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Research article

Constructed pine log piles facilitate plant establishment in mining drylands

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ABSTRACT

Ecological facilitation, though accepted as a main mechanism of plant community assembly, is just starting to be utilized in restoration programmes. Constructing nurse objects that mimic the effect of natural nurse species can be an option to trigger plant nucleation processes in disturbed stressful ecosystems.

We hypothesized that arranged log piles might imitate plant facilitation by alleviating abiotic stress and expanding the regeneration niche of beneficiary species, eventually promoting plant establishment, fitness and diversity. With this aim, within a pilot restoration programme in abandoned mining structures in SE Spain where climatic and edaphic stresses concur, we constructed 133 pine log piles from natural wastes generated by local silvicultural activities. We monitored 51 of them plus their adjacent open areas for 15 months, measuring soil temperature, radiation and humidity. We recorded natural seedling establishment, plant nutritional status and heavy metal accumulation. We further performed a seed sowing experiment to investigate how log piles affect plant taxonomic and functional diversity based on 11 establishment and phytostabilization traits.

Pine log piles significantly softened microclimatic conditions and accelerated plant establishment in unfertile and metal-polluted mining substrates, simultaneously capturing water, providing shade and pine seeds. Plant communities that naturally established beneath the piles were 15 times denser and five times taxonomically more diverse than those in open areas, despite being skewed towards pine recruitment. Experimental communities sown under log piles were also 1.4 times functionally more diverse, as theory predicts for relaxed abiotic conditions. Log piles improved seedling nutritional status, in terms of P and K content, at the cost of increased metal accumulation.

At the landscape scale, nurse objects triggered plant establishment promoting taxonomic and functional diversity in extremely stressful environments. This study exemplifies how soft restoration tools can be based on mechanisms that are widely accepted in the ecological theory.

1. Introduction

Ecological facilitation between plants is one of the main processes that structure biodiversity and assemble communities in abiotically stressful ecosystems (Brooker et al., 2008). Nurse plant species colonize barren substrates and, in a period of a few years, significantly modify the microclimate and soil conditions in their influence area (Navarro-Cano et al., 2015). This process triggers plant nucleation through expanding the realized niche of other less stress-tolerant species (Bruno et al., 2003), thus shaping multispecific plant patches that work as isles of resources in barren areas (Brooker et al., 2008). Both the local alleviation of warm and dry conditions and the co-existence of evolutionarily distant species within the patch neighbourhood can eventually promote functional diversity (Navarro-Cano et al., 2019a). Nurse-based restoration practices have been implemented in research afforestation projects in drylands (Castro et al., 2002; Rey et al., 2009; Tongway and Ludwig, 2011; Kimiti et al., 2017). Wild nurse plants can also provide suitable microsites for the establishment of target species in mine tailings (Navarro-Cano et al., 2018). However, their usual low density and plant cover in these extremely stressful ecosystems can lead to a fragmentary and incomplete restoration.

Mining activities are among the most environmentally harmful industries worldwide. Mine pollutants can persist for decades and be exported through soil erosion and runoff to neighbouring areas. Many

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drylands across the world are major areas where metal-mining industry operates, and thousands of hectares of mine tailings from the metal concentration process still wait for restoration (Mendez and Maier, 2008). These tailings create barren and polluted micro-deserts where high metal and metalloid concentration, as well as salinity, coincide with warm and dry climatic conditions. All of these factors, together with mass movement risks, pose a big challenge for the use of conventional mine-restoration methodologies based on physical or chemical stabilization such as on-site containment by dam building, sealing with a geological layer or with organic adhesives (Tordoff et al., 2000; Gómez-Ros et al., 2013; Mendez and Maier, 2008). These expensive methods do not guarantee soil stabilization due to crack formation from wetting-drying cycles or earthquakes (Mendez and Maier, 2008). Phytoextraction through hyperaccumulator plants is usually a long-term and limited-efficiency method only applicable to low or moderate levels of pollution (Ali et al., 2013). For mine tailings enclosed within natural areas, phytostabilization poses a cheaper and environmentally friendly method, as it is based on the use of local metal-tolerant species and can be executed with a limited use of heavy machinery (Mendez and Maier, 2008; Conesa and Schulin, 2010; Navarro-Cano et al., 2018). The main limitations of this method are: i) its low effectivity in the short term due to the lack of sufficient plant cover, which needs time to grow, and ii) its partial effectivity for soil remediation, since this technology reduces soil erosion but can contribute to exporting bioaccumulated pollutants out of the system through herbivory or runoff of released leaf litter (Gómez-Ros et al., 2013; Parraga-Aguado et al., 2014). Recent advances in phytostabilization combine physical and organic amendments with plantation of local tolerants to accelerate the growth of a plant cover by extensive soil preparation methods (Zornoza et al., 2012; Gil-Loaiza et al., 2016).

Log piles made by packing bundles of woody material from pruning, logging or burnt wood are also named fascines and have been used as ecological engineering solutions for slope stabilization and erosion control (Coppin and Stiles, 1995). They are used as erosion barriers on slopes up to 45° (Howell et al., 1991). Densely packed bundles of fresh wood have also been used to vegetate riverbanks by rooting of live cuttings (see e.g. Evette et al., 2009). In less steep slopes in drylands, cut branches have been grouped (Padilla and Pugnaire, 2009) or piled (Ludwig and Tongway, 1996; Castillo-Escrivà et al., 2019Castillo-Escrivà et al., 2019) to assist plant establishment, protect planted saplings or serve as bird perches. All of these techniques are absent in mine tailing restoration programmes (but see the pioneer experiences in Australia reviewed by Tongway and Ludwig, 2011), as their extreme edaphic stress has been traditionally considered an overwhelming filter for plant colonization. However, our recent experiments indicate that metal-tolerant pioneer plants that naturally recruit in mine tailings can significantly reduce the climatic stress beneath their canopy and subsequently allow the emergence of functionally-diverse plant communities (Navarro-Cano et al., 2019a). A diverse understory within these facilitation-driven patches also has a medium-to long-term effect on edaphic stress, mainly promoting soil fertility and microbial productivity both through biodiversity and biomass effects (Navarro-Cano et al., 2019b).

The Cartagena – La Union district (SE Spain) has a 2500 year mining tradition up to its closure in 1991. Currently, around 5000 ha are affected by mining structures, including up to 218 ha of highly polluted mine tailings. After three decades of abandonment, only 15 out of 89 tailings have been removed or capped (Conesa and Schulin, 2010). For most of the remaining tailings, their locations are relatively far from urban areas that has delayed their costly rehabilitation. Most of these tailings are enclosed by a valuable natural landscape, a feature that makes the use of phytostabilization a likey softer and cheaper restoration technology. Within the mining district, the Calblanque Natural Park holds one of the most prominent semi-arid Western Mediterranean forests. The necessity for better management of the fire-prone *Pinus halepensis* and *Tetraclinis articulata* mixed forest in the Park suggests reusing local burnt wood and woody debris from firebreaks for in situ restoration programmes. Based on previous field observations, we hypothesized that, besides a role as erosion barrier, pine log piles (fascines) can mimic the nurse plant canopies in barren tailings, thus facilitating the establishment of a plant community through the amelioration of abiotic stress conditions. We further expected, based on ecological theory, that the attenuation of temperature and radiation through fascine construction might increase the diversity of the facilitated community. We tested these hypotheses in a pilot restoration programme based on the pine fascine construction on an abandoned mine tailing. Through recording natural and sowed seedling recruitment underneath fascines and adjacent open areas we specifically tested whether fascines i) ameliorate the microclimatic conditions, ii) facilitate the establishment of taxonomically and functionally diverse plant communities and iii) improve the nutrient status of facilitated seedlings.

2. Materials and methods

2.1. Study site and soil properties

We studied the effect of pine fascine construction on plant establishment in a mine tailing from Cartagena-La Unión Mining District (SE Spain; 30 S 689151 E, 4164433 N). The area is a coastal mountain range shaped by metamorphic nappes, limestones and igneous rocks where different heavy metals (iron, copper, lead, zinc, manganese, etc.) have been exploited since ancient times. The climate is semi-arid Mediterranean with 17.9 °C mean annual temperature, 316 mm precipitation and 762 mm evapotranspiration. The studied tailing was shaped by wastes from the refining process of metals, and was active until around 1982. The tailing is enclosed within a *Pinus halepensis* - *Tetraclinis articulata* mixed forest. It covers 1.98 ha of abandoned barren mine substrates, which have very low levels of fertility, very high metal(loid) concentrations, moderate salinity and basic pH (Navarro-Cano et al., 2018). The levels of all these variables expose some spatial heterogeneity within the tailing due to the presence of cracks, incipient gullies and some vegetation patches (Parraga-Aguado et al., 2013).

Currently, a sparse plant community of stress-tolerant plants (39 species) from the surrounding area is colonizing the tailing and covers only 17% of the tailing surface. Dominant plants are *Pinus halepensis*, *Tamarix canariensis*, *Piptatherum miliaceum*, *Dorycnium pentaphyllum, Zygophyllum fabago* and *Limonium carthaginense*, some of which facilitate the creation of high-diversity patches in the tailing (Navarro-Cano et al., 2018). In December 2017, 133 short fascines were homogeneously distributed over the almost flat (2–5% slope) part of the tailing to promote its phytostabilization (Fig. 1). Fascines were made by manually packing bundles of coarse woody debris (Fig. 1) from pruning and logging of the pine forest in neighbouring sites (less than 2 km from the experimental area). This material was brought to the tailing border by truck in November 2017 previous to the fascine construction. The average fascine size was 4.1 ± 1.0 m long, 0.7 ± 0.1 m wide and 0.4 ± 0.1 m high.

Surface soil samples (0–5 cm) were collected from nine 1 m^2 plots regularly distributed across the tailing on March 2019. We sampled only the soil surface as this is the layer that mainly affects seed germination and seedling establishment. The coordinates in the centre of each plot were registered with a handheld GPS device (Garmin Oregon 750t). In each plot, five subsamples (ca. 200 g each) were taken from the centre and four cardinal points, and mixed into a single composite sample. Soil samples were transported to the laboratory, sieved $\leq$2 mm and kept at 4 °C. Soil gravimetric humidity (GH), pH, electrical conductivity (EC), total organic carbon (TOC) and nitrogen (TN) were measured using standard procedures as in Navarro-Cano et al. (2015). Total concentrations of other nutrients and heavy metals were determined by digestion with HNO_3 and H_2O_2, using an Ultraclave microwave digestion system (Milestone, Milan) followed by analysis by Inductively Coupled Plasma Optical Emission Spectroscopy (ICAP 6500 ICP-OES Spectrometer,

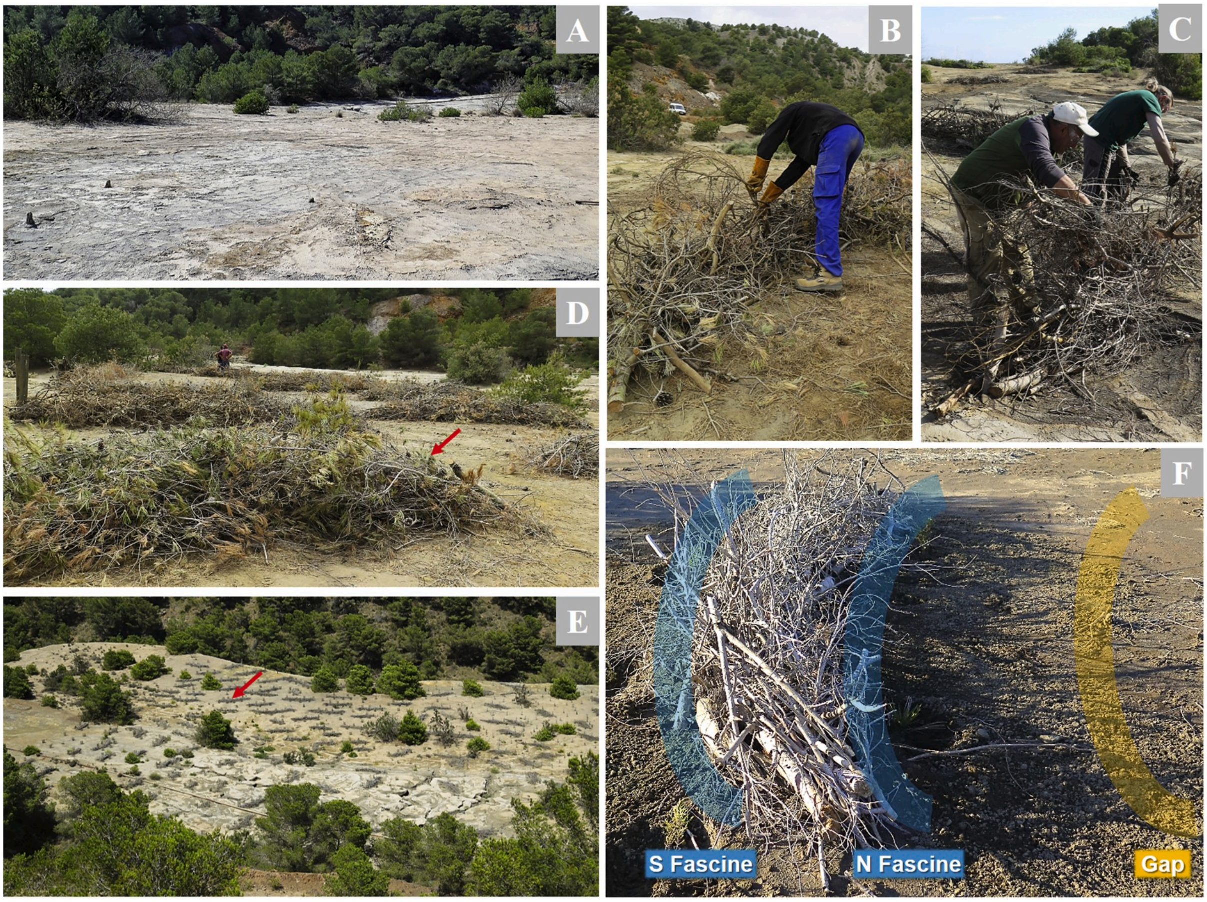

Fig. 1. Different views of the studied mine tailing from (A) the initial abandonment state (2017) to (B–C) manual labours for fascine construction within the LIFE *Tetraclinis* project, and (D–E) the current state of the tailing (2019) and the location of one of the fascines (red arrow). A view of the sampled microsites Gap, S Fascine and N Fascine is shown in (F). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Thermo Fischer Scientific, Waltham). Data were expressed on an oven-dried (105°) weight basis. Contour maps for each soil property were performed by inverse distance interpolation with SigmaPlot 10.0 (Systat Software, San Jose, CA).

2.2. Fascine effects on microclimatic conditions

To quantify the microclimatic shifts beneath the fascines we randomly established thirty plots across the tailing. Each plot was composed of a single fascine and its adjacent open area (hereafter 'gap'). Gaps were systematically located parallel and northwards from their corresponding fascines at a distance roughly twice the fascine width. The perimeter of each gap was delimited with a tape with a shape and area similar to the adjacent fascine. We established three sampling microsites within a plot: north side of the fascine (N Fascine), south side of the fascine (S Fascine) and Gap. N Fascine and S Fascine were defined as the first 20 cm-wide belt along the fascine canopy at its northern and southern aspects, respectively. A belt of similar size was sampled in Gap (Fig. 1).

Air temperature, humidity and light intensity were measured in the microsites by using a thermo-hygrometer HANNA HI 9564 and a lux-meter HANNA HI 97500 (Hanna instruments, Woonsocket RI USA) onto the soil surface. Measurements were taken on 22nd-23rd July 2019 at midday, as the most climatically stressful annual conditions. For each parameter, mean values were calculated from three measurements taken regularly along each microsite.

2.3. Fascine facilitation of natural plant establishment

Natural plant establishment in the tailing was recorded 15 months after fascine construction. Seedling density, richness and evenness were registered in the 30 fascines and adjacent gaps described above. Seedling density was standardised by sampling area according to fascine length and width, thus yielding the number of seedlings$\cdot$m^{-2} in each microsite. To explain the observed density of *Pinus halepensis* seedlings beneath the fascines we used two types of predictors: first, the soil properties (TOC, TN, P, K, As, Cd, Cu, Pb, Zn, pH and EC), which were interpolated from the contour maps described above; second, three potential pine seed sources including i) the mixed pine forest adjacent to the tailing, ii) the adult pines growing scattered on the tailing prior to fascine construction, and iii) the pine cones in the same fascine. To do so, we measured for each fascine the distance both to the pine forest nearby and to the nearest adult pine on the tailing, as well as the number of pine cones in the branches used to build the same fascine.

2.4. Fascine effects on the nutritional status of pine seedlings

We tested the effect of fascines on nutrient (C, N, P, K, C:N and N:P ratio) and heavy metal (As, Cd, Cu, Pb, Zn) concentrations of pine seedlings. We used these metabolic cues of stress instead of morphological traits as the date of seedling emergence would likely vary in some weeks, even within the same fascine, which would lead to size differences not related to stress response. Seedlings were collected beneath five fascines and their adjacent gaps, which had a number of seedlings high enough (from 5 to 15 seedlings) so as to provide the required amount of aerial dry mass for subsequent analyses. The size of the sampled adjacent gap was increased if no sufficient seedlings were found in the initial sampled area. All seedlings from the same fascine or gap were grouped into a single sample and transported to the laboratory. C and N were quantified as for soils from 1g of fresh ground needles and stems per fascine. Other nutrients and heavy metals were quantified in ground and digested samples, and analysed by ICP-OES as above. Data are expressed on an oven-dried (65°) weight basis.

2.5. *Fascine effects on the establishment of sowed species*

To further analyse the effects of fascines on the diversity of facilitated species, we carried out a sowing experiment since our observational study was biased towards the establishment of pine seedlings due to the presence of pine cones in the fascines. In the sowing experiment, we tested the effect of fascines on the establishment of a mixed set of seeds from seven local plant species that colonize mine tailings in the same area: *Atriplex halimus*, *Dactylis glomerata*, *Lavandula stoechas*, *Lygeum spartum*, *Piptatherum miliaceum*, *Rhamnus lyciodes* and *Salsola oppositifolia*. For this experiment, 21 new fascines and 21 new gaps were randomly selected as microsites across the tailing to avoid the use of previously sampled fascines. Seeds were collected on nearby tailings and grouped into mixed seed sets. One hundred seeds per species (but 10 seeds for *L. spartum*, that are two orders of magnitude bigger than the rest) were grouped per microsite. They were sowed on February 2018 by manually ploughing a narrow furrow (3 cm depth × 5 cm wide) along each fascine in its northern area of influence (Fascine) and along each gap (Gap). After sowing the seed mixture (610 seeds per microsite), seeds were buried with the same soil. No irrigation was carried out. Seedling emergence was monitored every two weeks until March 2019, except for the dry season (July–September).

Functional diversity of the emerged plant community was estimated according to 11 qualitative and quantitative traits that can influence seedling establishment, soil exploration and phytostabilization potential in the study area: photosynthetic metabolism (C3, C4), dispersion type (wind dispersion, drop by gravity, animal dispersion), halophytic adaptation (yes, no), seed weight, seed size:weight ratio, time to reach 50% germination under controlled conditions (T50), Raunkiaer life-form (nanophanerophyte, chamaephyte, hemicryptophyte and geophyte), specific leaf area (SLA), root depth and root laterality. Information on trait values was either obtained from the literature or generated from plants and seeds collected in the study area (Table S1). Mean trait values of seeds were obtained from 30 seeds per species. T50 was calculated from 4 seed sets ($n = 25$ seeds) per species that were incubated in a growth chamber (SANYO MLR-351H) under alternating temperatures (15/25 °C) and a 12 h light photoperiod (150 μmol m^{-2} s^{-1}), with the light period matching the highest temperature. Seeds were sown in Petri dishes on two disks of filter paper moistened with deionized water, and watered twice a week. Germinated seeds were counted and removed. Cumulative germination was calculated for each replicate and T50 estimated by fitting the germination curve to a Gompertz function (sigmoidal equations class) using SigmaPlot 10.0. Mean trait values of the SLA and root traits were either obtained from five adult plants per species that were fully harvested in mine tailings.

Functional diversity was calculated as the abundance-weighted mean phenotypic distance among species within each fascine or gap, using the *picante* package for R (Kembel et al., 2010). The *daisy* function was used to generate a phenotypic distance matrix based on Gower's distance and simultaneously deal with nominal, categorical and continuous variables (Kaufman and Rousseeuw, 2009) in the *cluster* package *v* 2.0.7 for R (Maechler et al., 2017).

2.6. *Statistical analyses*

Differences in temperature, humidity and light intensity among the three microsites N Fascine, S Fascine and Gap were analysed by generalised linear mixed models (GLMM). For each model, 'microsite' was used as a fixed factor and the 'plot' as a random factor, to account for the lack of independence among microsites within the same plot. We used the *lme* function in the *nlme* package *v* 3.1–143 for R (Pinheiro et al., 2019).

Seedling density and diversity metrics were analysed by GLMMs with the microsite as fixed factor and the plot as random factor. A quasi-Poisson error distribution was used to account for data overdispersion. We used the *glmmPQL* function in the *MASS* package for R (Venables and Ripley, 2002).

To explain the observed density of *Pinus halepensis* seedlings beneath the fascines we first analysed the role of soil properties. The individual effect of each soil variable on pine seedling density was tested using GLMs. The *p*-values of these GLMs were adjusted for multiple comparisons with the Benjamini-Hochberg correction (Benjamini and Hochberg, 1995). Second, we analysed the role of the three potential pine seed sources on pine seedling density. These potential seed sources were: i) the distance to the closest forest, ii) the distance to the closest pine tree and iii) the number of pine cones within the coarse woody debris of the fascine. These seed sources were used jointly as predictors of pine seedling density in a single GLM.

The effect of fascines on the density of seedlings belonging to species other than *P. halepensis* was analysed following the former procedure. In this case, however, we considered the understory community in the surrounding forest as the only potential seed source.

The effect of the microsite (fascine *vs.* gap) on nutrient and metal concentration in the seedlings was analysed by paired *t* tests, except for N:P ratio and Pb that were analysed with non-parametric Wilcoxon tests since they did not fit the normality and homocedasticity assumptions. We also tested whether the soil properties beneath the fascines and gaps had a relationship with seedling nutrient and metal concentration. Soil properties were analysed by paired *t* tests, except for P and As, for which we used non-parametric Wilcoxon tests. The *p*-values of these tests were adjusted for multiple comparisons with the Benjamini-Hochberg correction.

The effect of fascines on the seedling emergence of sowed species was analysed by a GLM with the microsite (Fascine vs Gap) as a fixed factor. A quasi-binomial error distribution was used to account for statistical overdispersion. The effect of the microsite on the composition and structure of the sowed community was tested from species richness, evenness and the mean phenotypic distance. These variables were analysed by GLM with the microsite as a fixed factor and a gaussian error distribution. All GLMs were performed with the *glm* function in the *stats* package for R (R Core Team, 2018).

3. Results

3.1. *Fascines ameliorated microclimatic conditions*

Fascines significantly decreased surface soil temperature (5 °C on average) and light intensity (56%), while increasing humidity (10%) compared to adjacent gaps (Fig. 2). Moreover, light intensity was significantly lower on the N side of the fascines (N Fascine). Overall, fascines shaped an ameliorated microclimate for seedling establishment.

3.2. *Fascines facilitated natural plant establishment*

Fifteen months after the construction of fascines, we found seedlings from 13 species. Most of them belonged to *Pinus halepensis* (60% of counts), followed by *Dittrichia viscosa* (13%) and *Diplotaxis harra* (10.5%). Other seedlings belonged to *Limonium carthaginense, Inula chritmoides, Dorycnium pentaphyllum, Zygophyllum fabago, Cistus monspeliensis, Helicrhysum stoechas, Leontodon longirostris, Piptatherum miliaceum, Polygala rupestris* and *Quercus coccifer*a (Fig. S2). Each of them represented less than 4% of the total community. Seedlings were significantly more abundant beneath the fascines, ranging from 0 to 45 seedlings·m^{-2}, than in the gaps where we detected 0–1 seedlings·m^{-2}

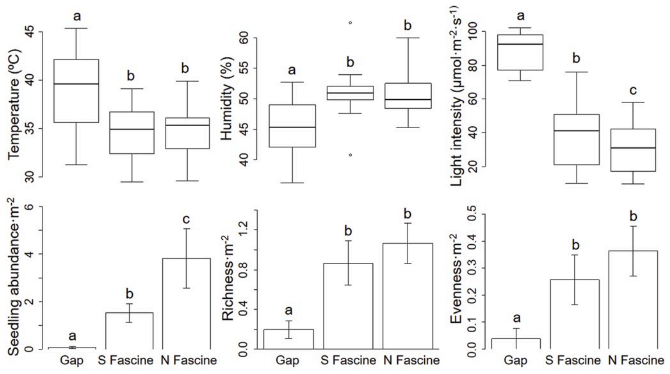

Fig. 2. Microsite characterization of pine fascines in the mine tailing (upper graphs) and microsite effects on seedling density per m^2, species richness and evenness (lower graphs). For each plot (n = 30), different letters denote significant differences among microsite levels (GLMM, $p \leq 0.05$).

(Fig. 2). Moreover, more seedlings established in the N Fascine than in S Fascine. All richness and evenness of seedling communities established beneath the fascines, irrespective of their aspect, were significantly larger than those in the adjacent gaps (Fig. 2). No relationships (Pearson correlation, $p > 0.05$) among the seedling abundance and the soil temperature, light intensity and humidity were found within the fascines.

The observed density of wild *P. halepensis* seedlings (Fig. S1) did not respond significantly to the soil properties (Fig. S3). However, pine seedling emergence was significantly higher in fascines located closer to the mixed pine forest growing adjacent to the tailing (range: 0.4–71.5 m) and having a larger number of pine cones in the branches used to construct the fascine (7–241 cones per fascine) (Table 1). Our data do not indicate that adult pines growing scattered in the tailing prior to fascine construction act as a relevant seed source for the fascines, as the distance of each closest adult pine (0.4–16.9 m) to the closest fascine was not a significant predictor of seedling density (Table 1). The statistical model testing the effect of all three pine seed sources explained 29% of the total variance.

Fascines also increased significantly the spontaneous establishment of 12 species other than *P. halepensis* compared to their success in adjacent gaps (Fig. S4). Moreover, seedlings of these species were significantly more abundant in N Fascine than in S Fascine. Five of these species are dispersed by wind, and seven respond to other dispersal vectors. However, there was no significant difference in the number of seedlings recorded according to the dispersal mode ($□^2 = 0.67$, $df = 1$, $p = 0.41$). Neither the soil properties (Fig. S5), nor the distance to the adjacent forest could explain seedling density in this case (GLM, *estimate* = −0.05, *SE* = −0.04, $t = -1.50$, $p = 0.146$).

3.3. Fascines improved the nutritional status of pine seedlings

Pine seedlings emerged underneath the fascines had approximately four times higher P and K concentration (Fig. 3) in the aerial tissues than those growing in the gaps. The N:P ratio was significantly higher (Wilcoxon test, v = 10, $p = 0.03$) in gaps (26.5 ± 15.5) than fascines (9.7 ± 2.1). The seedlings also had significantly or marginally higher concentrations of Cu, As, Cd, Pb and Zn (Fig. 3) in fascines. Soil properties were very similar to those found in the tailing before log piles construction (Navarro-Cano et al., 2018). There were no significant differences for soil properties (TOC, N, P, K, As, Cd, Cu, Pb and Zn, pH and EC) between fascines and gaps (Fig. S6).

Table 1
Effects of distance to the closest pine, to the adjacent forest, and the number of pine cones within the coarse woody debris on the abundance of *Pinus halepensis* seedlings·m^{-2} beneath the fascines. The three variables were jointly used as predictors of seedling emergence. Significant *p*-values ($p \leq 0.05$) are shown in bold.

Predictor	Estimate	SE	*t*	*p*
Distance to closest pine	0.057	0.068	0.844	0.4066
Distance to adjacent forest	−0.035	0.016	−2.197	**0.0371**
Number of cones	0.009	0.004	2.758	**0.0105**

3.4. Fascines increased the diversity of sowed communities

Seedling emergence of sowed species was significantly different in fascine and gaps (analysis of deviance for the GLM, *deviance* = 33.6, *residual df* = 292, $p < 0.01$), with a higher emergence in fascines. There was a significant effect of the species (*deviance* = 3671, *residual df* = 286, $p < 0.001$) and the interaction microsite × species (*deviance* = 91.1, *residual df* = 280, $p < 0.01$) on seedling emergence. Overall, the model explained 75% of the variance. Only *A. halimus*, *S. oppositifolia* and *R. lycioides* showed significant or marginally significant higher emergence in fascines than gaps (Fig. 4).

Within the first year after sowing, plant communities at the seedling stage were richer as well as functionally more diverse underneath the fascines than those in gaps (Fig. 5). Plant richness and functional diversity also increased by 25% under fascines.

4. Discussion

Within the framework of a pilot restoration project of dry mining areas, we show for the first time that arranged log piles promote plant colonization processes by alleviating the abiotic stress similarly to the effect of nurse plants.

4.1. Fascines ameliorated microclimatic conditions

Natural canopies of nurse structures exert wide microenvironmental benefits that facilitate the establishment of less stress-tolerant species. The nurse's shade is able to soften photoinhibition and plant desiccation, which are amongst the main deleterious effects for plants in drylands (Callaway, 2007). Our previous results in dry mining areas indicated that the main abiotic filter for plant establishment is climatic (high temperature and radiation; low soil gravimetric humidity) rather than edaphic (high metal concentration and salinity) (Navarro-Cano et al., 2019b). Here, we showed that pine log piles fascines significantly reduce radiation and air temperature on the soil surface through shading, without the belowground competitive effects on the water that living plant nurses exert. In addition, fascines increased air humidity, which might lower soil evaporation and plant evapotranspiration. Our results also showed that the South sides of the fascines are more exposed to radiation than North sides, with effects on seedling recruitment. Even though seasonal soil moisture was not monitored, the log piles likely enhance rainfall infiltration and elevate soil moisture during the summer as shown by Tongway and Ludwig (1996). The extent to which light and temperature can decrease underneath nurse plants is associated with species-specific morphological traits that determine the canopy structure. Moreover, natural canopies are usually heterogeneous, and shape a spatial mosaic of microenvironmental conditions beneath each nurse that can improve the establishment of different understory species (Moro et al., 1997). Microenvironmental conditions on the soil surface also shift with time, improving throughout the ontogenetic development of the nurse plant species, and allowing the establishment of progressively less stress-tolerant beneficiaries (Navarro-Cano et al., 2015). After the plant establishment stage, the belowground microenvironmental conditions around the rhizosphere might positively influence the soil microbial activity. Our log piles were also largely heterogeneous in space since they were built with natural branches. However, we expect no significant shifts in their microenvironmental properties in the short-to mid-term (roughly the first decade) due to their coarse woody structure, with a dominant proportion of lignin, that is very recalcitrant

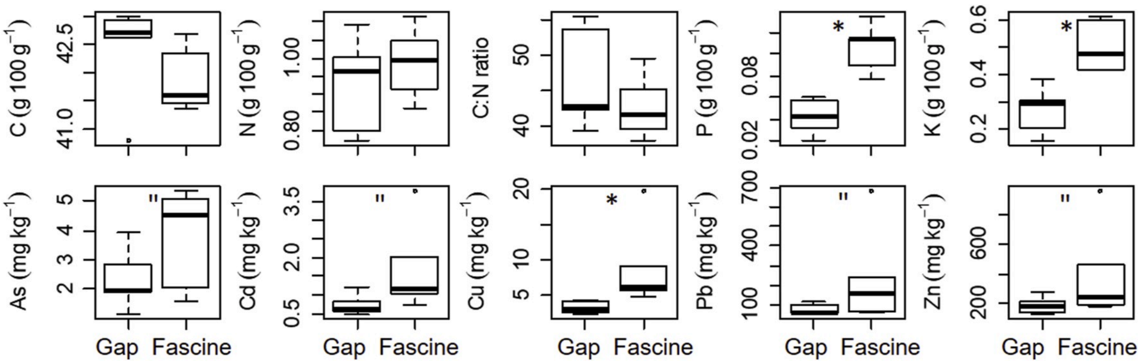

Fig. 3. Nutrient and metal concentration in the aboveground tissues of *P. halepensis* seedlings in fascines and adjacent gaps. Values were analysed within each box plot by paired *t*-test, except for Pb concentration, which is compared by the non-parametric Wilcoxon's test; significant tests are indicated by " $p < 0.1$, *$p \leq 0.05$.

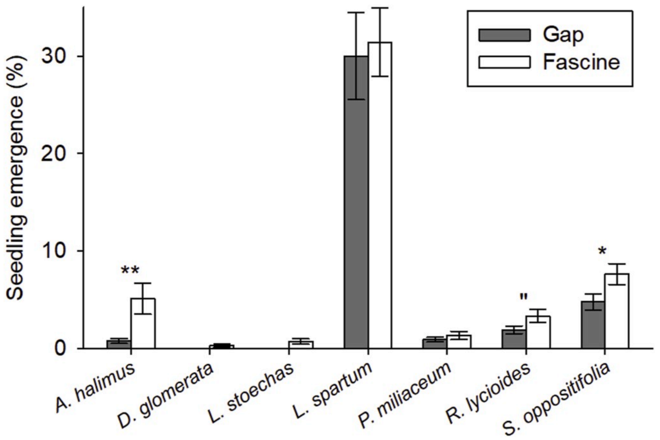

Fig. 4. Seedling emergence of sowed species in fascines and gaps within the mine tailing. The results of individual generalised linear models to explain the effect of the microsite on the seedling emergence for each species are shown. " $p < 0.1$, *$p \leq 0.05$, **$p < 0.01$.

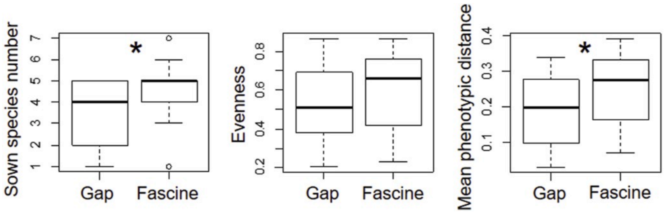

Fig. 5. Effects of the microsite fascine *vs* gap on plant richness, evenness and mean phenotypic distance of the seedling communities established within the first year after sowing of mixed seed sets. Sowed species were *Atriplex halimus*, *Dactylis glomerata*, *Lavandula stoechas*, *Lygeum spartum*, *Piptatherum miliaceum*, *Rhamnus lyciodes* and *Salsola oppositifolia*. The significant results of individual GLMs are shown; *$p \leq 0.05$.

under low precipitation conditions (Mackensen et al., 2003).

4.2. Fascines facilitated natural plant establishment

It has been traditionally assumed that under extremely stressful conditions, ecological facilitation between plants is overwhelmed by competition (Brooker et al., 2008). However, we have previously demonstrated that facilitation is a fundamental process for plant community assembly in severely infertile, saline and metal-polluted mining structures (Navarro-Cano et al., 2018). At least 25 out of 74 abandoned tailings in the study area show facilitation-driven spontaneous succession led by pines, shrubs and perennial grasses (Navarro-Cano, JA, unpublished data). This natural colonization is, however, slow (Parraga-Aguado et al., 2013) and the average plant cover in the tailings is lower than 20% after ca. 40 years since abandonment (Navarro-Cano et al., 2018). Our fascine-based restoration method could be potentially applied to phytostabilize all of these tailings or any other where the local context (topographical barriers, barren landscape) hampers natural seed arrival, thus hindering passive restoration (Prach and Pyšek, 2001). Nevertheless, if the raw wood used to make fascines does not carry seeds, a seed supply needs to be used instead. Only those tailings with very severe abiotic filters, such as extremely acidic pH, very high salinity and metal concentrations would discourage the construction of log piles in favour of more aggressive eco-technologies such as soil sealing or extensive soil amendment (Tordoff et al., 2000; Zornoza et al., 2012; Gómez-Ros et al., 2013).

Seminal studies that used cut natural canopies and evaluated plant recruitment beneath them, primarily aimed at estimating their role in recreating productive patches (Ludwig and Tongway, 1996) and examined the net outcome of competitive and facilitative mechanisms of plant community assembly (Callaway, 2007). Subsequent studies used this idea with a restoration purpose, and either employed logs or cut branches to protect natural or planted saplings (Gómez-Aparicio et al., 2005; Padilla and Pugnaire, 2009; Tongway and Ludwig, 2011) or to increase pine recruitment and survival in burned ecosystems (Castro et al., 2011). Kimiti et al. (2017) combined different natural and artificial erosion barriers covered with cut branches to achieve low-cost grass restoration in African rangelands. Recently, Castillo-Escrivà et al. (2019) have also tested the use of piled branches as perches for frugivorous birds that disperse fleshy-fruited shrubs in steppe areas. Here, we move a step forward and demonstrate that manipulating cut branches has a positive effect on natural seedling establishment of the whole plant community. Despite our pine log piles mainly promoted pine recruitment, we found twelve other species that performed better beneath them compared to surrounding areas.

4.3. Fascines increased the diversity of sowed communities

Through a seed sowing experiment with a known set of mixed seeds, which allowed us to control for seed availability, we further showed that fascines expand the regeneration niche of beneficiary species as natural nurses do (Bruno et al., 2003). In particular, more seedlings and species were recruited beneath the fascines than in adjacent areas, resulting in increased levels of taxonomic and functional plant diversity at the establishment stage. This result is coherent with the relaxation of a severe abiotic filter (high temperature and radiation) in the log piles, whereby a wider range of species with more stringent regeneration niches are able to enter the community (Webb et al., 2002). As we measured not only establishment traits but also adult traits related to phytostabilization potential and erosion resistance, the fact that emerged communities in fascines were more functionally diverse could favour functional complementarity in mature stages, as facilitation-driven patches also do (Navarro-Cano et al., 2019a). Castro et al. (2011) have speculated that the absence of a real nurse plant might also avoid significant adjustments in the subsequent adult community structure due to nurse-facilitated competitive exclusion. The use of log piles to restore barren ecosystems allows enhancing water infiltration and nutrient retention (Tongway and Ludwig, 2011), besides optimizing water use efficiency through the softening of competition for soil water. In addition, these objects can create safe sites for plant regeneration through sheltering wild or sowed plants against herbivores (Ludwig and Tongway, 1996; Kimiti et al., 2017; Martelletti et al., 2018). Nevertheless, sowing application may need to consider that establishment of small-seed species can be ineffective if they are sown deeply. This could be the reason for the low seedling emergence of *Dactylis glomerata*, the smallest species we sowed.

Beyond serving as nursing objects, log piles carried an aerial seed bank (pine cones) that acted as an effective seed source to accelerate the colonization of the mine tailing. As far as we are aware, this is the first time that this potential use of cut pine branches is reported in restoration. We observed that the higher the number of pine cones per fascine, the more the pine seedlings that emerged.

4.4. *Fascines improved the nutritional status of pine seedlings*

Seedlings in both microsites had P and K contents that were 20–50% below the normal values for plants (Azcon-Bieto and Talón, 2000), as has been generally reported for mining areas (Conesa and Schulin, 2010; Parraga-Aguado et al., 2014; Parra et al., 2017). Moreover, the stoichiometric imbalance reflected by the very high N:P ratios in gaps compared to fascines are indicators of a severe P deficiency, according to Koerselman and Meuleman (1996). Salazar-Tortosa et al. (2018) have recently demonstrated that the pine leaf N:P ratio is inversely correlated with stomatal conductance and transpiration. Thus, a lower water availability in gaps than in fascines might induce nutrient deficit and a diminished plant performance. Phosphorous deficiency might affect ATP and ADP synthesis, with important consequences for photosynthesis, respiration and general metabolism. Likewise, K deficits can disrupt osmoregulation and increase the vulnerability to pathogens (Azcon-Bieto and Talón, 2000). Thus, it is relevant that the pine seedlings beneath the fascine canopy had P and K concentrations in their aboveground tissues that were significantly higher than those out of the fascines. Plant nutrient concentrations in the fascines are within the ranges found by Díaz and Roldán (2000) and Valdecantos et al. (2006) for *P. halepensis* seedlings under similar semiarid conditions, whereas seedlings in the gaps were nutritionally depleted. Kemp and Moody (1984) concluded that P and K are higher in drought-stressed conifers, whereas Turtola et al. (2003) did not find significant differences in seedling nutrient concentrations across a gradient of water stress.

Our results add further complexity to the relationship between plant nutrients and stress conditions. We speculate that the higher water infiltration and reduced water stress due to lower radiation and temperature boosted plant macronutrients in fascines, but also triggered metal and metalloid uptake. Indeed, Pb concentrations in seedlings from both microsites were an order of magnitude above the normal levels (Kabata-Pendias, 2001). Similarly, As, Cd and Zn concentrations in fascines' seedlings were 2–3 times above normal levels, whereas those in gaps were just slightly higher (Kabata-Pendias, 2001). Abnormally high metal concentrations in plants can induce growth inhibition. Moreover, metals such as Cd are known to interfere both with nutrients and with other metals (e.g. Zn and Cu), ultimately altering plant metabolism (Zhang et al., 2002). Obviously, increased metal concentrations in plants imply a higher risk of transference to other trophic levels (Ali et al., 2013). Nevertheless, it should be considered that patterns found for seedlings might change in the adult stage, as both below- and aboveground parts of these plants grow out of the fascine. Although most of the naturally-colonizing species, including *Pinus halepensis*, expose some metal tolerance (Conesa and Schulin, 2010; Parraga-Aguado et al., 2013; Navarro-Cano et al., 2018) and are able to accumulate moderate to high metal concentrations (Table S2), a long-term monitoring program would be important to assess the risk of metal translocation in the food web. The long-term influence of the fascines on the soil properties might be monitored in order to detect fertility improvements derived from the slow organic matter decomposition of pine wastes and the likely enrichment from litter and root exudates provided by the colonizing plants. Bioavailable metal fractions would be also measured for a better monitoring of changes in the potential soil toxicity (Parraga-Aguado et al., 2014; Alan and Kara, 2019).

5. Conclusions

We constructed log piles on an abandoned mine tailing based on natural wastes from local forestry operations, thus avoiding transportation costs.

We show that logged wood can be arranged to create microsites that alleviate abiotic stressors, thus promoting plant establishment, functional diversity and a more balanced nutritional status of plants.

Turning log piles from silvicultural or agricultural management into a resource not only for erosion control but also for plant nucleation can help to restore disturbed drylands worldwide.

Global warming is currently rising massive mortalities in tree afforestations due to more and more recurrent droughts (Allen et al., 2010; de la Serrana et al., 2015). This dead wood may be reutilized for in situ construction of canopies as here stated.

Devising strategies that, as ours, recover functional diversity is the basis to restore ecosystem functions and foster ecosystem resilience in the face of large-scale anthropogenic disturbances (Montoya et al., 2012).

Author contribution

J.A.N.-C. designed and conducted the research. J.A.N.-C., B.O. and M.G. collected data. J.A.N.-C. wrote a first manuscript and all authors contributed to the final version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2020.111015.

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