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# Effects of early irrigation and compost addition on soil and vegetation of a restored semiarid limestone quarry are undetectable after 13 years

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## Abstract

Semi-arid environments are strongly limited by water and nutrients, which hinders their recovery after anthropogenic disturbances. Application of compost and irrigation can improve soil fertility and enhance vegetation growth during the restoration of these environments. However, these restoration techniques may also favor the establishment of opportunistic communities and arrest natural succession. Mid and long-term assessments (>10 years) of the improvements in soil conditions and water availability after ecological restoration are scarce, although this is particularly important given the slow dynamics characterizing these environments. We assessed the effect of two levels of irrigation and compost addition (full-factorial design) in a limestone quarry under semi-arid conditions after a 13 years-period. These treatments were applied in addition to topsoiling, hydroseeding and plantation of woody species in the entire study area. Whereas the latter restoration treatments produced an overall increase in soil carbon content and salinity during this period (78% more soil carbon, over 200 µS/cm [nearly four times] more salinity), watering and compost addition did not affect the accumulation of soil organic carbon (at 0-10 cm and 10-20 cm) or soil salinity. In contrast to the observed short-term effects, water and compost addition did not affect the cover, biomass and diversity of the herbaceous layer, or the survival and growth of planted woody species 13 years after the treatments ended. Fading treatment effects occurred despite substantial changes in vegetation structure and composition between year 1 and year 13 (25% more herbaceous species, 13% less biomass, up to 80% decline in woody seedling survival). Conversely, similar to what we observed 13 years ago, the survival of woody plants was affected by the composition of the herbaceous layer, with species-specific responses to their cover and composition. Our study illustrates temporal shifts in the effects of two commonly applied restoration treatments, and highlights the need for mid- and long-term monitoring programs to properly assess the effectiveness of restoration actions.

***Key-words***: ecological restoration, legacy effects, long-term assessment, Mediterranean, plant-soil interactions, soil carbon

# 1. Introduction

Opencast mining causes irreversible damage on the structure and function of ecosystems and their surrounding (Lubke and Avis, 1998). In these areas, secondary succession may be hindered by the lack of fertile topsoils and the steep slopes characteristic of many abandoned mines (Bradshaw and Chadwick, 1980; Alday *et al.*, 2011). This is particularly true in harsh environments such as arid and semi-arid climates (Puigdefábregas and Mendizabal, 1998; Cortina *et al.* 2011). To aid revegetation under these limiting conditions, restoration has commonly focused on improving soil fertility and reducing water stress (Bochet and Garcia-Fayos, 2004; Rey-Benayas *et al.*, 2009; Soliveres *et al.*, 2012).

Compost addition and irrigation are common techniques to enhance nutrient and water availability (Vallejo *et al.*, 2012). In the short term, both techniques can increase soil fertility and enhance the establishment and growth of introduced herbaceous and woody species (Clemente *et al.* 2004; Moreno-Peñaranda *et al.*, 2004; Soliveres *et al.*, 2012). Whether or not these effects persist at longer time scales is poorly known (Rey-Benayas and Camacho-Cruz, 2004; Valdecantos and Fuentes, 2017). For example, compost may increase salinization (Bünemann *et al.*, 2018), hindering vegetation growth and altering community composition. Irrigation attenuates water stress, and may buffer the physiological stress of salinity, increasing the chances of seedling survival (Rey-Benayas and Camacho-Cruz, 2004). Conversely, both the addition of compost and irrigation may enhance the production of herbaceous biomass, with potentially negative effects on the survival and growth of late-successional woody species, due to competitive interactions (Temperton *et al.*, 2004; Soliveres *et al.*, 2012). These competitive woody-herbaceous interactions, however, could shift to facilitation, particularly in harsh years, when herbaceous vegetation dries out, or when woody species escape from aboveground or belowground competition (Puigdefábregas *et al.*, 1999; Gómez-Aparicio, 2009; Soliveres *et al.*, 2010).

The balance between the positive and negative effects of restoration practices in the long-term are poorly known, and this is particularly relevant under semi-arid conditions, where ecosystems may respond slowly to restoration efforts (Bautista *et al*, 2009; Alados *et al.*, 2011; Cortina *et al.*, 2011). In addition, the balance between positive and negative effects of restoration practices may shift with time (Oliveira *et al.*, 2011; Ojeda *et al.*, 2015). This could compromise management decisions supported only by short-term studies. Increased fertility may accelerate revegetation, but this may come at a cost of the establishment of competitive species hindering secondary succession (Moreno de las Heras *et al.*, 2008). Alternatively, restoration could revert the thresholds characterizing dryland degradation (Puigdefábregas and Mendizabal, 1998; Berdugo *et al.*, 2020). Hence, restoration could trigger positive feedbacks in restored ecosystems, accelerating their recovery long after restoration activities are over. For example, compost addition may enhance soil carbon sequestration after 17 years by increasing soil organic matter stability and protection within soil aggregates (Ojeda *et al.*, 2015; Hueso-González *et al.*, 2018). Aiding the colonization of a large pool of native species via seeding or planting could also foster ecosystem development, by improving soil fertility and triggering nucleation processes (Bochet and García-Fayos, 2004; Alados *et al.*, 2011; Cortina *et al.*, 2011). Such positive feedbacks could render even stronger and more positive effects of restoration in the mid- (5-15 years) and long- (>15 years) terms, in comparison to those found in the short-term (Ruiz-Jaen and Aide, 2005). It is important, therefore, to evaluate the effectiveness of restoration practices years after their application because of potential differences in short- vs long-term responses, the inherent slow dynamics of semi-arid ecosystems, and the need to design efficient restoration programs (Puigdefábregas, 1998; SER, 2004; Cortina *et al*., 2011).

In this study, we assess the mid-term (13 years) effects of compost and water on the restoration of a limestone quarry under semi-arid conditions, and compare these effects with those found one year after the restoration (Soliveres *et al*. 2012). Whereas a 10+ year period can be considered long-term, we chose here mid-term for a study lasting <15 years due to the slow dynamics characterizing semi-arid environments, and the long-term recovery processes often required in quarry restoration (Ruiz-Jaen and Aide 2005; Prach *et al*. 2016; Prach and Walker, 2018). We evaluated the effects on soil properties, herbaceous vegetation, and woody plant establishment to test the following hypotheses: i) the application of compost and irrigation modify soil organic carbon content and salinity after 13 years, ii) changes in soil properties are linked to changes in the cover and composition of the herbaceous plant community, and the survival and growth of woody plants, and iii) short-term (1 year) and mid-term (13 years) changes are consistent.

# 2. Materials and methods

## 2.1 Study area

The study area is located in a limestone quarry in Serra Mitjana, Alicante, southeastern Spain (38°22'33.3" N, 0°35'28.4" W). The area has semi-arid climate, with warm temperatures, irregular rainfall and pronounced summer drought. Between 2006 and 2018, an average temperature and precipitation of 17 ºC and 290 mm, respectively, was recorded nearby (El Rebolledo weather station, Province Alicante; https://www.avamet.org/). Mature natural vegetation characterizing semi-arid environments growing on thin limestone soils, such as those surrounding our study site, is commonly sparse, dominated by patches of grasses and small shrubs (*Anthyllis citisoides* L., *Brachypodium retusum* (Pers.) Beauv., *Rosmarinus officinalis* L., *Stipa tenacissima* L., *Thymus* spp.), and scattered resprouting shrubs (*Ephedra fragilis* Desf., *Juniperus oxycedrus* Sibth. & Sm., *Quercus coccifera* L., *Pistacia lentiscus* L., *Rhamnus lycioides* L.; Tormo *et al*., 2020). This community was the target for restoring the study site. The mining site drains onto a flat saline wetland (Saladar de Fontcalent, Alicante), which is less than 2 km away. It is dominated by *Phragmites australis*, accompanied by salt-tolerant woody species as *Tamarix* spp. and *Salsola* spp., and *Limonium* spp. steppes.

## 2.2 Experimental design

In the summer of 2005, a 20 m-high mining slope was filled with sterile material, creating an area of approximately 3000 m$^2$, with a 16º North-facing slope (Fig. S1). We then established four treatments with three replicated 15 m × 15 m plots each ($N = 12$). These consisted of a full factorial design combining two treatments (irrigation and compost addition) with two levels each. We established two irrigation levels, based on the spacing of 0.8 m and 2.4 m between drip hoses, which provided a weekly flow rate of 12 mm and 4 mm for one year, and increased average annual precipitation by 100 and 60%, respectively, as watering took place once a week. A separation of 80 cm in between drip hoses is the standard in commercial quarry restoration in the area (J. Fort, Projar SA, Spain, pers. com.). The low watering treatment was based on previous studies on the average distance between vegetation patches in semiarid steppes (Maestre *et al*., 2006), and aimed at reducing water inputs while maintaining the effectiveness of the treatment. Drip hoses and drippers were regularly spaced, and did not necessarily match the position of planted seedlings (see below). The organic amendment was composted sewage sludge produced in a nearby plant (SEARSA, Aspe, Alicante, Spain), and was applied at a rate of 4 kg × $m^{-2}$ and mixed with the top 40 cm of soil in half of the plots selected at random (see further details in Soliveres *et al*., 2012). This amount of compost is the standard recommended in Mediterranean forest plantations (Fuentes *et al*., 2007).

We hydroseeded the whole area at the beginning of the experiment (summer 2005). The hydroseeding was composed of a commercial mix of seeds of herbaceous species *(Dactylis glomerata* L., *Lolium rigidum* Gaudin, *Agropyrum cristatum* L., *Medicago lupulina* L. Sp. Pl. and *Trifolium alexandrinum* L.). None of them was abundant in the community 1 or 13 years after application. We also planted 25 individuals of each of the following six woody species per plot: *Anthyllis cytisoides*, *Juniperus oxycedrus*, *Pinus halepensis* Miller, *Pistacia lentiscus*, *Rhamnus lycioides* and *Salsola genistoides* Juss. ex Poir. These species represent different ecological strategies (early-successional vs. late-successional species) with contrasting responses to resource addition and herbaceous competition at the short term (Soliveres *et al.*, 2012). Hence, 150 planting holes (30 × 30 × 30 cm) were dug at each plot, along staggered rows that followed contour lines. Seedling species were later distributed at random, and all seedlings were planted in December 2015.

### 2.3 Soil properties

In 2018, we took a composite sample of three soil cores of 5 x 5 x 10 cm, at two depths: 0-10 cm and 10-20 cm in each plot, for a total of 24 samples (12 samples × 2 depths). We determined organic carbon content (Walkley and Black, 1934), and electrical conductivity with the saturated paste methodology. These results were compared with those obtained in 2006 following the same protocol, shortly after the application of the treatments.

### 2.4 Vegetation structure and composition

We determined the composition and abundance of the herbaceous vegetation in three 2 x 2 $m^2$ quadrats located within each plot in May, during the maximum seasonal biomass accumulation. With these data, we calculated vegetation and species cover (averaged across the three quadrats), estimated species richness (absolute number of species found in three quadrats) and Shannon´s evenness index, and performed a non-metric multidimensional ordination to characterize herbaceous composition. We also sampled aboveground biomass in three 50 cm x 50 cm quadrats in each plot. We placed each sample in a paper bag and dried them in an oven at 70ºC for 24 hours to obtain the dry weight. Finally, we measured the survival and growth (maximum stem height and root collar diameter) of all individuals of the six woody species planted in 2005.

### 2.5 Statistical analysis

We analyzed the effect of compost, irrigation, and their interaction, on i) the increase in organic carbon measured at 0-10 cm of depth between the year 2006 (1 year after the restoration) and the year 2018, ii) soil organic carbon content (10-20 cm depth) and salinity in 2018, iii) cover, diversity (richness, evenness), composition, and biomass accumulation of the herbaceous community, and iv) survival and growth (stem height and basal diameter) of woody species. Height and basal diameter were highly correlated (Spearman´s $\rho > 0.7$), providing somewhat redundant information. Therefore, we did not analyze basal diameter to avoid multiple testing and increased type II errors. We performed an analysis of variance (ANOVA) for each response variable, using compost/irrigation as fixed factors with two levels each, and considering their interaction (with two exceptions, see below). All variables fulfilled the assumptions of normality and homoscedasticity. We analyzed survival and growth of all woody species together. For this, we added an additional factor “species”, together with compost and irrigation and all three- and two-way interactions, in order to account for species-specific responses to the treatments. We analyzed herbaceous composition with a permutational version of ANOVA (PERMANOVA) with 999 permutations, calculating the Bray-Curtis dissimilarity distance on previously transformed data (square-root), to equalize the influence of common and rare species.

We were interested in explaining the performance of woody species based on the properties of the soil and the herbaceous community. Therefore, we analyzed the relationship between the survival of woody species with soil properties (organic carbon, salinity) and several indicators of potential competitive strength of the herbaceous community (biomass accumulation, plant cover, species richness, and community composition) through linear regression analyses. To summarize herbaceous composition into two variables, we used the two axes of the non-metric multidimensional scaling (NMDS) ordination, which showed a stress value of 0.12. The first NMDS axis indicated changes in the abundance of salt-tolerant species, and the second one was related to changes in the abundance of annual species (see Results). We performed the multivariate analyses using PERMANOVA+ module for PRIMER (PRIMER-E Limited, Plymouth Marine Laboratory, UK; Anderson et al. 2008), and other analyses using SPSS version 13 (SPSS Inc. Chicago, IL, USA).

# 3. Results

## 3.1 Soil and herbaceous vegetation attributes do not respond to early watering and compost addition 13 years after their application

Although soil organic carbon and soil salinity increased between 2006 and 2018 (from 1.60 to 2.85% of soil organic carbon, from 64 to 276 µS/cm salinity on average in 2006 vs 2018, respectively; Fig. 1), our treatments had no effect on soil properties at any depth. The ineffectiveness of water and compost addition on soil properties was consistent between the short and mid-term assessment. Similarly, compost and irrigation did not affect the richness, cover, biomass or composition of the herbaceous community (Table S1).

Herbaceous responses to water and compost addition, however, did differ between the 1- and 13-years assessments. Initially (2006), herbaceous biomass increased with irrigation, whilst in 2018 the effect of irrigation vanished. Indeed, and contrary to soil carbon, herbaceous biomass decreased substantially from 2006 (277 ± 78 g/m$^2$) to 2018 (141 ± 8 g/m$^2$). Time allowed colonization of new species, as species richness was greater in all treatments in 2018 than in 2006 (<15 species average in 2006 vs. >20 species in 2018; Fig. 2). We identified 37 vascular plant species, of which only 15 were already present in 2006 (data not shown).

## 3.2 Woody vegetation does not respond to water and compost addition but to changes in its herbaceous neighbours

The survival of woody species declined substantially regarding that found after the first summer (maximum of 30% across all species and treatments; Fig. 3). Indeed, we found no surviving individuals of two of the six planted species (*Pinus halepensis*, survival in 2006 ca. 60%, *Juniperus oxycedrus*, survival in 2006 ca. 40%), and *Rhamnus lycioides* was only present in three out of the 12 study plots. In contrast to our findings in 2006, seedling survival and growth were not affected by compost or water addition in 2018 (Table S1; Fig. S3). Contrary to results found in the first year after planting, we observed no species-specific responses to compost or water (no significant species × compost, species × irrigation, or species × irrigation × compost interactions for seedling growth or survival). Despite the low survival rates, the growth rate of surviving seedlings was relatively high (stem height increased by 5.24 cm · year$^{-1}$, on average, across all species and treatments; Fig. S3), and most seedlings reached reproductive age (data not shown).

In contrast with the lack of effects when adding water or compost, the survival of woody seedlings was influenced by the composition of their herbaceous neighbours, and this response was species-specific. The survival of *Pistacia lentiscus*, a late-successional species in this area, increased with herbaceous cover (Fig. 4). Although this relationship was marginally significant, it explained 29% of the variation observed in *P. lentiscus* survival. *Anthyllis cytisoides* survival was higher in plots colonized by salt-tolerant species (marginally significant relationship between seedling survival of this species and the NMDS axis 1), but decreased when surrounded by annual plants (NMDS axis 2). The survival of *Salsola genistoides*, instead, increased when neighbours were dominated by annual plants (marginally significant relationship between survival and NMDS axis 2). Growth responses of woody seedlings to their herbaceous neighbours were fairly similar to those observed for survival: they increased with herbaceous cover and declined when surrounded by salt-tolerant species (Fig. 4). These responses, however, were only significant when analyzing the average across all species, but not for any given species individually. The richness, evenness and biomass of the herbaceous community did not show any relationship with the survival of any of the woody species, and neither were they affected by soil attributes (data not shown).

# 4. Discussion

## 4.1 Compost addition and irrigation do not modify soil, herbaceous or woody vegetation 13 years after their application.

Soil organic carbon almost doubled between 2006 and 2018, which is perhaps related to the gentle slope, topsoiling, and plantation of woody seedlings that were applied in our entire study area. The latter suggests a generally positive effect of the overall restoration of the limestone quarry, and could support the potential of restored mine-sites as effective sinks for atmospheric $CO_2$ (Frouz and Vinduskova, 2020), even under semi-arid conditions. Second, despite the relatively low survival rates, we managed to establish reproductive populations of some resprouting species which are key in *Stipa tenacissima* steppes (Cortina *et al*., 2011; Tormo *et al.*, 2020). However, despite these positive trends found in the study area, the restoration treatments applied in our experiment (water and compost addition) did not modify restoration success. Indeed, organic carbon was not affected by the application of compost or irrigation at the earliest stages of ecological restoration, neither in 2006 nor in 2018. This is in contrast with various studies showing increases in soil carbon content after the application of organic amendments under semi-arid environments (Bastida *et al*., 2008; Luna *et al*., 2016; Kowaljow *et al*., 2017), and under Mediterranean climates on similar soils (Clemente *et al.*, 2004; Miralles *et al.*, 2009; Ojeda *et al*., 2015; Valdecantos and Fuentes, 2018). The lack of response to compost in our site could be related to: i) the smaller amount of compost added (regarding some of the above-cited studies), or ii) to the relatively high fertility of the substrate used on top of the restored slope (a 40 cm-depth layer of topsoil with average soil organic carbon concentration of 1.6%; Soliveres *et al*. 2012), which probably supplied the soil resources demanded by growing herbaceous vegetation. We may note, however, that compost affected the survival of woody seedlings (Fig. 3) and herbaceous composition

(Fig. S2) in 2006, suggesting that plants were then more sensitive to the additional soil fertility brought by the compost (Soliveres *et al.*, 2012). In addition, compost addition may have affected the quality (which we did not measure) but not the quantity of organic matter in the soil, as observed in a long-term survey of the effects of compost addition on semi-arid soils (Ojeda *et al.*, 2015). The latter revealed no significant differences in soil carbon in control vs. amended soils (as we found), but a more protected and stable organic matter in the case of amended soils after 17 years.

Although not related to compost addition as we expected, salinity substantially increased in our study area between 2006 and 2018. This increase was probably facilitated by the accumulation of salts in the topsoil caused by: i) deposition of wind-transported soluble salts from a nearby saline wetland (Saladar de Fontcalent, Alicante, 2 km from the experimental site) and/or ii) irrigation with poor-quality water, as observed in other semi-arid areas (Utset and Borroto, 2001). Indeed, although this trend was not statistically significant, salinity was higher in those plots receiving a larger amount of irrigation (301 ± 22 $\mu S \times cm^{-1}$ vs 251 ± 14 $\mu S \times cm^{-1}$, mean ± SE). The possible effect of irrigation water on soil salinity, together with the poor response of long-term survival of woody species and herbaceous biomass, suggest that irrigation may not be as beneficial for the restoration of semi-arid environments in the long run as previously thought, particularly if water is not of high quality and competition with herbaceous vegetation is likely. It must be noted, however, that although 3-fold less, our "control" treatment was also irrigated, which could have reduced the differences between treatments during the first year (see contrasting results in Rey-Benayas and Camacho-Cruz, 2004; Estela *et al.*, 2009, with unwatered controls). Finally, we must consider variability in rainfall amount and distribution, and their effects on planting success (Vallejo *et al.*, 2012). Additional long-term studies including a gradient in water addition in a multi-species context would allow identifying target levels of water availability to maximize early plant establishment and survival. Yet, our results suggest that irrigation, a common and costly practice in this water limited area, may be reduced, with consequent reductions in the use of water and the costs of deploying and maintaining the irrigation system.

### 4.2 Effects of restoration treatments may change when assessed 1- vs 13-years after their application

Mid- and long-term assessments of the effectiveness of restoration treatments are increasing (Wortley *et al*., 2013), but those that focus on Mediterranean semi-arid areas are rare. Although multi-species approaches and a broad focus on a comprehensive set of soil and vegetation attributes is frequently called for (SER, 2004; Padilla *et al*., 2009), mid- to long-term restoration assessments including all these characteristics, such as ours, are uncommon (Wortley *et al*., 2013). Our study shows that these mid- to long-term assessments are necessary in order to properly plan effective restoration programs under semi-arid conditions, as mid- to long-term results may substantially differ from those obtained in the short-term (Oliveria *et al*., 2011, but see Rey-Benayas and Camacho-Cruz, 2004; Ojeda *et al*., 2015).

The establishment of woody species is a widespread restoration target in Mediterranean semi-arid environments (Cortina *et al*., 2011). Our results clearly recommend caution against species selection based upon short-term studies. Woody species showing high survival rates after the first summer (e.g., *P. halepensis*, *J. oxycedrus*, *R. lycioides*) could even disappear after a decade in the field, whereas others performing poorly in the short-term (e.g., *P. lentiscus*) may generate reproductive populations large enough to trigger nucleation processes, as we observed. It is worth noting that the period of study (2006-2018) included some of the driest years on record in this area (particularly 2014; García de la Serrana *et al*., 2015). Regarding survival of woody seedlings, many studies invoked the first summer drought as a major bottleneck for plant establishment in semi-arid plantations (Vallejo *et al.*, 2012). However, this was not our case, as we found decreases of up to 80% in survival even after this first summer. Our results suggest that, in addition to the first-summer filter, extreme droughts may compromise the survival of established seedlings and trees (see also Padilla *et al*., 2009; García de la Serrana *et al.*, 2015). As rainfall is already extremely variable in semi-arid environments and this is expected to increase with climate change (Puigdefábregas and Mendizabal, 1998), it could be wise to perform afforestation using multiple-year windows, in order to minimize risks of die-off during extremely dry years.

Consistently with previous long-term assessments (Moreno de las Heras *et al*., 2008; García-Palacios *et al.*, 2011), our results suggest caution in focusing only on rapid vegetation establishment in drylands. Such communities may increase their richness over time, as we observed, although this may be due to the colonization of fast-growing annual and salt-tolerant species, which can affect the survival and growth of late-successional species (see also Gómez-Aparicio, 2009). As we found during the first year (Soliveres *et al*., 2012), and similarly to other studies (Oliveria *et al*., 2011; Padilla *et al*., 2011), woody plant responses to environmental changes are highly species-specific. In our case, each of the three surviving species in 2018 (Fig. 4; as *R. lycioides* only survived in three plots and therefore was not analyzed), responded differently to herbaceous vegetation, hindering generalizations. An exception to this, however, is that a fundamental trade-off in the restoration of degraded slopes (that between fostering the growth of herbaceous vs. woody species) can be solved with time, as none of the woody species responded negatively to herbaceous cover (Fig. 4) or biomass. The seemingly current weak competition between herbaceous and woody species 13 years after the restoration took place may reflect gradual separation in belowground niches between these groups (Puigdefábregas *et al*., 1999) or an escape from light competition in woody seedlings large enough to overgrow the herbaceous layer (Valladares and Pearcy, 2002; Soliveres *et al*., 2010). In any case, the seemingly high stochasticity in the survival of woody species in our study calls for further research to test the validity of previous generalizations on early woody plants´ response in afforestation programmes (Padilla *et al*., 2009; Soliveres *et al*., 2012).

### 4.3 Concluding remarks

Professor Puidefábregas´ contributions to the study of degradation trajectories and thresholds changed our views of the way drylands respond to degradation drivers, and decisively contributed to develop new approaches for dryland restoration (e.g., Puigdefábregas and Mendizabal, 1998; Whisenant, 2001). Mining activities commonly cross biotic and abiotic degradation thresholds (Bradshaw and Chadwick, 1980; Lubke and Avis, 1998; Puigdefábregas and Mendizabal, 1998). Thus, after abandonment, quarries must be restored from scratch, assembling the totality of their abiotic and biotic components. This is a major challenge in quarry restoration: how to activate ecosystem processes avoiding undesired successional trajectories and keeping the fidelity to target, often historical, ecosystems. We found that ameliorating environmental conditions, particularly diminishing slope steepness, deploying a relatively thick and fertile soil, and adding a minimum amount of water for one year, was enough to trigger the establishment of plants from the soil seed and bud banks and from neighbouring ecosystems, and activate soil processes. Adding additional short-term inputs of organic matter and nutrients (via compost addition), or water, showed mostly transient effects on soils and vegetation, which were evident one year after their application but largely vanished after 13 years. Our results suggest that late-successional species, either those planted or those colonizing from nearby environments, may establish in the area, and drive the assemblage of the whole community. Thus, the restoration of extremely degraded semiarid landscapes was initiated by an improvement in environmental conditions (i.e., crossing the abiotic threshold), which promoted the establishment of planted woody species and spontaneous colonizers (i.e., crossing biotic thresholds). Due to the slow dynamics of semi-arid environments (Puigdefábregas, 1998), longer-term monitoring of this area is needed to test whether pioneer species will be gradually replaced by the patchy shrubland characteristic of this area. Similarly, as land degradation can affect surrounding areas (Puigdefábregas and Mendizabal, 1998), we argue that so could land restoration. Studying how these “restored islands” provide plant propagules and other resources to surrounding areas (or else, act as sinks of resources) is a research area worth investigating, and one which would help unifying our understanding of the functioning of drylands with their restoration at large scales.

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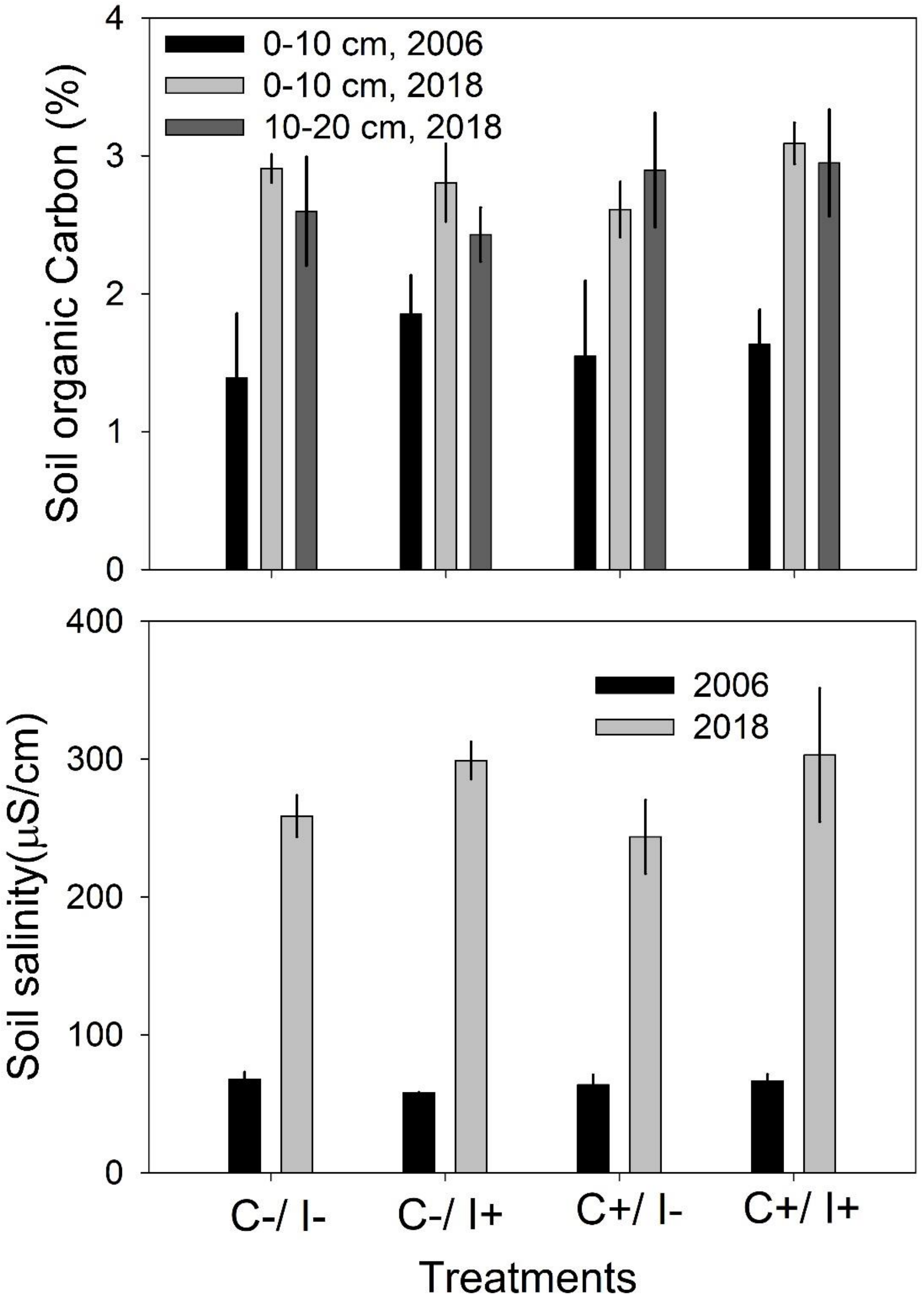

**Figure 1.** Mean ± standard error (N = 3) of organic carbon percentage at 0-10 cm and 10-20 cm of soil depth for the year 2006 and 2018 (panel above); conductivity (µS/cm) for the year 2006 and 2018. Treatments are: no compost and low irrigation (C- / I-), no compost and high irrigation (C- / I +), with compost and low irrigation (C + / I-), with compost and high irrigation (C + / I +)

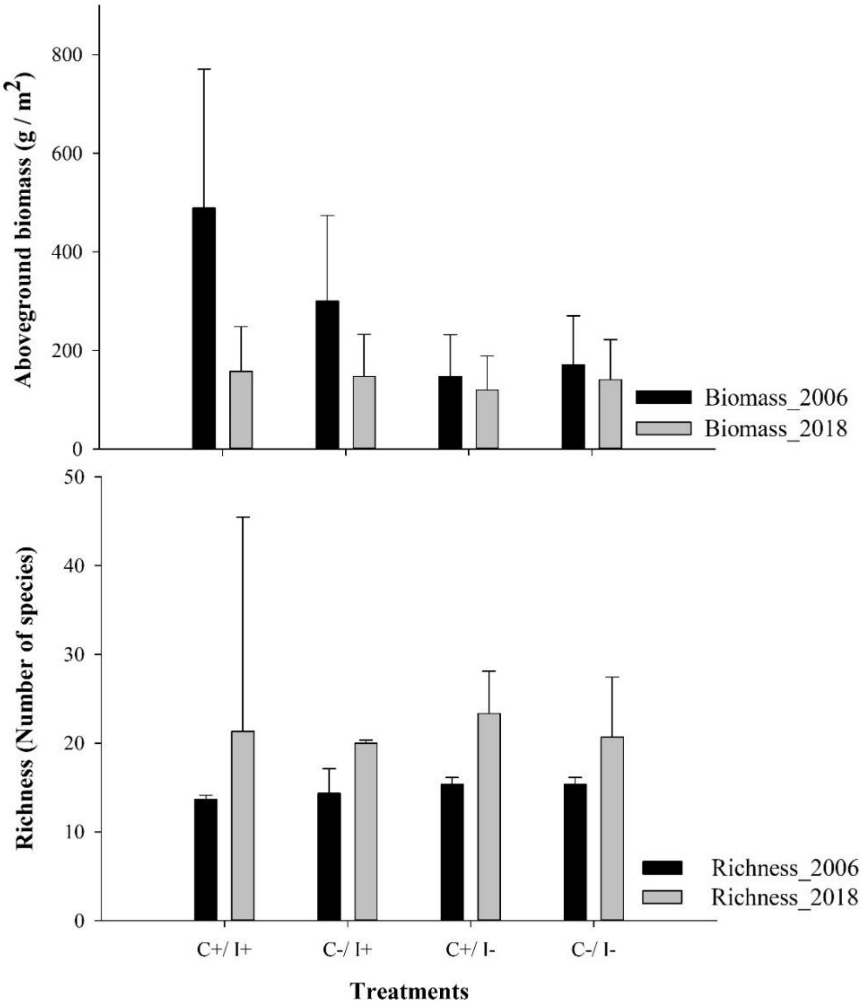

**Figure 2.** Mean ± standard error (N = 3) of aboveground biomass (g / m$^2$; panel above) and richness (number of species; panel below) registered in the treatments: no compost and low irrigation (C- / I-), no compost and high irrigation (C- / I +), with compost and low irrigation (C + / I-), with compost and high irrigation (C + / I +) in the years 2006 (black) and 2018 (grey).

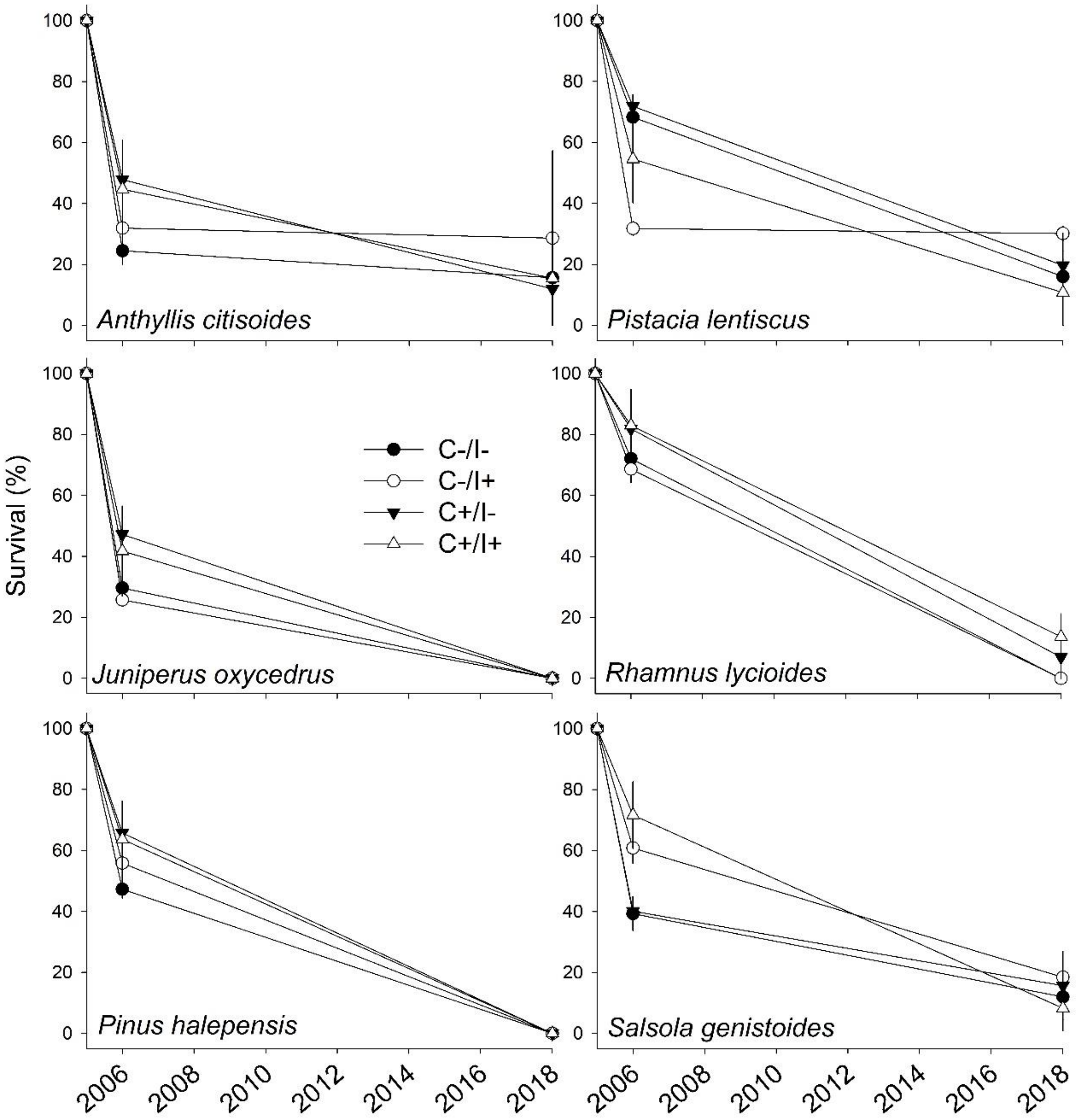

**Figure 3.** Mean ± standard error (*N* = 3) of the survival percentage of each of the planted woody species in the year of planting (2005), after one year (2006) and after 13 years (2018). Each symbol indicates a treatment: no compost and low irrigation (C-/ I-), no compost and high irrigation (C-/ I+), compost addition and low irrigation (C+/ I-), with compost and high irrigation (C+ / I+).

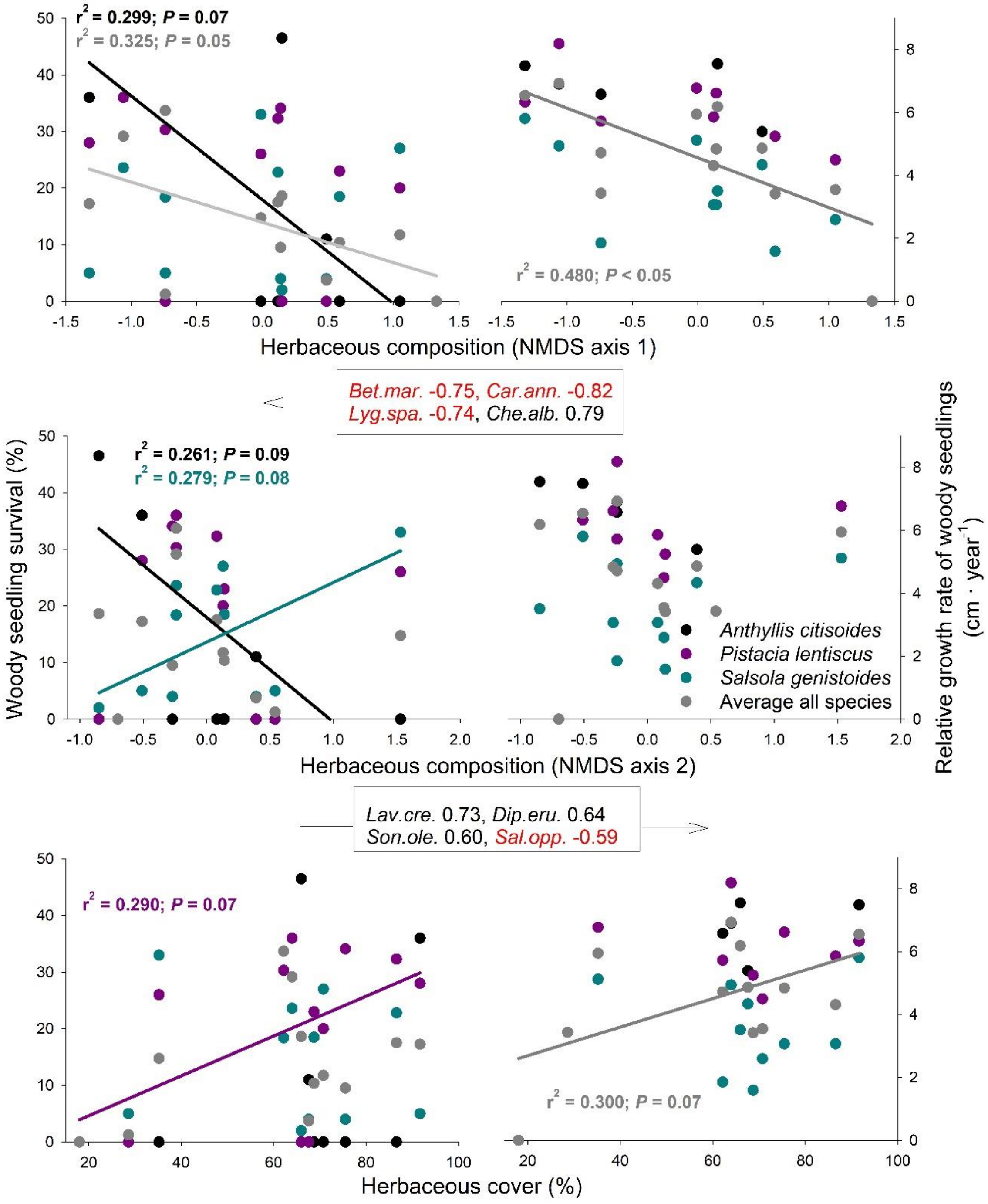

**Figure 4.** Relationship between survival (left panels) and growth (right panels) of woody seedlings and characteristics of herbaceous vegetation across the 12 study plots. Different colours represent different woody species. Names within boxes are those species more highly correlated with the multivariate ordination performed to analyze their composition: Bet.mar = *Beta maritima*, Car.ann = *Carrichtera annua*, Lyg.spa =

*Lygeum spartium*, Che.alb = *Chenopodium album*, Lav.cre = *Lavatera cretica*, Dip.eru = *Diplotaxis erucoides*, Son.ole = *Sonchus oleraceus*, Sal.opp = *Salsola oppositifolia*. Results are the $R^2$ and p-values associated to a linear regression between each herbaceous predictor and each woody seedling´s performance measure ($N$ = 5, 8, 11, and 12 for *Anthyllis cytisoides*, *Pistacia lentiscus*, *Salsola genistoides* and the average across all species, respectively), only significant slopes are shown.