



Facilitation by *Baccharis sarothroides* (desert broom) during revegetation of a hard rock mine in Southern Arizona, USA

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Abstract Post mining revegetation efforts are often faced with challenges associated with poor soil conditions and sparse vegetation. Revegetation in arid regions faces further challenges due to scant and infrequent rainfall during the initial phases of plant establishment. Early successional plants may provide utility for targeted management to enhance remediation outcomes as these species have high dispersal capabilities and rapid growth rates, enabling them to successfully dominate landscapes very quickly after degradation. This research aims to test whether the native *Baccharis sarothroides* Gray (desert broom), a common early successional species, facilitates the growth of native plant communities on a copper mine in Southern Arizona. Fifty *B. sarothroides* individuals of varying sizes were randomly selected on a mine tailings waste pile and the plant communities growing

both under their canopies as well as in exposed areas were characterized. Soil chemical composition and abiotic conditions were also assessed. We found higher plant density, cover, diversity, and species richness under *B. sarothroides* canopies in comparison to the exposed areas, however, the height of the individual had no effect. *Baccharis sarothroides* provides some alleviation from abiotic stresses by creating a cooler understory with higher soil moisture levels and lower soil temperature. *Baccharis sarothroides* demonstrates value for increasing revegetation success on copper mine tailings storage facilities.

Keywords *Baccharis sarothroides* · Reclamation · Restoration · Revegetation · Facilitation · Arid lands

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Introduction

Climate change, rapid population growth and unsustainable land use have all contributed to a critical need to restore degraded lands globally. In arid systems, land degradation is particularly challenging due to the rate and extent to which healthy landscapes are lost (Dregne, 1994). Although a range of restoration techniques are available to combat degradation in arid lands, the use of revegetation is often thought of as the most successful inexpensive, long-term solution to stabilize soils (Buta et al., 2019; Tordoff et al., 2000). Revegetation is not always effective, however. Revegetation in arid lands faces difficulties due to

infrequent precipitation events and extreme temperatures (Zhang et al., 2021). Arid mining sites provide ideal areas to study the challenges of revegetation as a restoration strategy because deteriorating soil microbial communities, biotoxicity, and diminished plant diversity are common characteristics of degradation (Mendez & Maier, 2008; Sheoran et al., 2010). Several approaches can mitigate these challenges to enhance revegetation outcomes. First, consideration of belowground fertility with plant establishment can significantly enhance ecosystem regeneration on degraded sites. Second, using seed mixes that include pioneer species, which serve as nurse plants, may provide a management strategy that bolsters the success of restoration in arid systems. This occurs because nurse plants build soil fertility and shelter from abiotic stress, thus facilitating growth of other native species (Hulvey et al. 2017).

Facilitation has been extensively studied in semi-arid (Gómez-Aparicio et al., 2004; Pugnaire et al., 1996; Quon et al., 2019) and arid ecosystems (Fowler, 1986; Kéfi et al., 2007), where infrequent rainfall and extreme temperatures are major hindrances to plant survival and growth. Established trees and shrubs, often called nurse plants, ameliorate stressful environmental conditions through interactions including providing or sharing resources with neighboring plants, reducing soil temperatures, increasing soil moisture (Cross et al., 2021; Martyn et al., 2022). The way in which facilitation occurs in arid systems is not consistent across sites and species because it is trait-dependent. For example, plant size can modify the magnitude of facultative effects on the nurse plant (Peláez et al., 2019; Pugnaire et al., 1996). Larger plants are able to ameliorate abiotic conditions better than small plants due to an increase in nurse plant biomass (Callaway & Walker, 1997; Peláez et al., 2019; Tewksbury & Lloyd, 2001). Increased nurse plant size may also offer protection from biotic stress such as herbivory as larger nurse plants create physical barriers against browsing (Perea & Gil, 2014). However, in mine habitats, plants often do not demonstrate robust growth due to soil nutrient limitations and heavy metals (Anawar et al., 2013), and thus how size affects facilitation in these systems is unknown.

Apart from direct facilitative effects, dominant shrubs can increase the density and diversity of understory plants through indirect means. Shrubs greatly influence the movement of wind and water

around their canopy, which can directly trap seeds in suitable microclimates for germination and growth (Facelli & Temby, 2002; Giladi et al., 2013). While this increase in seed and seedling density may lead to negative density-dependence (Aicher et al., 2011; Barney et al., 2016), the net benefit of shrubs in this regard is positive as they support the development of desert seedbanks and seedling recruitment (Price & Reichman, 1987). Additionally, shrubs provide habitat for wildlife, which may also indirectly facilitate the arrival of seeds via seed-carrying birds, or granivorous mammals (Beck & Vander Wall, 2010; Carlo et al., 2013; Price & Reichman, 1987).

In addition to supporting aboveground processes, shrubs greatly impact belowground rehabilitation in degraded environments. Pioneer plant species improve belowground development by increasing soil fertility (Ossanna et al., 2023). Soil organic carbon, for example, can be significantly enhanced by nurse shrubs through root growth, water capture, and development of soil microbial communities (e.g., Hortal et al., 2013; Rodríguez-Echeverría et al., 2015). Nitrogen is also largely enhanced by the presence of nurse shrubs as a result of litterfall from roots and above ground material, which leads to mycorrhizal proliferation (Varela et al., 2017). Although variability in changes to soil nutrients under plants can be high (Mihoč et al., 2016), often depending on environmental effects (Celaya-Michel & Castellanos-Villegas, 2011; Svriz et al., 2013), nurse effects can occur rapidly and maintain within the system for long periods of time (Navarro-Cano et al., 2015).

Because facilitation can be used to enhance seedling survival, growth, and ultimately influence community development in degraded systems (Gómez-Aparicio et al., 2004; McIntire & Fajardo, 2014; Padilla & Pugnaire, 2006; Siles et al., 2008), it is often leveraged in typical arid-land restoration projects (e.g., Stapleton et al., 2023). Curiously, however, facilitation is almost never considered for mine reclamation activities (Sheoran et al., 2010).

Baccharis sarothroides, an early successional shrub native to Arizona, has a history of utility in mine revegetation due to its rapid growth, high dispersal via wind, and the ability to hyperaccumulate numerous species of metals in its shoots (Day & Ludeke, 1980; Haque et al., 2007). *Baccharis sarothroides* is known to attract pollinators who contribute greatly to ecosystem function and development (Meyer et al., 1979;

Naganuma & Hespenheide, 1988). In general, the use of species reliant on wind dispersal has demonstrated success in copper mine revegetation; however, *B. sarothroides* is a common volunteer species, and not often included in seed mixes due to its widespread and vigorous growth (Lázaro-Lobo et al., 2021). *Baccharis sarothroides* shows promise as a species beneficial for phytoremediation of post-mining sites and for facilitating the growth of other native species (Haque et al., 2008).

The specific aim of this research was to (1) test whether *B. sarothroides* facilitates the growth of native plant species and (2) determine whether the size of the *B. sarothroides* individual impacts its facilitative effects. We hypothesize that *B. sarothroides* functions as a nurse plant in disturbed lands, supporting the growth of plants beneath its canopy via amelioration of abiotic conditions and increases in soil fertility, and that larger individuals will host a greater abundance and diversity of species. In this study, we compare plant communities growing beneath *B. sarothroides* canopies of varying sizes to those growing in exposed areas. Microsite conditions including solar radiation, soil moisture, and soil temperature were monitored using environmental sensors and abiotic substrate properties were quantified through soil chemistry analysis.

Methods

Site description

The study site was a closed tailings storage facility located in an inactive section of a copper mine near Sahuarita, AZ, USA. Mine tailings from hardrock mining are the finely ground material remaining after

mineral extraction from rock ores, materials that are nutrient poor with low water-holding capacity. Mine tailings were selected for this study because copper mines often generate thousands of acres of tailings waste; a material that must be reclaimed because the tailings are a dust hazard and can remain unvegetated for decades. This tailings storage facility was bound by native desert on the west and south sides, another closed tailings storage facility on the north, and an interstate highway on the east. The facility was capped in 2009 with 15 cm of native soil excavated from a desert area located adjacent to the facility, and seeded in the summer of 2014. The cover soil varied in texture classification from a loamy sand to sandy loam. Clay content ranged from 3.2 to 13.9%. Soils sampled across the tailings pile contained greater than 50% fines. Fines are the soil fraction defined as < 2 mm. It is assumed, based on records and conversation with members of the environmental team, that the capping and seeding material were the same for the entire facility. Nine native plant species (Table 1) were drill seeded over the 400-acre area. *Baccharis sarothroides* was not included in the seed mix; however, it colonized the site likely via wind dispersal.

Average daily temperatures in Sahuarita, AZ, range from 34 °C during the summer and 22 °C in the winter. Sahuarita, AZ, experiences bimodal precipitation events where the majority of the year's rain arrives between December and February and from July to August. Average annual precipitation is 26.9 cm, but this average is highly variable with ranges in the Sonoran Desert of 7.6–40 cm (Weiss & Overpeck, 2005). A recent five-decade climate study suggests that timing and duration of dry intervals may be a more significant metric impacting successful

Table 1 Native seed mix used on site. The seed mix was applied using a drill

Scientific name	Common name	lbs/acre	Functional type
<i>Bouteloua barbata</i> var. <i>rothrockii</i>	Rothrock grama	0.5	Annual grass
<i>Bouteloua curtipendula</i>	Side oats grama	1.0	Perennial grass
<i>Sporobolus cryptandrus</i>	Sand dropseed	0.5	Perennial grass
<i>Plantago patagonica</i>	Indian wheat	5.0	Annual forb
<i>Setaria vulpita</i>	Plains bristlegrass	1.0	Perennial grass
<i>Atriplex canescens</i>	Four wing salt bush	1.0	Shrub
<i>Larrea tridentata</i>	Creosote	1.0	Shrub
<i>Prosopis velutina</i>	Velvet mesquite	0.5	Tree
<i>Parkinsonia floridum</i>	Blue palo verde	1.0	Tree

plant establishment than total annual precipitation (Zhang et al., 2021). Further, the analysis of precipitation patterns (1976–2019) revealed that the Desert southwestern USA shows critical trends in reduced precipitation totals, increasing interannual variability, and longer-duration dry intervals between precipitation events. The observed increases in mean dry interval length and maximum dry interval duration were substantial suggesting that the abiotic stress imposed by variability in precipitation is complex.

Measurements

Five 40-m permanent transects were installed on the site, and each transect was located 20 m from each other. Ten *B. sarothroides* plants were randomly selected along each transect, marked, and sampled in 2023, for a total of 50 individuals. Height was measured for each individual. As *B. sarothroides* is classified as an erect shrub, we used height as a metric for size (Jepson Flora Project, 2024). A 0.5 m × 0.5 m quadrat was placed at the base of each *B. sarothroides* in each of the four cardinal directions, producing four sample locations under the canopy of each individual. Within each quadrat, percent cover of litter was visually estimated, and the percent cover and density of every species was also measured. Additionally, for each *B. sarothroides* individual, four more quadrats were sampled outside of the canopy in open areas that were a minimum of 1 m away from any *B. sarothroides* in all four cardinal directions.

To assess how *B. sarothroides* influences the local abiotic conditions, environmental sensors including the TEROS 11 and pyranometers (METER Group, Inc, USA) were installed near the base of two *B. sarothroides* individuals, as well as in two nearby open areas. TEROS 11 sensors measure soil moisture and temperature and the pyranometers assessed solar irradiance. The recording interval was set for every 30 min. The *B. sarothroides* individuals chosen were not ones included in the transects but were near the average height (cm³) of the transect individuals and within the bounds of both the upper and lower 95% CI.

Soil samples for chemical analyses were collected 0.25 m from the stem of each *B. sarothroides* on the transects and two randomly selected open areas along each of the five transects totaling 60 soil samples. Samples were collected in 2023. Soil was collected from 10 cm deep pits dug in four cardinal directions

around each *B. sarothroides*. Soils were homogenized and sieved (2 mm pore size), then sent to Brookside Laboratories (New Bremen, OH) and analyzed for pH, organic matter, estimated nitrogen release, Olsen phosphorus, exchange capacity, percent base saturation of cation, ammonium acetate Ca, Mg, K, Na, S, DTPA (diethylenetriaminepentaacetic acid) extractable Fe, Mn, Cu, Zn and available nitrogen (NO₃-N + NH₄-N; S015N soil analysis package) and water extractable organic nitrogen (S114 soil analysis package).

Statistical analyses

All analyses were performed using R version 4.2.3 (R Core Team 2023). A mean diversity and cover value was calculated for each *B. sarothroides* individual by averaging the values across the four sampling locations set in each of the cardinal directions (Fig. S1). Linear effects models with location (canopy or open) and height of the *B. sarothroides* individual as fixed factors was used to analyze plant cover, density, diversity, richness, and soil chemical characteristics. Soil characteristics were analyzed using Type III SS to account for the unbalanced design. A correlation was run to test the relationship between *B. sarothroides* height and little cover. The multcomp package (Hothorn et al., 2008) was used to generate pairwise comparisons.

Results

In total, 27 plant species were found on site (Table S1). Of the nine species included in the seed mix (Table 1), six were found in our plots: *Bouteloua barbata* var. *rothrockii*, *Bouteloua curtipendula*, *Atriplex canescens*, *Larrea tridentata*, *Prosopis velutina*, and *Parinsonia floridum*. Seeded species accounted for 20.4% of the total vegetative cover and 18.3% of the measured density. Three non-native (invasive) species were found on site at the start of the experiment in 2021 (Table S1), *Eragrostis lehmanniana* (lehmann lovegrass), *Pennisetum ciliaris* (buffel grass), and *Pennisetum setaceum* (fountain grass). When the plots were surveyed in 2023, *E. lehmanniana* was associated with 76% and 32% of *B. sarothroides* plants for canopy and open area plots, respectively. In contrast, *P. ciliaris* was associated with just 8% and 2% of plant

individuals for canopy and open, respectively. The cover of *E. lehmannian* was significantly higher under the *B. sarothroides* canopy than in the associated open areas ($p=0.006$); however, the cover was highly variable. Average cover was $2.03 \pm 4.25\%$ under canopies and $0.28 \pm 0.82\%$ in the open areas. No significant difference was observed between *P. ciliaris* cover in canopy and open plots. *P. setaceum* was not detected in the sample plots in 2023.

The height distribution of *B. sarothroides* individuals ranged from 50 to 228 cm with a mean height of 130.5 cm with 54% of individuals falling in the range of 100 to 150 cm (Fig. 1). Both vegetation density and cover were higher in canopy locations in comparison to open areas (Table 2, Fig. 2). The size, measured by height, of the *B. sarothroides* individual did not significantly affect either the understory vegetation cover nor density (Table 2). Litter cover was positively correlated with *B. sarothroides* height ($R^2=0.29$; Fig. 3). Mean litter cover was significantly higher in canopy locations and under larger *B. sarothroides* individuals (Table 2, Figs. 3 and 4). Species diversity and richness were significantly higher under *B. sarothroides* canopies, and neither were influenced by the size of the individual (Table 3).

Of the soil chemical properties measured, organic matter (OM) and estimated nitrogen release (ENR;

Table 2 ANOVA table from linear effects model testing for effects of location and individual height on plant cover, density, and litter cover. Significant values are bolded ($p < 0.05$)

Response variable	Effect	<i>F</i>	<i>p</i>
Cover	Location	54.20	<0.001
	Height	0.02	0.90
Density	Location	21.70	<0.001
	Height	1.61	0.21
Litter	Location	145.10	<0.001
	Height	12.60	<0.001

Table 4) were significantly higher in canopy soils. The mean ENR for the canopy locations was 27.4 lbs/acre while the mean for open locations was 19.5 lbs/acre. Mean OM in canopy areas was 0.69% while OM in open areas was 0.49%. No soil characteristic was significantly higher in open locations (Table 4; Table S2). The pH of the canopy and open locations was similar, with canopy locations having a soil pH of 8.7 (σ^2 0.011) and open soils a pH of 8.6 (σ^2 0.046). Bioavailable phosphorous (BAP) was the only soil characteristic measured that was significantly affected by the size of the *B. sarothroides* individual but not

Fig. 1 Histogram of the height distribution of measured *B. sarothroides* individuals. The mean height was 130.5 cm, represented by a dashed red line

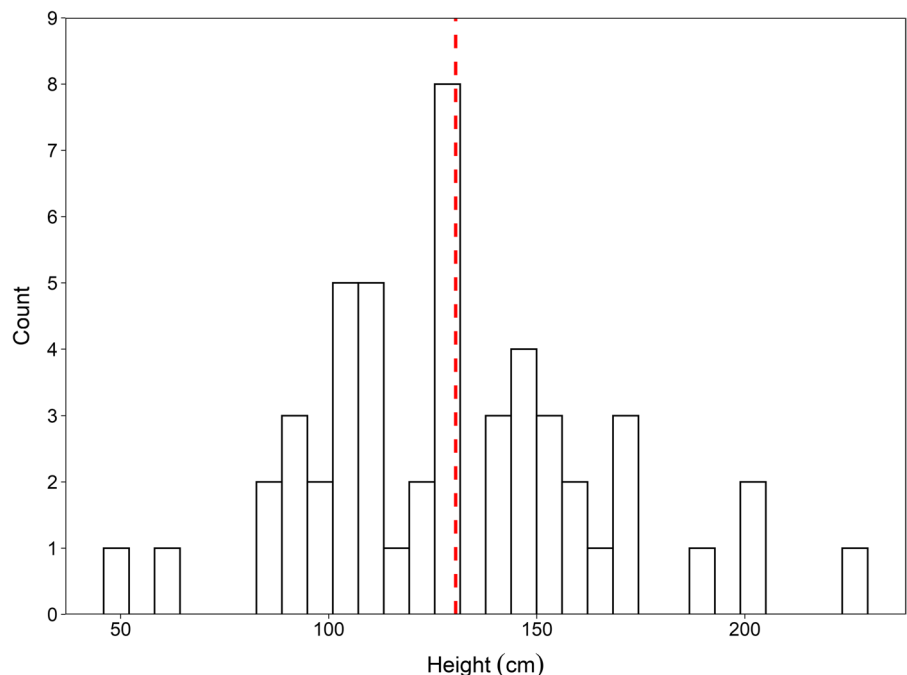
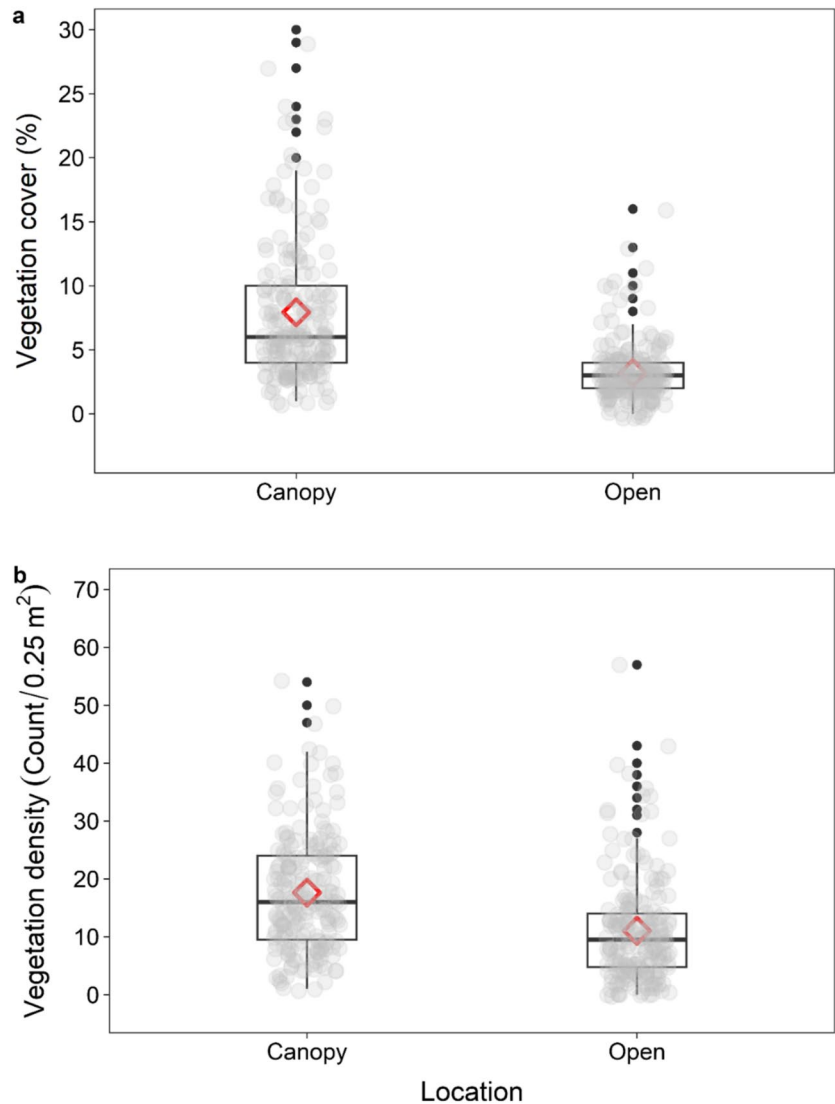


Fig. 2 Mean vegetation cover (a) and density (b) measured in both canopy and open areas. Boxplots represent the lower and upper quartiles and median; the red diamond represents the mean. Raw data is represented by grey circles



by location (Table 4). BAP values ranged from 1 to 12 mg/kg.

The differences seen in maximum solar radiation, soil moisture, and soil temperature between canopy and open locations varied seasonally (Fig. 5). During precipitation events, soil moisture in canopy locations increased more than in open locations except for the precipitation event in January 2022. Soil moisture was consistently higher in canopy locations from April 2022 through summer 2022 (Fig. 5). Maximum daily solar radiation was consistently higher in exposed areas compared to under the canopy of *B. sarothroides*, and there was a larger seasonal difference in maximum solar radiation in

canopy locations. Mean soil temperature was consistently lower in the canopy locations (Fig. 5).

Discussion

Facilitation plays an important role in structuring plant communities in arid lands and the utility of this interaction in revegetation efforts may yield greater success. As such, it is important to evaluate the potential for species growing on-site to function as nurse plants for both current and future revegetation efforts. In this study, *B. sarothroides* was associated with increased plant density and cover compared to

Fig. 3 Correlation of litter cover (%) across *B. sarothroides* heights. Measurements taken in open locations were not included

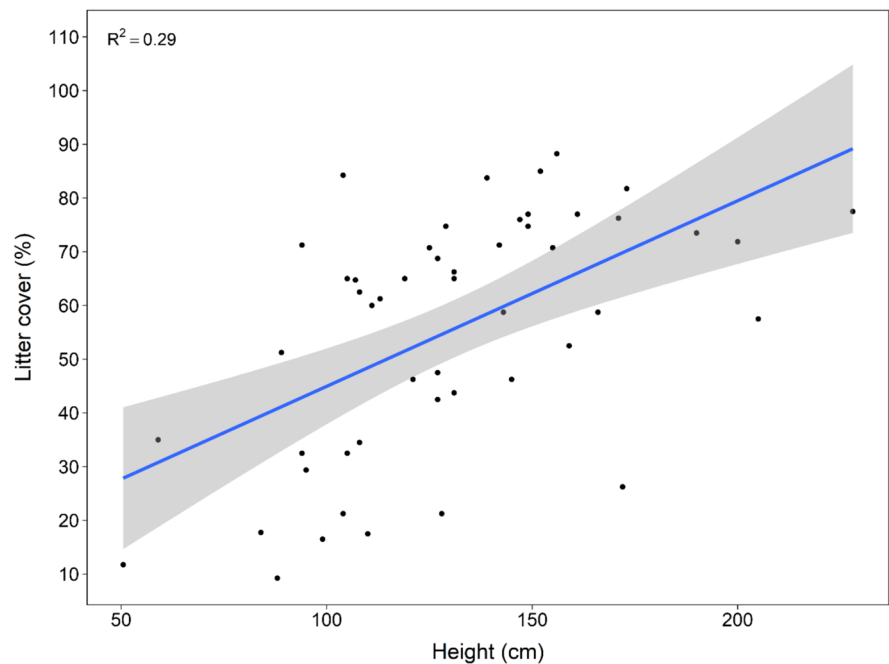
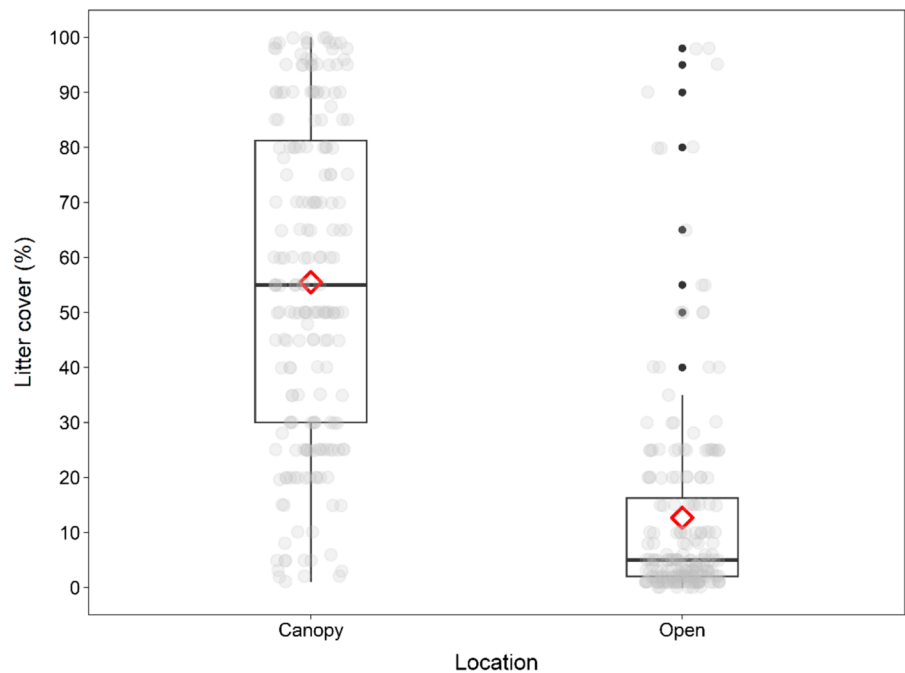


Fig. 4 Mean litter cover (%) measured in both canopy and open areas. Boxplots represent the lower and upper quartiles and median; the red diamond represents the mean. Raw data is represented by gray circles



open areas. Abiotic conditions under *B. sarothroides* canopies hosted higher soil moisture levels and lower soil temperature and solar radiation levels, creating a suitable microclimate for understory vegetation growth. Furthermore, precipitation events yielded

higher levels of soil moisture under *B. sarothroides* canopies when compared to open locations. This benefit becomes progressively more important for reclamation efforts in the desert southwestern USA as multi-decadal trends show a critical combination

Table 3 ANOVA table from linear effects model testing for effects of location and individual height on diversity and richness of plant communities between locations. Significant values are bolded ($p < 0.05$)

Response variable	Effect	<i>F</i>	<i>p</i>
Diversity	Location	3.85	0.05
	Height	0.83	0.36
Richness	Location	11.68	< 0.001
	Height	0.04	0.84

Table 4 ANOVA results testing the effects of plant height and location (canopy or open) on soil chemical characteristics. OM, organic matter; TC, total carbon; EC, electrical conductivity; BAP, bioavailable phosphorous; ENR, estimated nitrogen release; WEN, water extractable nitrogen. Significant values are bolded ($p < 0.05$)

Characteristic	Effect	
	Height (<i>p</i>)	Location (<i>p</i>)
pH	0.69	0.47
Nitrate (ppm)	0.61	0.85
Ammonium (ppm)	0.56	0.08
OM (%)	0.02	0.01
BAP (mg/kg)	0.01	0.95
TEC (meq/100 g)	0.80	0.79
ENR (lbs/acre)	0.01	0.01
WEN (ppm)	0.10	0.14

of decreasing annual precipitation, increasing inter-annual precipitation variability, and longer-duration dry intervals between precipitation events (Zhang et al., 2021). The benefits offered by shrubs have been long recorded in the Sonoran Desert. Butterfield et al. (2010) analyzed 65 years of data and found strong positive effects on plant recruitment by canopies when compared to open sites. Additionally, the presence of shrubs amplified the positive effects of precipitation on recruitment beneath canopies than in open areas due to reduced evaporation rates (Butterfield et al., 2010; Navarro-Cano et al., 2015).

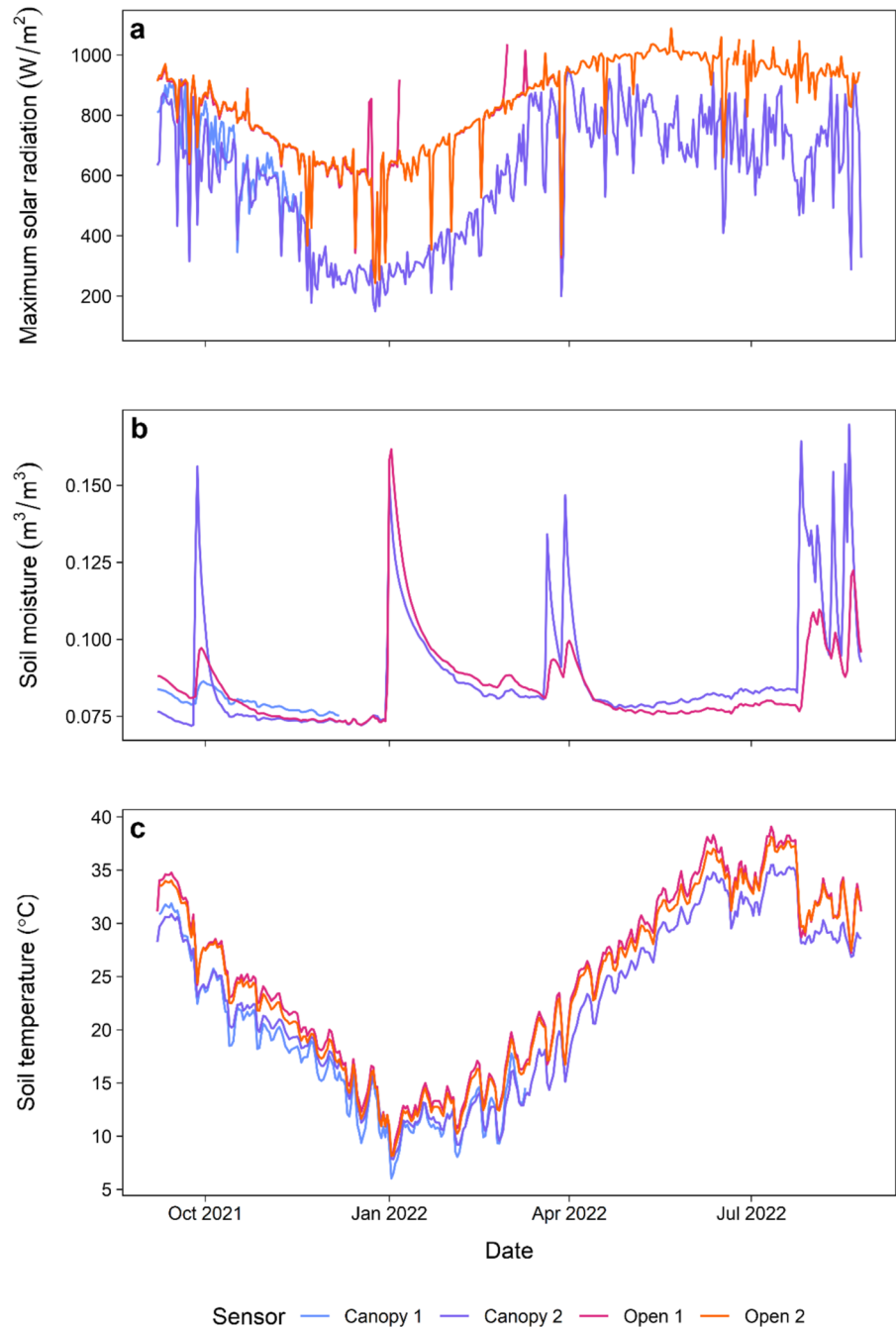
Our findings support that simply the presence of *B. sarothroides*, and not its size, has a significant direct impact on plant community diversity and development. Contrarily, studies have found that shrub size influences annual plant composition (Facelli & Temby, 2002; Maestre & Cortina, 2005) and enhances facilitative effects (Callaway & Walker, 1997; Peláez et al., 2019; Pugnaire et al., 1996; Vetaas, 1992). In

this study, benefits that were expected with larger nurse plants might have been offset by potential negative interactions. Several growth inhibiting allelopathic compounds have been identified in *B. sarothroides* (Self, 1988). The relationship between plant size, or age, and its allelopathic potential is species specific, as some species release more allelochemicals as seedlings (Zhang et al., 2010), while others exude more with age (Wardle et al., 1993; Chen and Wang, 2013). It is not known whether larger individuals of *B. sarothroides* have greater allelopathic potential; however, they did not have a significant negative impact on understory vegetation, further supporting its role as an effective nurse plant.

The favorable conditions created under the canopy of nurse shrubs promote denser and more diverse understory assemblages (Facelli & Temby, 2002). While these effects are generally expected to increase with nurse plant size, increased plant densities may, in turn, result in negative density dependence (Goldberg et al., 2001; Shilo-Volin et al., 2005), and therefore an overall reduction in understory plant cover. Competition with invasive species growing underneath nurse shrub canopies may also have resulted in unchanged overall plant density and cover underneath larger *B. sarothroides* individuals. *E. lehmanniana* was found growing underneath 76% of the *B. sarothroides* individuals and at a higher cover than in the open areas. Invasive grasses in the southwest are known to outcompete native annuals and juvenile perennials (Lyons et al., 2013; Olsson et al., 2012), and the growth of these species may also be facilitated by the presence of *B. sarothroides*, to the detriment of native species (Rodríguez-Buriticá & Miriti, 2009). Despite the presence of invasive grasses under the *B. sarothroides* canopy, diversity and richness were significantly higher under canopy than in the open. A longer term study is needed to determine whether the native species can co-exist and eventually out-compete *E. lehmanniana* over time. The study revealed that facilitation did not enhance establishment of *P. ciliaris* or *P. setaceum*.

In our study, some measures of soil fertility, unlike plant cover and density, were impacted by plant size. Soil organic matter (OM) and estimated nitrogen release (ENR) were significantly positively affected by both the presence of *B. sarothroides* as well as the size of the individual. This effect could have been direct as with bioavailable phosphorous (BAP) that

Fig. 5 Maximum solar radiation (**a**), mean soil moisture (**b**), and mean soil temperature (**c**) under *B. sarothroides* canopies and out in open locations. Gaps or missing lines indicate sensor failure



was only affected by the size of the *B. sarothroides* individual. The direct effects could be explained by the fact that larger *B. sarothroides* individuals produce more litter, thus contributing to greater litter decomposition and overall soil fertility (Zhang et al., 2023). This effect also extends to root decomposition and rhizosphere size (Hobbie, 2015). In addition,

bioavailable phosphorous is known to be closely tied with plant age and root growth as phosphatases (a type of root exudate) mediate the conversion of organic phosphorous into inorganic phosphorus in the plant rhizosphere (Gianfreda, 2015; Krämer & Green, 2000). Diverse groups of bacteria and fungi are also associated with phosphorous-solubilizing activity.

This is relevant because arid-land research studies that include *B. sarothroides* have shown that microbial biomass is greater under shrubs than in associate open spaces (Kushwaha et al., 2020; Ossanna et al., 2023). Alternatively, the effects could have been indirectly modified by the greater cover of facilitated plants that grew beneath the canopy (Mihoč et al., 2016).

The higher native plant diversity as well as species richness observed under the canopy of *B. sarothroides* can be attributed to facilitation, which is known to be a ubiquitous driver of biodiversity (Wright et al., 2017), because nurse plants use resources and alter the local biotic and abiotic conditions. This, in turn, changes the number of available niches, allowing for greater species diversity (Levine & HilleRisLambers, 2009). Species richness and diversity are both important considerations in revegetation as it is widely recognized that biodiversity improves ecosystem functions such as nutrient cycling and hydrological processes (Tilman et al., 2014). Richness and diversity can be used to monitor site stability and revegetation success (Gastauer et al., 2021; Sheoran et al., 2010; Smyth & Dearden, 1998).

Conclusions

The benefits of early successional shrubs, particularly in disturbed arid environments, are substantial and not to be overlooked in revegetation efforts. Facilitation is a critical interaction in desert ecosystems as it supports the growth and survival of seedlings and annual plants, promotes soil development, resource accumulation, and net productivity. Understanding how to capitalize on these facilitative effects in mine revegetation may lead to more successful efforts. We have shown that *B. sarothroides* successfully enhances plant diversity and richness through facilitation. *B. sarothroides* has also been shown to successfully colonize heavily disturbed sites where mortality of other native shrub species was high (Norem et al., 1982). Shrub species known to be successful nurse plants, particularly those that colonize degraded habitats, often exhibit opportunistic strategies that may be advantageous in unpredictable, exposed environments (Butterfield & Briggs, 2011). These opportunistic traits that confer tolerance to more stressful growing conditions

often deter practitioners from utilizing these species in revegetation efforts due to fear of monoculture stands forming (Lázaro-Lobo et al., 2021). However, by including a diverse set of species in the seeding mix, the risk of dominance by a single species is reduced (Fargione & Tilman, 2005; Hobbs & Huenneke, 1992; Maron & Marler, 2007). Moreover, pioneer species such as *B. sarothroides* are relatively short lived and are expected to be gradually replaced by later species. Synergistic improvements to both soil fertility and plant community development due to influences of shrub size may be seen with longer monitoring, as pioneer species can have long-lasting impacts on communities (Navarro-Cano et al., 2015). Long-term monitoring of this site will also document the progression in plant community development and determine whether this pioneer species facilitates the development of a diverse and stable native plant community. Finally, our findings should be interpreted with caution as our study was conducted in one site and environmental effects across sites modify facultative effects (Guo et al., 2018; Lozano et al., 2017).

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Author contributions S.L. came up with the study and deployed the experiment. S.L., J.N. and E.G. wrote the manuscript. J.N. and E.G. edited and revised the manuscript.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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