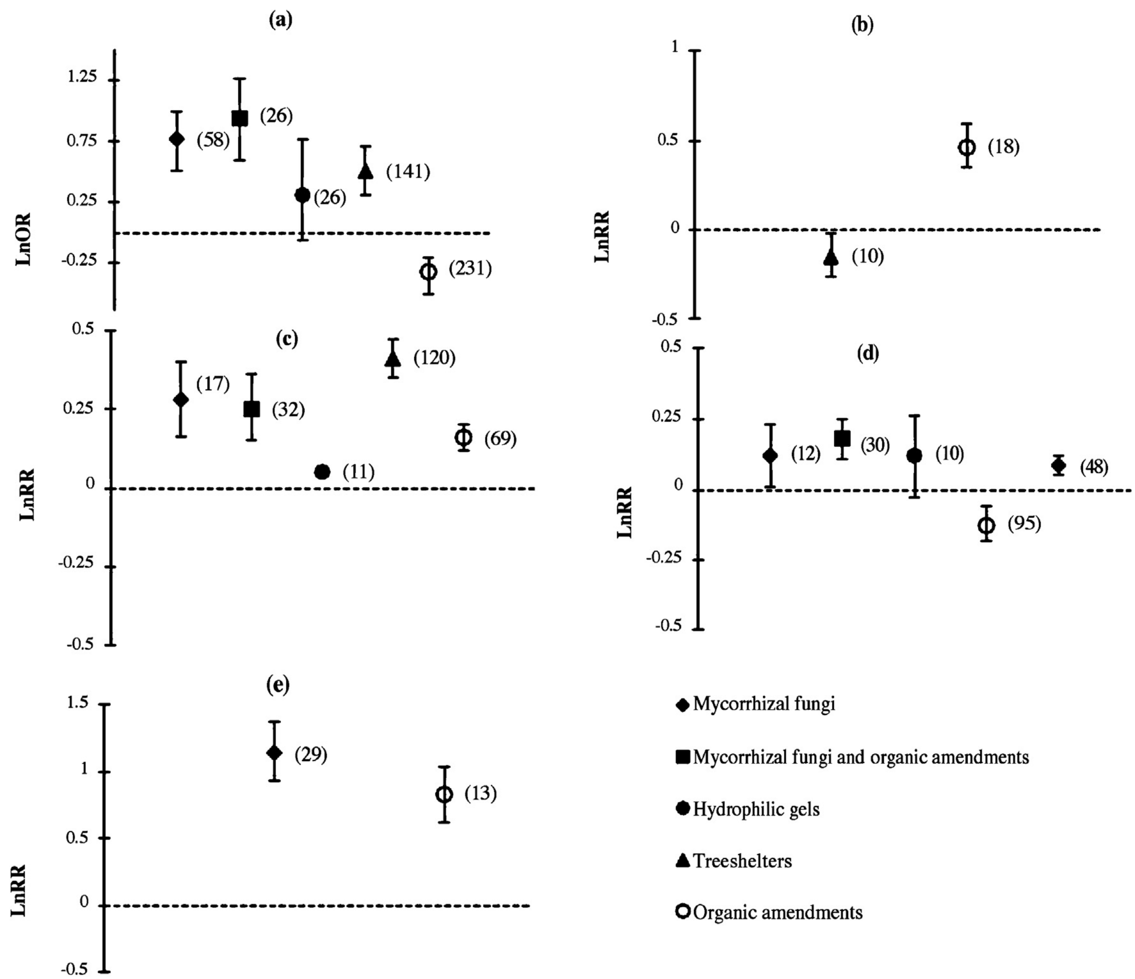

Fig. 1. Mean treatment effect values for survival (a), root biomass (b), height (c), diameter (d) and shoot biomass (e). Error bars are 95% bootstrapped confidence intervals. Significant treatment effects are indicated by confidence intervals that do not overlap zero. The number of study cases included in each case is in brackets. Note the different scales in the *Y*-axes.

Table 1
Summary of the non-parametric meta-analyses conducted. Median response ratios are reported in all cases. The null hypothesis of the Wilcoxon test is that median values do not differ from 0. n = number of study cases included in the analysis; $\sigma\{T\}$ = variance of Wilcoxon test statistic (T); Z = Z-score of median response ratios. Mf = mycorrhizal fungi; Mf + OA = mycorrhizal fungi combined with organic amendments; Hg = hydrophilic gel; Ts = treeshelters; OA = organic amendments.

Treatment	Response variable	Wilcoxon test				
		Median	n	$\sigma\{T\}$	Z	P-value
Mf	Diameter (ln RR)	0.29	52	219.61	−5.1	<0.001
	Height (ln RR)	0.24	76	386.29	−5.1	<0.001
	Shoot biomass (ln RR)	0.76	72	356.29	−6.8	<0.001
	Root biomass (ln RR)	0.58	27	83.24	−4.5	<0.001
Mf+OA	Diameter (ln RR)	0.22	35	122.1	−3.8	<0.001
	Height (ln RR)	0.30	42	159.95	−4.4	<0.001
	Shoot biomass (ln RR)	0.86	27	83.24	−4.0	<0.001
	Root biomass (ln RR)	1.15	8	14.28	−2.4	0.015
Hg	Diameter (ln RR)	0.12	13	28.61	−2.1	0.032
	Height (ln RR)	0.04	17	42.24	−1.5	0.137
Ts	Diameter (ln RR)	−0.09	101	581.67	3.7	<0.001
	Height (ln RR)	0.48	135	910.63	−5.4	<0.001
	Shoot biomass (ln RR)	−0.32	18	45.92	3.1	0.002
	Root biomass (ln RR)	−0.33	21	57.54	3.2	0.002
OA	Diameter (ln RR)	0.05	54	232.28	−3.7	<0.001
	Height (ln RR)	0.15	97	555.82	−6.9	<0.001
	Shoot biomass (ln RR)	0.50	27	83.24	−4.1	<0.001
	Root biomass (ln RR)	0.18	22	61.60	−2.1	0.033

Table 2
Summary of total heterogeneity analyses conducted with survival and growth variables. Q_T = total heterogeneity; Q_M = between-group; Q_E = within-group heterogeneity OR = odds ratio; RR = response ratio. Mf = mycorrhizal fungi; Mf + OA = mycorrhizal fungi combined with organic amendments; Hg = hydrophilic gel; Ts = treeshelters; OA = organic amendments.

Treatment	Response variable	Random effects model			Mixed effects model			
		Q_T	df	*P*-value (Q_T)	Q_M	Q_E	df	*P*-value (Q_M)
Mf	Survival (ln OR)	52.39	60	0.741	0.92	50.89	2, 55	0.626
	Diameter (ln RR)	14.96	12	0.248	0.08	12.64	1, 10	0.771
	Height (ln RR	27.10	17	0.056	0.56	21.91	1, 15	0.458
	Shoot biomass (ln RR)	31.61	28	0.290	0.02	0.87	1, 27	0.879
Mf + OA	Survival (ln OR)	22.69	25	0.593	-	-	-	-
	Diameter (ln RR)	34.56	30	0.257	5.00	32.24	1, 28	**0.021**
	Height (ln RR)	46.66	66	0.041	3.06	43.01	1,30	0.084
Hg	Survival (ln OR)	21.34	25	0.675	8.93	14.38	1, 16	**0.002**
	Diameter (ln RR)	4.98	9	0.830	0.28	4.53	1, 8	0.593
	Height (ln RR)	8.81	10	0.557	0.01	8.52	1, 9	0.910
Ts	Survival (ln OR)	111.2	122	0.742	0.52	118.46	1, 125	0.473
	Diameter (ln RR)	60.70	94	0.994	9.76	55.24	1, 85	**0.001**
	Height (ln RR)	185.5	119	<0.001	22.27	148.77	1, 106	**<0.001**
	Root biomass (ln RR)	12.75	9	0.174	–	–	–	–
OA	Survival (ln OR)	191.1	230	0.973	30.49	175.75	1, 198	**<0.001**
	Diameter (ln RR)	32.91	48	0.952	6.67	24.51	1, 39	**0.009**
	Height (ln RR)	42.68	69	0.994	2.06	32.55	1, 56	0.152
	Shoot biomass (ln RR)	17.86	13	0.166	6.17	8.78	1,11	**0.013**
	Root biomass (ln RR)	25.80	17	0.072	26.90	16.42	1,16	**<0.001**

performance variables evaluated (Table 4). These results were supported by Rosenthal's fail safe numbers, and by the funnel/normal quantile plots and weighted histogram (Table 4, Figs. A1–A12).

3.2. *Mycorrhizal fungi combined with organic amendments*

A total of 20 studies fulfilled the selection criteria, providing 124/112 case studies that were included in parametric/non-parametric meta-analyses depending on the evaluated variable (Fig. 1a–e, Table 1). Due to the low number of case studies found for both shoot and root biomass ($n < 10$), these variables were not analyzed. The combined effects of mycorrhizal inoculation in the nursery and the addition of organic amendments in the field significantly increased seedling survival and growth, regardless of the performance indicator and statistical approach used (Fig. 1a–d, Table 1). The total heterogeneity tests were significant for height (Table 2). Site preparation techniques were not evaluated in the survival database because all of the studies gathered used hole digging. For growth in plant diameter, effect sizes for subsoiling were more positive than those for hole digging (Fig. 2e, Table 2). The relationship between the TE and the length of the study was positive and negative for the case of survival and growth in height, respectively (Table 3). All the different tests conducted indicated the absence of publication bias in this treatment (Table 4, Figs. A13–A21).

Table 3
Results from linear regressions between the effect size and the duration of the study. OR = odds ratio; RR = response ratio. Mf = mycorrhizal fungi; Mf + OA = mycorrhizal fungi combined with organic amendments; Hg = hydrophilic gel; Ts = treeshelters; OA = organic amendments.

Treatment	Response variable	Regression results			
		Interception	Slope	R^2	*P*-value
Mf	Survival (ln OR)	1.00	−0.011	0.05	0.045
	Diameter (ln RR)	0.41	−0.004	0.07	0.050
	Height (ln RR	0.33	−0.004	0.04	0.075
	Shoot biomass (ln RR)	0.87	−0.002	<0.01	0.856
	Root biomass (ln RR)	0.69	−0.001	<0.01	0.988
Mf + Oa	Survival (ln OR)	−0.010	0.012	0.22	0.015
	Diameter (ln RR)	0.27	−0.001	0.05	0.089
	Height (ln RR)	0.39	−0.003	0.08	0.034
Hg	Survival (ln OR)	0.04	0.005	0.02	0.421
	Diameter (ln RR)	0.26	−0.001	0.04	0.318
	Height (ln RR)	0.08	−0.001	0.05	0.374
Ts	Survival (ln OR)	0.48	0.0001	<0.01	0.974
	Diameter (ln RR)	−0.26	0.005	0.15	<0.001
	Height (ln RR)	0.59	−0.001	<0.01	0.935
	Shoot biomass (ln RR)	−0.74	0.030	0.27	0.026
	Root biomass (ln RR)	−0.74	0.033	0.21	0.032
OA	Survival (ln OR)	−0.63	0.011	0.07	<0.001
	Diameter (ln RR)	0.17	−0.001	0.01	0.389
	Height (ln RR)	0.28	−0.002	0.05	0.027
	Shoot biomass (ln RR)	0.28	0.010	0.07	0.172
	Root biomass (ln RR)	0.92	−0.020	0.26	0.013

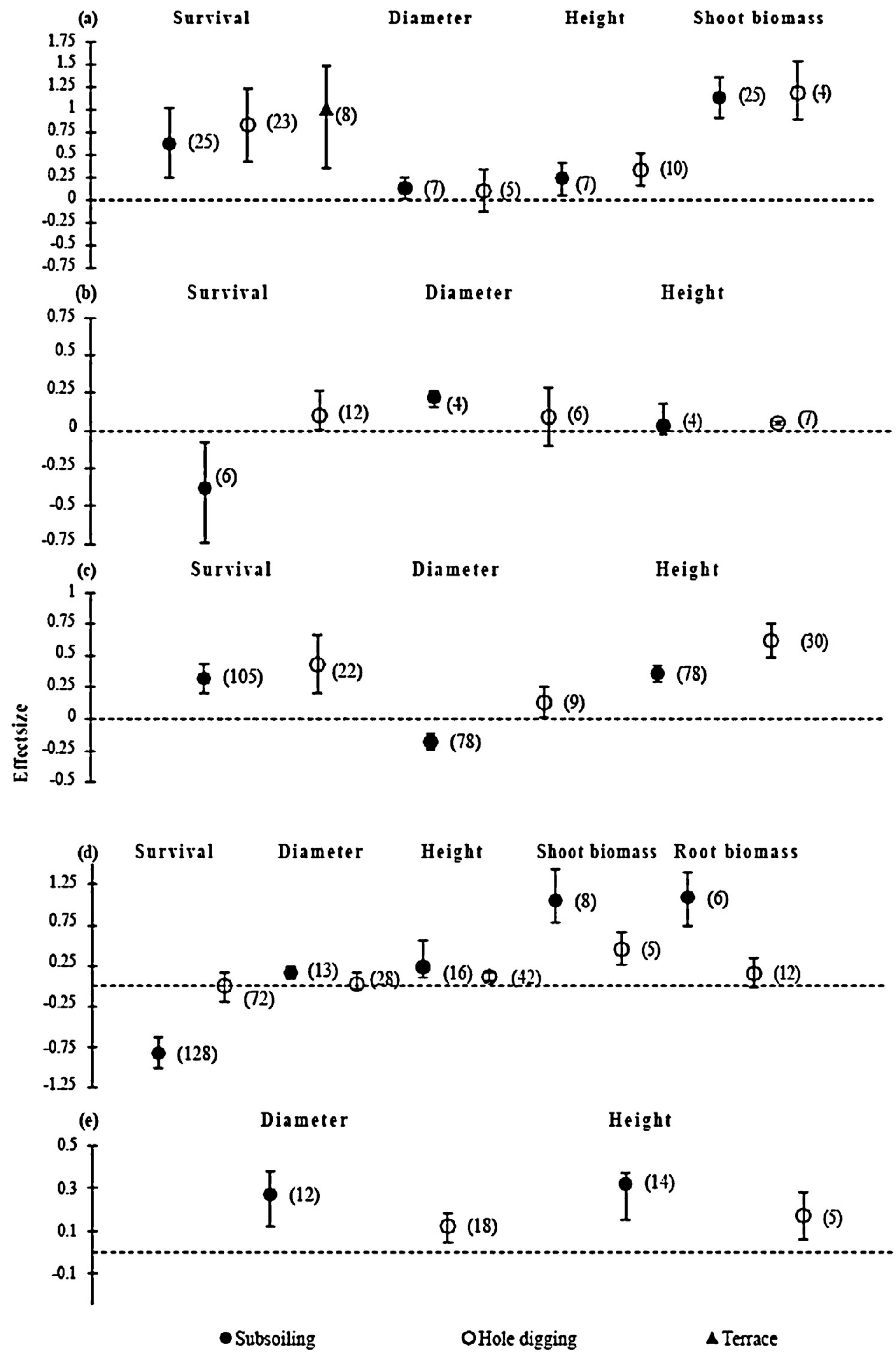

Fig. 2. Mean treatment effects according to the site preparation technique employed in nursery mycorrhization (a), hydrophilic gels (b), treeshelters (c), organic amendments (d), and nursery mycorrhization combined with organic amendments (e). Error bars are 95% bootstrapped confidence intervals. Number of cases is shown in parentheses. Significant effects of the site preparation techniques are indicated by confidence intervals that do not overlap zero. The effect size metrics employed for survival and growth results are the Ln Odds Ratio and the Ln Response Ratio, respectively.

3.3. Hydrophilic gels

A total of eight studies complied with the selection criteria, providing 37/30 case studies that were included in parametric/non-parametric meta-analyses depending on the evaluated variable (Fig. 1a–d, Table 1). Due the low number of case studies found for shoot and root biomass ($n < 10$), these variables were not statistically analyzed. In the parametric analysis, the addition of hydrophilic gels had a positive and significant effect on seedling height (Fig. 1a–d), whereas no effects were found on seedling survival. The test of total heterogeneity was significant for seedling survival (Table 2). Mixed model analyses revealed differences among planting methods. When seedlings were planted using hole digging, hydrogels had positive effects on seedling survival,

Table 4
Results of the tests conducted to assess publication bias. R_S = Spearman rank correlation coefficient; OR = odds ratio; RR = response ratio. Mf = mycorrhizal fungi; Mf + OA = mycorrhizal fungi combined with organic amendments; Hg = hydrophilic gel; Ts = treeshelters; OA = organic amendments.

Treatment	Response	Spearman correlation		Rosenthal' fail-safe number
		R_S	P-value	
Mf	Survival (ln OR)	−0.23	0.071	652
	Diameter (ln RR)	−0.30	0.273	12
	Height (ln RR)	−0.15	0.554	190
	Shoot biomass (ln RR)	0.04	0.797	1378
Mf + Oa	Survival (ln OR)	−0.27	0.536	401
	Diameter (ln RR)	−0.05	0.774	237
	Height (ln RR)	−0.12	0.443	63
Hg	Survival (ln OR)	−0.40	0.036	0
	Diameter (ln RR)	0.36	0.304	44
	Height (ln RR)	0.01	0.978	105
Ts	Survival (ln OR)	−0.02	0.797	969
	Diameter (ln RR)	−0.06	0.543	346
	Height (ln RR)	−0.12	0.169	14450
	Root biomass (ln RR)	−0.15	0.676	5
OA	Survival (ln OR)	0	0.995	1154
	Diameter (ln RR)	−0.28	0.042	93
	Height (ln RR)	−0.25	0.036	527
	Shoot biomass (ln RR)	0.88	<0.001	327
	Root biomass (ln RR)	0.71	<0.001	102

a response that was the opposite when planting was performed using subsoiling (Fig. 2b, Table 2). The results of non-parametric tests are consistent with those for seedling diameter (e.g. positive effects of gels), but did not support the positive effect of hydrogels on seedling height (Table 1). The TE was not related to the length of the experiment in any case (Table 3). Spearman's correlation test was significant for survival (Table 4), suggesting the possibility of publication bias. These results were supported by a low value of Rosenthal's fail-safe number and by the funnel/normal quantile plots and weighted histogram (Table 4, Figs. A22–A33).

3.4. Treeshelters

A total of 27 studies complied with the selection criteria, providing 348/275 case studies that were included in parametric/non-parametric meta-analyses depending on the evaluated variable (Fig. 1a–d, Table 1). Due to the low number of case studies found for shoot biomass ($n < 10$), this variable was not statistically analyzed. Treeshelters significantly increased the survival and height of seedlings, but negatively affected their diameter and root biomass, regardless of the statistical approach used (Fig. 1a, c and d; Table 1). The total heterogeneity test was significant for growth in height (Table 2). When seedlings were planted using hole digging, the effects of treeshelters on diameter and height growth were more positive than those observed when using subsoiling (Fig. 2c, Table 2). The length of the study was positively related to seedling diameter, shoot and root biomass (Table 3). The different methods employed to detect publication bias indicated that it was not present in this treatment (Table 4, Figs. A34–A45).

3.5. Organic amendments

A total of 40 studies complied with the selection criteria, providing 377/200 case studies that were included in parametric/non-parametric meta-analyses depending on the evaluated variable. Overall, the addition of organic amendments (OA) had positive and significant effects on seedling growth, regardless of the variable and the analytical approach (parametric or non-parametric) used (Fig. 1b–e; Table 1). However, this treatment had negative effects on seedling survival (Fig. 1a). The total heterogeneity test was not significant for any variable (Table 2). Effect of site preparation techniques showed significant differences in survival, diameter, shoot biomass and root biomass (Fig. 2d, Table 2). The effects of OA on seedling survival were negative when seedlings were planted using subsoiling, while this treatment had neutral effects when the planting method was hole digging. The opposite was found when analyzing growth variables, as subsoiling effects were significantly greater (i.e. more positive) than those from hole digging (Fig. 2d, Table 2). The length of the study was positively related with seedling survival, and negatively with seedling height and root biomass (Table 3). Spearman' correlation test was significant for all the growth variables analyzed, suggesting the presence of publication bias (Table 4). These results were supported by Rosenthal fail-safe number and by funnel plots (except for diameter and height; Figs. A49 and A52) and weighted histograms (Table 4, Figs. A46–A60).

4. Discussion

4.1. Effectiveness of the ecotechnological treatments evaluated

Overall, the different ecotechnological treatments evaluated had positive effects on most of the response variables assessed. However, the direction and magnitude of the effects of treeshelters and organic amendments (OA) varied with the response variable considered. Whereas treatments that included mycorrhizal fungi had positive effects on all the performance variables evaluated, treeshelters and OA reduced the growth in diameter and survival of woody seedlings, respectively, but enhanced other performance variables. These differences were probably due to specific characteristics of each treatment and, consequently, to the changes in abiotic conditions that they produced.

We found that the inoculation with mycorrhizal fungi improved the survival and growth of woody seedlings, which is one of the most effective for promoting their establishment in drylands. This inoculation likely increased the water use efficiency of woody seedlings, allowing them to overcome water stress, and increasing their ability to uptake nutrients such as N and P, thereby enhancing their growth (Caravaca et al., 2003b; Querejeta et al., 2007; Barea et al., 2011). Mycorrhizal fungi typically improve soil aggregate stability in the environment around the seedling roots after planting (Caravaca et al., 2002). This promotes root growth, allowing seedlings to withstand abiotic (first dry period) and biotic (e.g., competition from herbaceous weeds) stresses they encounter after planting (Requena et al., 2001; Alguacil et al., 2005). It is also assumed that the effects of mycorrhizal fungi are particularly important in nutrient-limited ecosystems such as drylands (Rincón et al., 2007; Valdecantos et al., 2006).

The combined use of mycorrhizal inoculation and OA promoted seedling survival and growth, and the effects of both treatments on survival were more positive than when OA was used alone (i.e. confidence intervals of both effect sizes did not overlap, Fig. 1). The negative effects of OA on seedling survival have been attributed to different factors affecting soil water availability, a critical issue for the survival of planted woody seedlings in drylands (Larchevêque et al., 2006; Padilla & Puignare, 2007; Fuentes et al., 2010). High doses of OA can increase the content of soluble salts, and therefore reduce water availability (Valdecantos et al., 2011), which may cause seedling death during periods of extreme water shortage. Conversely, the presence of nutrients in the soil can promote the development of herbaceous weeds (Clary et al., 2004; Rey Benayas et al., 2005). These species can effectively compete with the planted seedlings for water and nutrients because of their faster growth rate and the attributes of their root systems (Schenk & Jackson, 2002; Ludwig et al., 2004; Van der Waal et al., 2009). Furthermore, in situations of water stress, increases in seedling size promoted by the addition of OA may not promote a higher survival under semiarid conditions (Trubat et al., 2011, but see Trubat et al., 2010 for contrasting results under more mesic conditions). Our results suggest the latter, as seedling survival was reduced by the addition of OA despite this treatment effectively promoting seedling growth (Fig. 1). However, the publication bias found when analyzing the effects of OA on this variable (Table 3) indicates that these effects should be interpreted with caution. Nonetheless, it is interesting to highlight how negative effects on survival of this treatment disappeared in the presence of mycorrhizal fungi, likely due to the increased ability of inoculated seedlings to acquire water (Querejeta et al., 2003; Allen, 2007).

Treeshelters increased seedling survival, but had contrasting effects on the different growth variables evaluated (e.g. increased height but reduced diameter and root biomass). The increase in height and reduction in diameter of seedlings is an adaptive response to the abiotic conditions generated within the shelters (Chaar et al., 2008; Pemán et al., 2010). In particular, it is assumed that the decrease in light, and the increases in temperature (Del Campo et al., 2006), together with the protection of shelters to mechanic pressure (e.g. wind), allow the plant to invest more resources in aboveground structures than in the root system. Thus, there is a trade-off towards greater height at the expense of increased girth (Oliet et al., 2003; Oliet & Jacobs, 2007; Chaar et al., 2008), particularly when seedling height is less than that of the treeshelter (Oliet et al., 2005). However, the significant increase in height we observed (detected using both parametric and non-parametric approaches) was accompanied by a decrease in shoot biomass (in non-parametric analysis, Table 1). This was likely due to the fact that protected seedlings invest in photosynthetic area mainly when water is not a limiting resource, which is not the case in ecosystems such as drylands (Oliet & Jacobs, 2007). Although the conditions generated inside the treeshelters could negatively affect the survival of seedlings (Navarro et al., 2005), the overall effect was positive. An increase in temperature within unventilated shelters can promote higher water losses via transpiration (Bergez & Dupraz, 2000; Bellot et al., 2002; Close et al., 2009). In addition, the reduced root development of protected seedlings (Fig. 1b) would prevent them achieving moister soil horizons, a response that has been associated with lower survival rates in previous studies (Padilla & Puignare, 2007). However, this could be compensated by the other positive conditions generated by treeshelters. Thus the reduction of radiation and mechanical damage would counterbalance detrimental effects of increased temperatures and reduced root growth experienced by seedlings (Del Campo et al., 2006; Puértolas et al., 2010), and hence improve their survival.

Previous studies have shown that hydrophilic gels increase the amount of water available for plants, and reduce seedling evapotranspiration (Agaba et al., 2010; Chirino et al., 2011). However, we found that these gels had no significant effects on seedling survival. We detected some publication bias in our analyses, which raises questions about the validity of these results. In addition, the effects of hydrogels on seedling growth were also dependent on the statistical approach used in the analyses (Fig. 1a–e, Table 1). Overall, our analyses indicate that the effects of this treatment on seedling survival and growth should be interpreted with caution, and further studies are needed before any generalization on the effects of hydrogels can be made.

4.2. Variations in treatment effects with site preparation and through time

The majority of studies analyzed lasted for two years or less, so our results must be interpreted in the context of the early stages of seedling establishment. However, this stage is critical to ensure the success of restoration actions conducted in drylands (Pausas et al., 2004; Vallejo et al., 2012). The inclusion of the study length as an explanatory variable of Q_T did not modify the results of our analyses (results not shown), although some significant relationships between particular effect sizes and such length were found.

The absence of differences among site preparation techniques (Fig. 2), and the weak relationship between the length of experiment and the effect sizes of mycorrhizal inoculation, indicate that the benefits of this treatment were consistent (Table 3). Regarding the addition of OA, subsoiling effectively promoted seedling growth (diameter, shoot biomass and root biomass) compared to hole digging, but decreased seedling survival. The length of the study was negatively related to growth variables in treatments including OA (height in mycorrhizal fungi and OA treatment, and height and shoot biomass in the OA treatment, Table 3), suggesting that positive effects of OA on plant growth were more important during the early stages after planting, in that their effects were reduced when the nutrients OA contained are completely mineralized. Some studies have observed that a rapid growth of aboveground tissues before the main dry period could jeopardize future seedling survival (Villar-Salvador et al., 1997; Villar-Salvador et al., 2011). Thus, the likely increase in growth promoted by OA could, in addition to other negative effects linked to this treatment (e.g. increased soil salinity and competition with herbaceous species), determine later survival, at least at the early stages after planting. The negative effects of OA on seedling survival declined over time (Table 3). Given the long residence time of many OA in soils (Fuentes et al., 2010), once the stress associated to planting is surpassed, the benefits of OA could improve the survival of seedlings at the medium to long term. These results suggest the need to consider potential seasonal effects of OA on the performance of planted seedlings in future research.

When planted using hole digging, seedlings protected with treeshelters had higher diameters than those without them, in contrast to the overall negative effects of treeshelters on this variable. The low number of studies used in this case (nine), however, indicates that these results, although intriguing, should be taken with caution. The duration of the experiment was positively related to the effect size of the treeshelters when analyzing growth variables (diameter, shoot and root biomass). These results confirm the notion that morphological changes produced by the abiotic conditions inside the shelters are reduced when seedling height reaches that of the shelters (Oliet & Jacobs, 2007). The significant heterogeneity found for height growth with this treatment could be related to the differences in the type of shelters used, as well as to the differential responses to them by the species included in our analyses. It must be noted, however, that negative effects in diameter growth were not conditioned by these sources of variation.

Results of hydrogels were not related to experiment length in any case, probably due to the low number of case studies included for each variable. Site preparation procedure by hole digging could improve survival in this treatment, but, as noted above, the publication bias found in this variable avoids generalizing results obtained from this treatment.

4.3. Limitations of our analyses and recommendations for future studies

Despite the relatively high number of studies complied in our synthesis, deficiencies in the presentation of data or the omission of important information in many of the original publications precluded us from carrying out additional analyses. The length of the first dry period after planting is especially important in determining the success of plantations such as those studied here (Pausas et al., 2004; Vallejo et al., 2012). However, we were unable to successfully assess the relationship between water availability in the first year of plantation and the effects of the treatments evaluated because of a lack of data on precipitation and/or temperature during the study period. Whenever possible, future studies should always include this information, as this would allow additional analyses of the potential causes of variation in the effects of ecotechnological treatments such as those studied here.

The results obtained for hydrogels should be interpreted with caution because we were only able to obtain eight studies, and found some evidence for the presence of publication bias in this treatment. Thus, more studies on this treatment are clearly needed before any generalization on their effects on seedling establishment can be done. Similarly, our analyses of growth data revealed the presence of publication bias in the OA treatment, suggesting that studies failing to demonstrate significant effects of this treatment are not being published.

The relationship between root and shoot biomass is crucial to determine the survival of woody seedlings in drylands (Navarro et al., 2006; Villar-Salvador et al., 2009). This relationship can be modified with treatments such as treeshelters and OA, and it would be useful to explore their effects on the root: shoot ratio. Unfortunately we were unable to do this because of lack of data, as very few studies harvested part of their replicates to report this information. Whenever possible, this information should be reported in future studies.

4.4. Concluding remarks: recommendations for dryland restoration

The recruitment of woody species is one of the major limitations on the revegetation of degraded drylands. Therefore, a significant main challenge facing restoration scientists and practitioners is to enhance the survival and early growth of planted seedlings (Gómez-Aparicio, 2009; Cortina et al., 2011). Our synthesis indicates that inoculation with mycorrhizal fungi in the nursery (alone or in combination with OA in the field), and the use of treeshelters were, in this order, the most effective ecotechnological treatments to enhance both seedling survival and growth. The use of OA in isolation decreased seedling survival, and while this response is attenuated when hole digging is used as the planting method, this treatment should be used carefully, as OA may enhance competition from herbaceous plants and increase soil osmotic potential, reducing water availability. We do not recommend the addition of OA during dryland restoration, but if this treatment is to be used, we advise that it be used jointly with mycorrhizal inoculation whenever possible. The morphological changes induced by treeshelters on the planted seedlings raise doubts about their long-term effectiveness. However, the positive relationship found between the length of the study and the increase in seedlings diameter and biomass (both above- and belowground) suggests that these morphological changes diminish with time. When using this treatment, we recommend that hole digging be used during planting whenever possible to improve diameter growth and minimize the effects of shelters on the height: diameter ratio. In addition, some studies have also shown the effectiveness of particular treeshelter designs (e.g. smaller and ventilated tubes, or tubes made with materials of greater transmissibility) to improve this ratio without reducing their positive effects on seedling survival (Oliet et al., 2005).

While our results provide general trends and guidelines for researchers and practitioners, it must be noted that factors such as the type of treeshelter, the mycorrhizal fungi species and the type and dose of organic amendment are of paramount importance in determining the outcome of the application of these techniques in particular situations. Thus, these aspects must be taken into account when designing new studies about the use of these ecotechnological treatments under specific field conditions. By doing this we will be able to refine the general recommendations provided by our synthesis, and therefore maximize the benefits of ecotechnological techniques for improving the establishment of woody seedlings in degraded drylands.

Acknowledgements

We thank the many colleagues who shared their data with us or drew our attention to unpublished and published sources, and David J. Eldridge, the editor and two reviewers for their edits, comments an suggestion on a previous version of this manuscript. This synthesis was made possible thanks to the support of the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013)/ERC Grant Agreement No. 242658 (BIOCOM), awarded to FTM. A.V. is supported by the project CASCADE (Seventh Framework Programme, FP7/2007-2013 grant agreement 283068). The Fundación CEAM is partly supported by Generalitat Valenciana, and the projects GRACCIE (Consolider-Ingenio 2010) and FEEDBACKS (Prometeo - Generalitat Valenciana).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2013.09.066.

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