

FINAL REPORT

Autogenic Restoration at the Boulder City Conservation Easement

CC DCP Project No. 2023-UNLV-2395A



Using On-Site Materials for Drought-Adapted Habitat Restoration

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EXECUTIVE SUMMARY

This project evaluated the performance of three abiotic restoration treatments – vertical mulch, pit-mound microcontouring, and litter addition – designed to create microsite structure, capture material, and support early stage recovery processes in a decommissioned road within Mojave Desert shrublands. Their primary goals were to determine whether these treatments could persist through variable seasonal conditions including dry periods, accumulate soil resources, and improve microhabitat conditions in ways that may facilitate future plant establishment. Specific objectives included assessing treatment persistence, quantifying organic matter accumulation, evaluating microsite conditions relevant to plant establishment, and examining early responses of native shrubs and annual plants.

Across the study period, pits and vertical mulch persisted despite gradual infilling and structural degradation, and both consistently captured litter and organic debris. These features remained distinct surface characteristics relative to untreated controls, demonstrating that simple, on-site materials can create stable resource-trapping microsites even during years with limited precipitation. Shrub recruitment was sparse and occurred only during wetter seasons, with no differences among treatments once seedlings were detected. Annual plant responses were strongly shaped by rainfall. Exotic annuals varied among treatment × litter combinations only in seasons with sufficient emergence, while native annuals remained uniformly low, showing no treatment effects, and also only emerged with sufficient rainfall. Evidence for a litter-addition influence was minimal, reflecting low emergence opportunities and limited native annual abundance.

Collectively, these results indicate that abiotic treatments can function as drought-adapted restoration tools that build physical heterogeneity and accumulate resources during dry years, preparing sites for future recruitment when climate conditions improve. Treatment performance likely depended on soil texture and available woody material, and structural persistence was reduced in the sandy, mobile substrates. Periodic maintenance or reinstallation may be necessary in such settings, but these actions remain far less costly than installing and maintaining manufactured infrastructure.

Treatment results highlight the value of simple, abiotic structures constructed from locally sourced materials as flexible, low-cost components of restoration strategies in warm deserts. By creating depressions and aboveground structures that trap litter and seed, these treatments establish microsites that can later accommodate seeding or planting when resources and favorable rainfall conditions align. Longer-term monitoring will be essential to determine whether the resource accumulation observed here translates into increased recruitment during future favorable seasons and contributes to the reestablishment of fertile-island processes that support plant community recovery.

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INTRODUCTION

Surface reengineering in arid ecosystem restoration serves multiple ecological functions beyond erosion control. In hot deserts, the thin layer of surface soil contains disproportionately high nutrient concentrations, organic matter, and microbial biodiversity (Schlesinger et al. 1996; Guo et al. 1998; Titus et al. 2002; Pombubpa et al. 2020). Maintaining this biologically active layer requires interventions that reduce erosion and dust effluent while also retaining soil resources, including physical soil material, litter, seedbanks, and microbial communities. Effective restoration must therefore stabilize surfaces, slow wind velocity, and trap dust, seeds, and organic matter to support natural recovery processes. These considerations direct need for restoration strategies that rebuild the physical environment as a precursor to biotic recovery. Degraded desert ecosystems in the Mojave Desert present substantial challenges for habitat recovery and disturbance mitigation, particularly where soil resources, surface-substrate structure, and perennial plant communities have been lost. Traditional active revegetation approaches, such as hand or aerial seeding and salvage or nursery-propagated outplanting, can rapidly revegetate sites (Abella et al. 2015a, 2015b; Abella & Chiquoine 2019) but are also costly, logistically complex, and prone to failure (Radar et al. 2022, Abella et al. 2023). These methods require tracking phenology of source populations, matching plant genetics to local conditions, collecting and processing seeds, and preparing seeds for seeding or propagating plants in nurseries. Even when implemented well, outcomes remain uncertain and vulnerable to uncontrollable factors such as post-planting anomalous drought, extreme weather, or additional disturbances that can result in total failure of seedling emergence or outplant survival (Abella et al. 2026). As climatological and ecological drivers of habitat sustainability and recovery continue to shift across the desert Southwest (Bradford et al. 2019, 2020; Singh et al. 2022), the risks, costs, and uncertainties associated with active revegetation will intensify. Mounting constraints, combined with the increased likelihood of ecological drought (Crausbay et al. 2017), requires reframing restoration practice by strategic integration of biotic and abiotic interventions. Under this framework, rebuilding the physical environment becomes the foundational step that enables ecosystems to recover through natural processes and supports more targeted biotic interventions when resources or conditions allow.

Restoring the abiotic foundation of desert ecosystems offers a pathway for improving long-term recovery outcomes by supporting natural ecosystem processes. In arid systems, this foundation includes stabilizing nutrient-rich surface soils, reestablishing microtopography that concentrates scarce water and nutrients, and installing physical structures that favor native plant recruitment or survival (Commander et al. 2020; Fendane et al. 2025). Abiotic treatments can initiate the accumulation of soil resources (Havrilla et al. 2020), although gradually (Li et al. 2017), promote the formation of heterogeneous microhabitats that provide localized improvements in moisture capacity and retention, temperature, and resource availability (Jahantigh & Pessarakli 2009; Commander et al. 2020), and facilitate colonization by native plants without requiring large inputs of seeds or nursery stock. Importantly, abiotic techniques can function as stand-alone treatments or complement revegetation efforts by improving microsite quality and offsetting resource limitations that constrain seedling establishment.

Vertical mulch, consisting of dead plant material installed upright in the soil, can trap sediment, arrest erosion, capture seeds, and create shaded microhabitats that mimic abiotic nurse-plant

effects (Rader et al. 2022; Chiquoine & Abella 2026). Rock arrangements can similarly create protected microsites that accumulate organic matter and support plant establishment or growth (Carlucci et al. 2011, Chiquoine et al. 2022). Soil microcontouring, or the manipulation of small-scale surface topography, includes techniques such as pitting, furrowing, and shallow depressions that concentrate water and nutrients (Houston 1965; Stavi et al. 2020; Ochoa et al. 2023). Microcontouring is typically limited by soil texture, compaction, and equipment access, and may be less effective in certain soil types (Eldridge & Ding 2023). When feasible, however, microcontouring enhances infiltration and resource retention at fine spatial scales (Jahantigh & Pessarakli 2009; Eldridge & Ding 2024). Assisted natural regeneration approaches can increase survival of naturally occurring seedlings without relying on propagule resource availability (Abella et al. 2020). Collectively, these strategies leverage the fertile-island dynamics characteristic of undisturbed Mojave Desert shrublands (Guo et al. 1998, Titus et al. 2002), whereby perennial plants create shaded, protected, nutrient-rich patches that support soil seed bank recovery and facilitate recruitment of new shrubs.

Abiotic treatments offer several advantages for initiating recovery of ecosystem processes, particularly when utilizing on-site materials. These techniques are relatively inexpensive and encourage recovery of soil conditions and seedbanks, ensuring genetic appropriateness of recovery materials. Importantly, abiotic structures may persist through dry years, maintaining function until favorable conditions return; in contrast, seeds and outplants are lost once they fail. Because soil resources in desert shrubland ecosystems are naturally patchy (Mudrak et al. 2014), reestablishing heterogeneity is essential for restoring ecosystem function. Abiotic treatments also serve as bet-hedging in drought-adapted restoration: they offset resource limitations by improving microsite quality during unfavorable years, which could increase the probability that recruitment will occur when climatic conditions eventually align. Although techniques such as vertical mulch or soil pitting are standard practices for mitigating disturbance in desert soils, the longevity and ecological performance of these native infrastructure treatments remain uncertain.

Project Goals and Objectives

The goal of this project was to evaluate the feasibility, persistence, and ecological performance of three abiotic restoration treatments, vertical mulch, pit-mound microcontouring, and litter addition, implemented at fine spatial scales in degraded Mojave Desert shrublands. These treatments were designed to modify microenvironments, rebuild soil resource patches, and support early-stage natural recovery processes without relying on large inputs of seeds or nursery stock.

The project objectives were to:

- Assess treatment persistence under Mojave Desert conditions, including structural integrity, durability, and failure modes over time.
- Quantify soil resource accumulation associated with each abiotic treatment, including litter, fine material, and organic matter relative to untreated controls.
- Evaluate microsite improvements relevant to plant establishment, such as shading, wind reduction, moisture retention, and protection from disturbance.

- Determine whether treatments facilitate colonization or survival of native annuals and foundational shrub species, including *Larrea tridentata* (creosote bush) and *Ambrosia dumosa* (white bursage).
- Examine how microenvironment-level responses scale to plot-level patterns of resource heterogeneity and early indicators of ecosystem recovery.

Together, these objectives address the need for restoration strategies that rebuild the physical environment as a precursor to biotic recovery, particularly in landscapes where disturbance has reduced soil resources, microsite structure, and native plant communities.

To address this gap, we tested the feasibility and performance of multiple abiotic treatments designed to modify microenvironments and promote the reestablishment of soil resource patches typical of mature Mojave Desert shrublands. Treatments included vertical mulch, soil microcontouring (i.e., pitting), and litter addition. Implemented at fine spatial scales and monitored at both microenvironment and site scales, these treatments were assessed for their ability to persist, accumulate soil resources, enhance microsite development, and support colonization or survival of foundational shrub species such as *L. tridentata* and *A. dumosa* and native annual plants. We asked: (i) how long do abiotic treatments persist under Mojave Desert conditions, and how does persistence vary among treatment types; (ii) do abiotic treatments enhance soil resource accumulation (e.g., litter, fine material, organic matter) relative to untreated controls; (iii) do abiotic treatments facilitate colonization or survival of native annuals and foundational shrub species, suggesting abiotic treatments improve microsite conditions relevant to plant establishment (e.g., shading, wind reduction, moisture retention); and (iv) how do treatment effects scale from microenvironment responses to site-level patterns of recovery? We hypothesized that abiotic treatments would persist for multiple seasons, although due to the sandy substrates at the field site, we would detect failure or a reduction in integrity of abiotic structure over time; that abiotic treatments would accumulate more fine material, litter, and organic matter than untreated controls; that treatments would create more favorable microsite conditions and support colonization and survival of native annuals and foundational shrubs relative to controls; and that microenvironment-level improvements will translate into detectable plot-level increases in resource heterogeneity and early stage recovery indicators.

METHODS AND MATERIALS

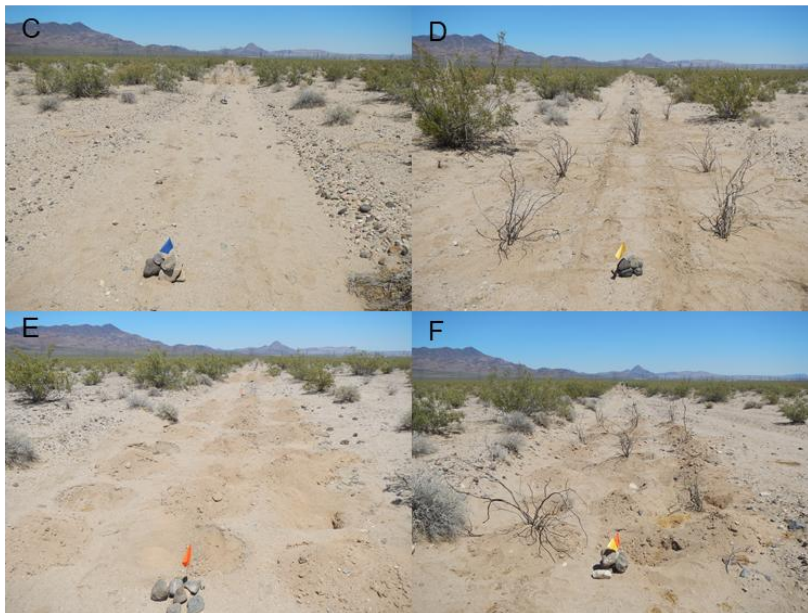
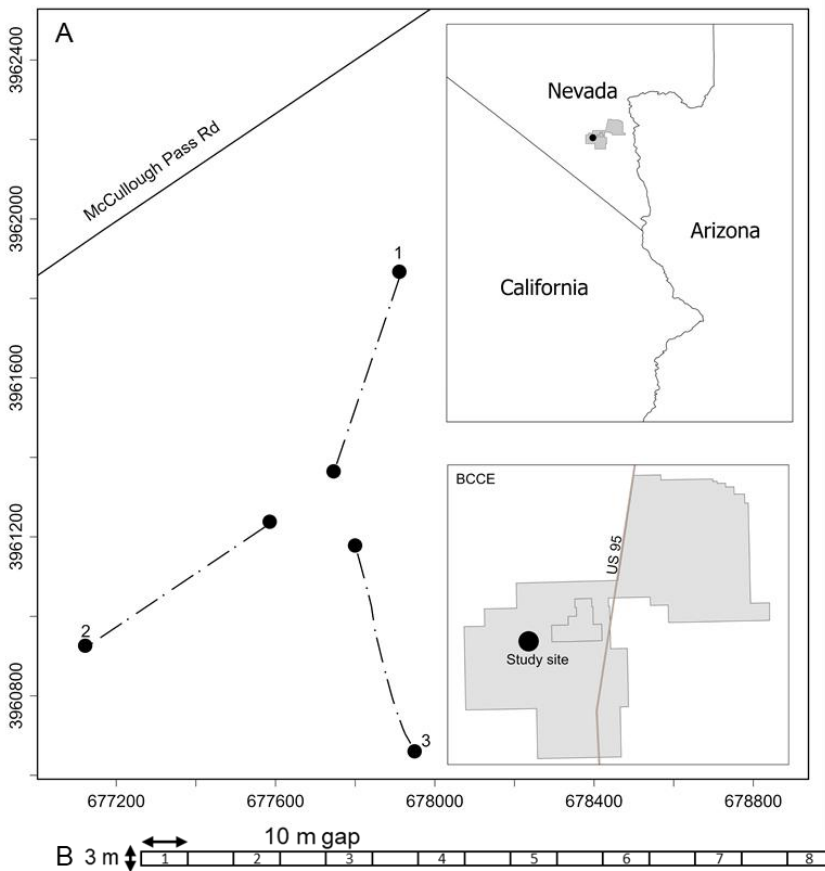
Study Site

We installed experimental abiotic (four levels) $\times$ litter addition (two levels) treatments along unrestored closed road segments in the Boulder City Conservation Easement (BCCE) administered by the Clark County Desert Conservation Program (CC DCP), Clark County, Nevada. The BCCE was established in 1995 by a partnership between Clark County, Nevada, and the City of Boulder City, Nevada, to create protected habitat for the Mojave Desert tortoise (*Gopherus agassizii*) and other species covered by the Clark County Multiple Species Habitat Conservation Program. The southern portion of the BCCE, west of US-95, encompasses 19,487 hectares (48,154 acres) and contains designated roads, some of which have been decommissioned, leaving unrestored segments accessible only at their endpoints. Working with CC DCP, we identified three unrestored 700-m road segments for experimental installation (Fig. 1). Endpoints for each road are provided in Table 1.

Table 1. Location of unrestored roads in the Boulder City Conservation Easement. End points are reported using UTM NAD 1983 Zone 11 Easting and Northing.

Road	End 1		End 2	
	Easting	Northing	Easting	Northing
1	677746	3961365	677911	3961867
2	677585	3961238	677122	3960926
3	677800	3961178	677949	3960660

Soils in this portion of the BCCE are sandy with minimal gravel or rock, and vegetation is dominated by *Larrea tridentata*-*Ambrosia dumosa* shrublands. Each road segment was divided into three sections, and each of the eight treatment combinations was installed once per section in 3-m $\times$ 10-m plots, resulting in three replicates per road segment and nine replicates per treatment combination. Plots were spaced ≥ 10 m apart along roads.



PM-VM treatment showing the checkerboard pit-and-mound microtopography and eight VM structures, with four placed on mound cells and four placed in pit cells.

Figure 1. (A) Location of the three unrestored road segments within the Boulder City Conservation Easement (BCCE), Clark County, Nevada. The top inset shows a regional map depicting the intersection of southern Nevada, Arizona, and California, with the BCCE highlighted as a grey block and study location marked with a black dot. The bottom inset shows a closeup of BCCE with the study site marked by a black dot on the west side of US-95. (B) Schematic of a road segment showing the arrangement of eight 3-m $\times$ 10-m plots spaced 10 m apart. The eight experimental treatments (four abiotic treatment levels $\times$ two litter-addition levels, totaling eight treatment combinations) were randomly assigned to the eight plots within each section of each road segment, resulting in one replicate of each treatment per section or three replicates per road. (C) Example of an unrestored control plot. (D) Example of a vertical mulch (VM) treatment plot showing eight VM structures. (E) Example of the pit-and-mound (PM) treatment installed in a checkerboard pattern. (F) Example of the combined

Seasonal Climate during Field Experiment

Treatments were installed in April 2024 following several consecutive years of below-average precipitation in southern Nevada (Table 2). Long-term mean annual precipitation for the region is approximately 102 mm, with cool-season (November – April) precipitation averaging 61 mm and warm-season (June – September) precipitation averaging 30 mm (1948 – 2025; hydrologic year, October-September, Harry Reid International Airport, Nevada, US, GHCN-Daily USW00023169; Menne et al. 2018). On average, 25 days per hydrologic year receive measurable rainfall, including roughly 15 cool-season days and 7 warm-season days.

The years preceding treatment installation were generally drier and more variable than long-term norms. Several years exhibited substantially reduced cool-season precipitation and fewer rainfall events, limiting the number and duration of moisture pulses that support germination and early establishment of Mojave Desert annuals and shrub seedlings. Only one year approached long-term cool-season averages. Other years were characterized by low cool-season precipitation, minimal warm-season rainfall, or both. The hydrologic year immediately preceding installation (2024) was notably dry, with very few cool-season rainfall events.

Table 2. Precipitation and the number of days with measurable rainfall during years preceding (2021 – 2023) and during (2023 – 2025) the field experiment (hydrologic year, October-September, HARRY REID INTERNATIONAL AIRPORT, Nevada, US, GHCN-Daily USW00023169; Menne et al. 2018).

Year	Precipitation(mm)			Number of days with measurable rainfall		
	Annual	Warm season	Cool season	Annual	Warm season	Cool season
2021	58.2	45	11.1	20	12	6
2022	114.9	73.1	41.8	29	11	18
2023	64.6	2	59.3	20	1	18
2024	59.3	7.6	15.1	10	3	3
2025	95.9	5.1	65.6	22	4	15

In addition to reduced precipitation, the experiment occurred during a period of sustained regional warming. Long-term climate records for the Las Vegas area show increasing mean annual temperatures, higher summer maximum temperatures, warmer winter minimum temperatures, and a rising frequency of extreme heat days. These trends reflect broader warming across the Mojave Desert and contribute to elevated evaporative demand and shorter soil-moisture durations during the years in which treatments were installed and monitored.

Treatments

Abiotic treatments included a pit-and-mound (PM) treatment, a vertical mulch (VM) treatment, a combination of the two treatments (PM-VM), and an unrestored control. Each plot was divided into 30 1-m × 1-m cells.

Pits were installed in a checkerboard pattern. In pit cells, pits were dug using shovels and hand trowels to 30 cm deep and 65 to 70 cm wide (Fig. 2). Excavated soil was placed onto adjacent

mound cells to create microtopographic heterogeneity that can influence infiltration, runoff, soil temperatures, and potentially support colonization. Eight VM structures were installed per plots, spaced at least one cell apart (Fig. 2). Each structure consisted of 8 to 10 dead *L. tridentata* branches collected from the surrounding landscape, bundled together and buried 20 to 30 cm deep in the center of cells, resulting in structures up to 80 cm tall with canopies 60 to 80 cm wide. VM structures mimic the physical form of a standing *L. tridentata* shrub. For the combination PM-VM treatments, PM treatments were installed first, followed by VM structures. Four VM structures were placed on mound cells and four in pit cells. To half of the abiotic treatment combinations (control, PM, VM, and PM-VM), 9 L of homogenized litter collected from beneath *L. tridentata*, *A. dumosa*, and depressions was distributed across plots by hand (Fig. 2). Litter contained flower parts, leaves, small twigs, fruits, and seeds, adding organic matter and seeds to plots.

Assessments

Treatments were installed April 2024 immediately following a pre-treatment survey that recorded annual and perennial plants, including shrub seedlings, present in plots. Cover was estimated per species using cover classes (Peet et al. 1998).

Pre-treatment and four post-treatment seasonal surveys – fall 2024, spring 2025, fall 2025, and spring 2026 – assessed the persistence and condition of abiotic structures, organic matter accumulation, annual plant colonization, and shrub recruitment by measuring pit depth, height of VM structures and cover of VM per cell, litter depth and cover per cell, annual plant cover per cell on a species basis, and the count of shrub seedlings on a species basis. Cumulative cover values per species or abiotic structure and mean values for height of VM and depth of pits were calculated at the plot level.



Figure 2. Examples of treatment installation: (A - B) the installation of the pit-and-mound treatment in a checkerboard pattern within plots, (C – D) the installation of vertical mulch using dead *Larrea tridentata* branches, and (E – F) litter collection and application to plots by hand with an inset in E showing the collected litter.

Statistical Analyses

Abiotic structure metrics (pit depth, vertical mulch height and cover, litter depth and cover) and plant response variables (native and exotic annual presence and cover and shrub seedling presence and abundance) were analyzed using generalized linear mixed-effects models (GLMMs) in SAS PROC GLIMMIX (9.4, SAS Institute Inc. 2016; Cary, NC, USA). Fixed effects included abiotic treatment, litter addition, season, and their interactions, with ROAD included as a fixed blocking factor to account for broad-scale spatial heterogeneity.

Model selection was based on AICc, and Satterthwaite denominator degrees of freedom was used to accommodate small and unbalanced samples. Random intercepts for road segment and plot were included when supported by AICc, reflecting the hierarchical sampling design. When random effects did not improve model fit, they were removed. Temporal autocorrelation within plots was modeled using the best-supported covariance structure selected using AICc. Response distributions were chosen according to variable scale and statistical properties. Continuous abiotic metrics were modeled with normal errors. Percentages were converted to proportion, and proportional cover variables bounded between 0 and 1 were modeled using beta regression. Shrub seedling counts exhibited overdispersion and were modeled using the negative binomial distribution. Abiotic structural responses that were only meaningful for specific treatments (e.g., pit depth in PM and PM-VM; vertical mulch cover in VM and PM-VM) were analyzed using treatment-restricted subsets to maintain model validity.

Plant responses were sparse and were analyzed using two-part hurdle models. The first component used logistic regression to test whether the probability of detecting a non-zero response differed among season, abiotic treatment, and litter addition and their interactions. The second component modeled positive responses conditional on presence, using beta regression for annual plant cover and negative binomial regression for shrub seedling counts and native plant richness. For shrub seedlings, the logistic model was reduced to main effects because higher-order interactions in the zero-inflation component caused non-convergence. Reducing the shrub seedling zero model to main effects provided stable, interpretable marginal effects while adjusting for other factors. Exotic and native annuals retained full factorial logistic models because they converged without issue.

RESULTS

Resource Accumulation

Litter Depth

Litter depth varied across seasons and among abiotic treatments, with a significant season $\times$ treatment interaction ($F_{3,121} = 21.48$, $p < 0.001$). In fall 2025, VM and PM-VM plots exhibited greater litter depth than controls, whereas PM plots showed intermediate values. By spring 2026, litter depth declined sharply in control plots but remained higher in PM and PM-VM plots, with PM-VM showing the greatest depth (Fig. 3a). VM plots showed moderate litter depth in fall but lower values in spring. Litter addition had a marginal effect on litter depth ($F_{1,124} = 2.76$, $p = 0.010$). Visually assessments indicated litter accumulation within pits and beneath vertical mulch structures (Fig. 3), whereas control plots generally exhibited lower litter retention.

Litter Cover

Litter cover differed significantly among abiotic treatments ($F_{3,105} = 51.70$, $p < 0.001$). Across seasons, litter cover was lowest in control plots and higher in all abiotic treatments. PM-VM plots showed the greatest litter cover, followed by PM and VM plots (Fig. 3b). Litter cover in PM-VM plots was up to eight times greater than in controls, and PM plots showed roughly five-fold higher cover than controls. These results show that plots containing pits, vertical mulch, or both generally exhibited higher litter cover than controls, with the highest values observed where both microtopographic and structural elements were present.

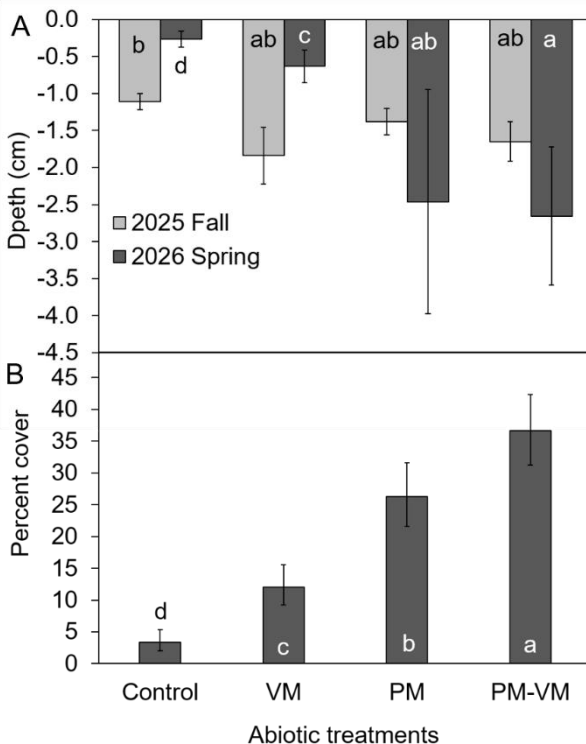


Figure 3. Significant effects of abiotic treatments on resource accumulation and retention. Treatments included unrestored controls, vertical mulch (VM), pit-mound (PM) microtopography, and a combined PM-VM treatment. Error bars are 95% confidence intervals. Lowercase letters represent significant groups. (A) Litter depth among abiotic treatments between fall 2025 and spring 2026. (B) Percent litter cover among

abiotic treatments. (C) Example of pits with litter. (D) Example of litter accumulation beneath VM canopy.

Abiotic Structural Integrity in Sandy Soils

Pit Depth

Pit depth varied significantly across seasons ($F_{2,94} = 17.05$, $p < 0.001$). Mean pit depth was greatest in spring 2025, declined in fall 2025, and increased again in spring 2026 (Fig. 4a). No differences were detected between PM and PM-VM treatments, and pit depth patterns were similar across plots containing pits.

Vertical Mulch Height

Vertical mulch height varied significantly across seasons ($F_{3,99} = 117.32$, $p < 0.001$). Height was greatest in fall 2024, decreased in spring 2025, and declined further in fall 2025 and spring 2026 (Fig. 4b). Field observations documented spreading structures and breakage of branches, and several structures were toppled by off-road vehicle trespass along one road segment, corresponding with the measured reductions in height.

Vertical Mulch Cover

Vertical mulch cover also varied significantly across seasons ($F_{3,89} = 27.17$, $p < 0.001$). Cover was lowest in fall 2024, increased markedly in spring 2025, and then decreased in fall 2025, remaining similar in spring 2026 (Fig. 4c). The increase in cover between fall 2024 and spring 2025 coincided with the period in which VM height declined, and field observations showed that structures tended to spread and collapse during this time. Subsequent decreases in cover corresponded with continued structural degradation, including branch breakage and toppled structures.

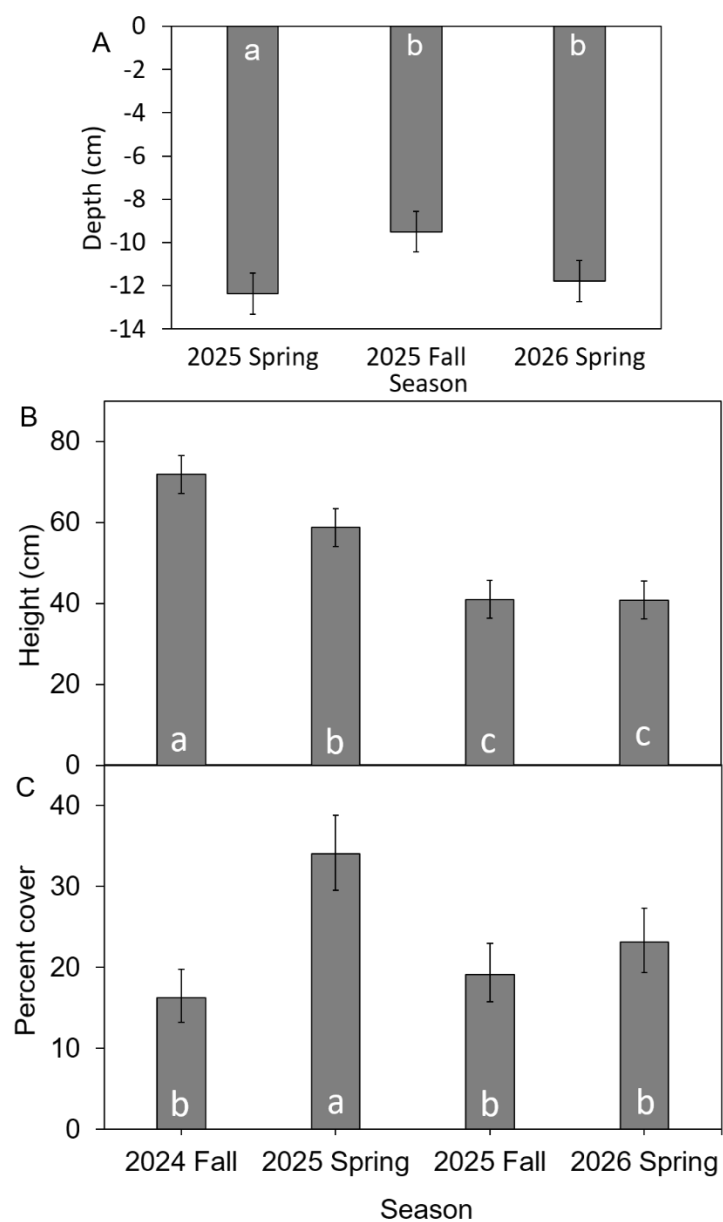


Figure 4. Abiotic structural integrity over time. Error bars are 95% confidence intervals. Lowercase letters represent significant groups. (A) Pit depth between spring 2025 and spring 2026. (B) Vertical mulch height between fall 2024 and spring 2026. (C) Vertical mulch plot-level cover between fall 2024 and spring 2026.

Plant Colonization

Shrub Recruitment

Shrub seedling recruitment was infrequent across the study period and was analyzed using a two-part hurdle model. In the logistic regression component, which tested the probability of detecting shrub seedlings in a plot, detection varied significantly among seasons ($F_{4,351} = 4.57$, $p = 0.001$). Seedlings were most frequently observed during fall 2025 and spring 2026. Abiotic treatment, litter addition, and all interactions were not significant.

In the conditional component, which evaluated seedling counts given detection, no significant effects of season, abiotic treatment, litter addition, or their interactions were detected (all $p > 0.10$). Once seedlings were present, their abundance did not show any discernible structure associated with treatment type or sampling period (Fig. 5).

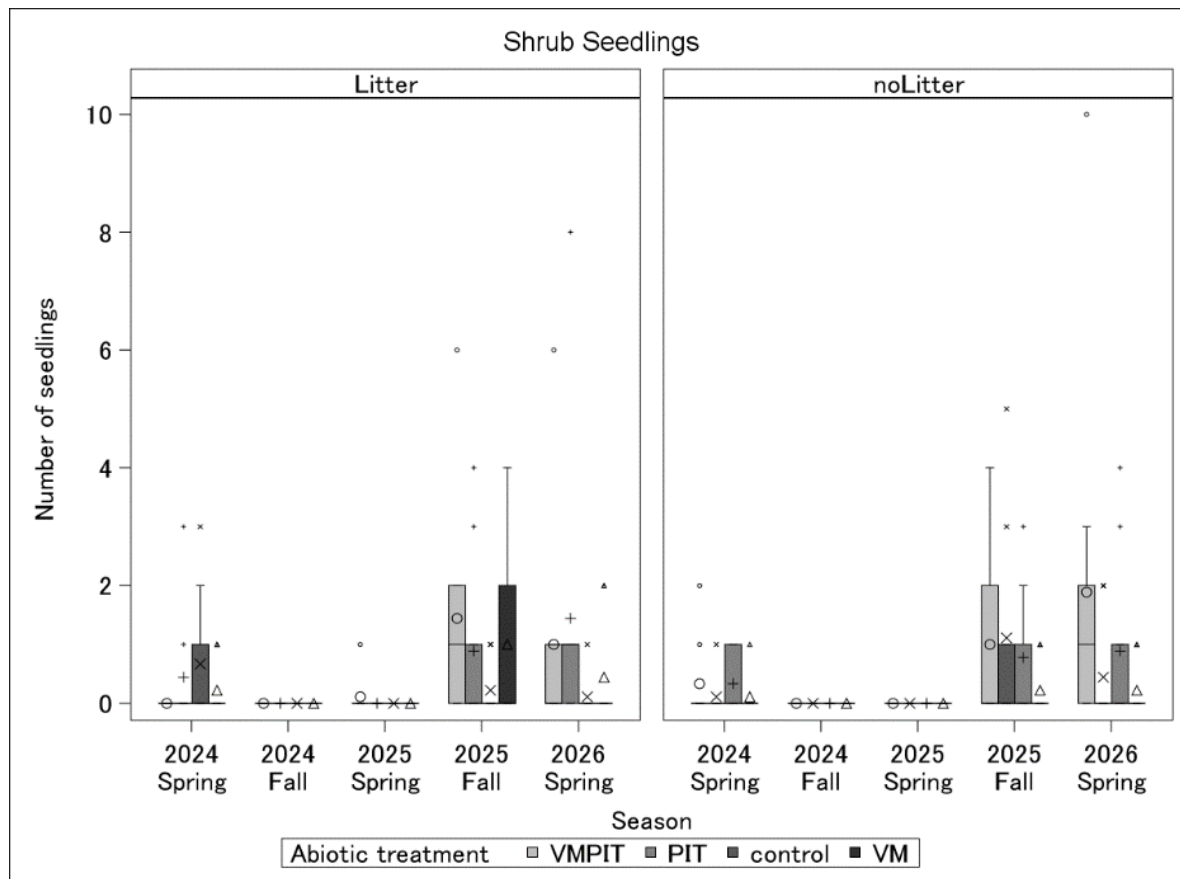


Figure 5. Shrub detection across seasons expressed as the median density of seedlings per 30 m². Box-and-whisker plots showing the distribution of shrub seedling counts across seasons and abiotic treatments, presented separately for plots with and without litter addition. Boxes represent the interquartile range (25th – 75th percentiles), and whiskers extend to 1.5× the interquartile range. Statistical outliers are represented by points outside the whiskers. Treatments included unrestored controls, vertical mulch (VM), pit-mound (PM) microtopography, and the combined PM-VM treatment.

Exotic Annual Plants

Exotic annual plant cover was sparse and was analyzed using a hurdle model. *Schismus* was the only non-native taxa detected among plots during the project period. This species was widespread in adjacent undisturbed areas and detected with higher frequency than native annuals during seasons when annual plants emerged. In the logistic component, which tested the probability of detecting *Schismus*, no significant differences were found among seasons, abiotic treatments, litter addition, or their interactions (all $p > 0.10$). *Schismus* was not detected during the fall 2024 survey, was incipient among plots when detected, and detection patterns did not correspond with treatment assignments.

In the conditional component, *Schismus* cover exhibited a significant three-way interaction among season, abiotic treatment, and litter addition ($F_{4,46} = 3.96$, $p = 0.008$). Slice tests indicated that no differences were present prior to treatment installation and that some seasons lacked sufficient non-zero values for comparison. During fall 2025, after rainfall occurred, *Schismus* cover differed among treatment $\times$ litter combinations, and marginal differences were observed in spring 2026 (Fig. 6a). During fall 2025, slightly greater *Schismus* cover was detected in control plots with litter addition compared to without litter addition.

Native Annual Plants

Like *Schismus*, native annual plant cover was sparse, and cover and richness were analyzed using hurdle models. In the logistic component, the probability of detecting native annuals did not differ among seasons, abiotic treatments, litter addition, or their interactions (all $p = 1.00$). Detection of native annuals was low across the study period, except for spring 2026. No native annual plants were detected during fall 2024 surveys.

In the conditional component for cover, native annuals showed no significant differences among seasons, abiotic treatments, or litter addition, or their interactions (all $p > 0.10$). Although descriptive summaries indicate slightly higher conditional cover during spring surveys and somewhat higher values in PM and PM-VM plots, these differences were not significant (Fig. 6b). Native annual cover remained low across all treatment $\times$ litter combinations and sampling periods, except for spring 2026. Native annual plant richness followed similar patterns, but conditional richness significantly differed by season ($F_{3,146} = 425.35$, $p < 0.001$). Conditional richness remained uniformly low across most seasons (Fig. 7), but there was a pronounced seasonal pulse observed in spring 2026. These patterns reflect the overall scarcity of native annuals during the study period and the strong influence of seasonal rainfall on native annual diversity.

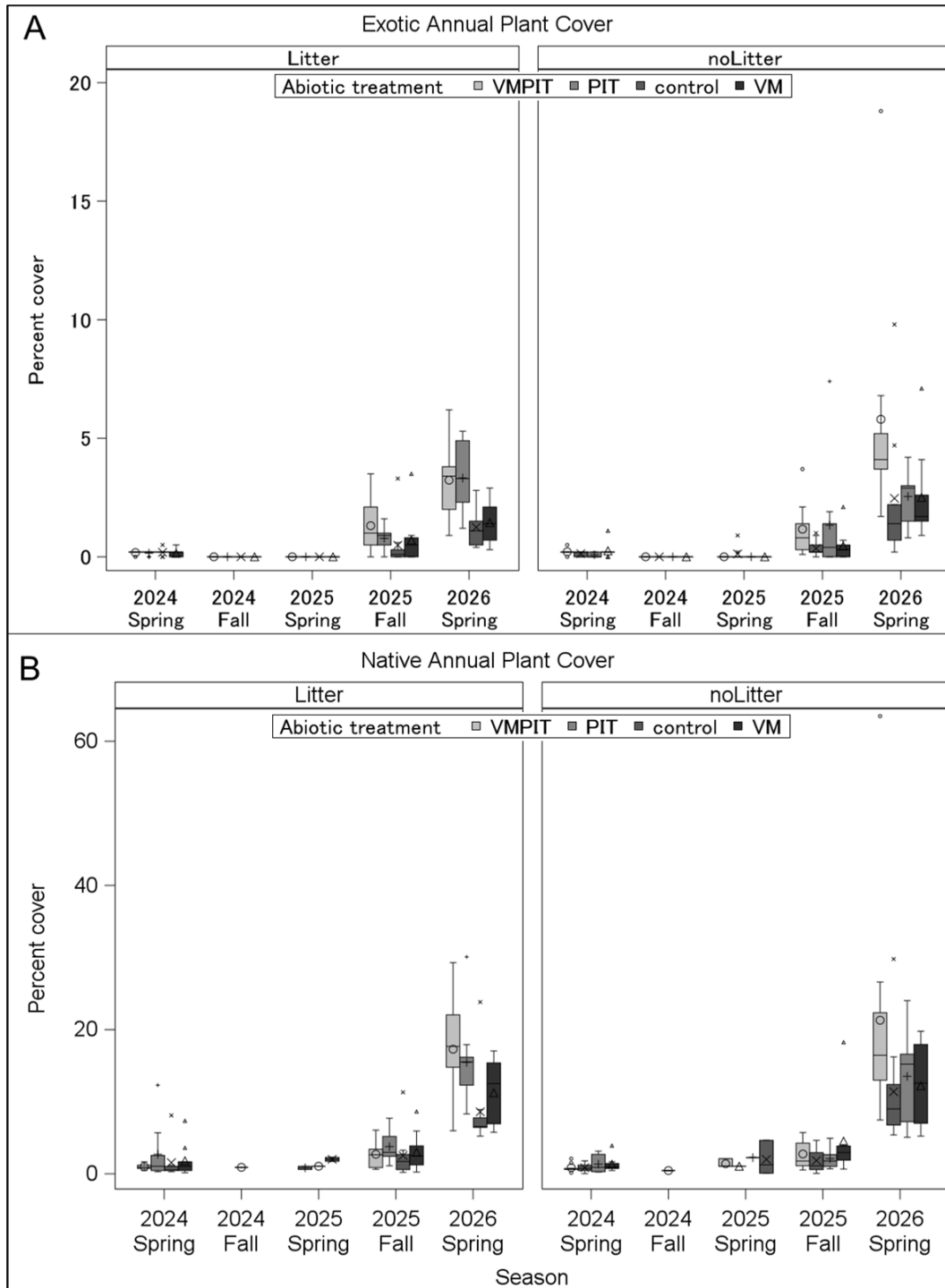


Figure 6. Annual plant detection across seasons as median plant percent cover. Box-and-whisker plots showing the distribution of (A) exotic and (B) native annual plant cover across seasons and abiotic treatments, presented separately for plots with and without litter addition. Boxes represent the interquartile range (25th – 75th percentiles), and whiskers extend to 1.5 × the interquartile range. Statistical outliers are shown as points beyond the whiskers. Treatments included unrestored controls, vertical mulch (VM), pit-mound (PM) microtopography, and the combined PM-VM treatment.

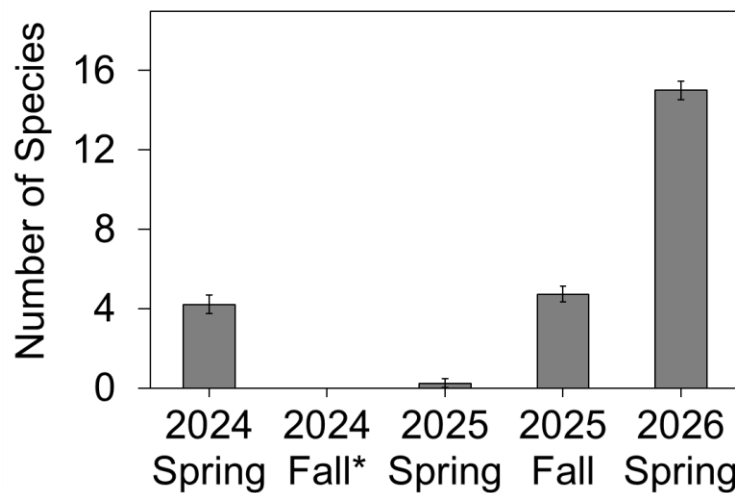


Figure 7. Native annual plant richness across seasons. Raw means with 95% confidence intervals are presented, but because some seasons lacked sufficient non-zero values, richness could not be statistically compared between seasons. The asterisk indicates no native annuals were detected that season.

DISCUSSION

Across the study period, the abiotic structures generally persisted through dry conditions and accumulated organic material, even as pits gradually filled and vertical mulch degraded. These structural features maintained distinct surface characteristics relative to controls and reliably retained litter, indicating that they functioned as stable microsites and resource traps during years with limited precipitation. Shrub recruitment was sparse and appeared only during the wetter fall 2025 and spring 2026 seasons, with no differences in seedling abundance when seedlings were detected. Annual plant responses reflected the influence of seasonal conditions, with exotic annual cover varying among treatment $\times$ litter combinations only in seasons with sufficient emergence. In contrast, native annual cover remained uniformly low and showed no statistically supported treatment or seasonal effects. These patterns suggest that abiotic treatments persisted through dry periods, accumulated organic matter and likely seed inputs, and maintained microsite structure even when plant responses were minimal due to limited emergence opportunities.

Abiotic Treatment Performance

The performance of the abiotic treatments aligns with observations that physical structures can influence microhabitat conditions and resource distribution in arid ecosystems (e.g., greater seedbanks under shrubs, Guo et al. 1998; plant structures trap seeds, Giladi et al. 2013, Filazzola et al. 2019). Pits and vertical mulch persisted through multiple dry seasons, even as pits gradually filled and vertical mulch degraded, and both features contributed consistently to capture of organic debris. These patterns reflect with the broader understanding that microtopography and aboveground structure contribute to the formation of resource-rich microsites in desert landscapes, similar to the physical aspects of fertile islands formed beneath shrub canopies. Pitting has long been recognized as a technique to capture water, soil particles,

and organic debris including seeds (Chambers 2000; Stavi et al. 2020; Ochoa et al. 2023), and the pits in this study functioned in that manner despite gradual infilling.

The gradual degradation of the abiotic structures demonstrates the physical constraints of the field site and materials available. Vertical mulch was constructed from relatively small *L. tridentata* stems, which provided limited canopy volume and reduced the ability of these structures to mimic the shading and debris-capturing functions of larger shrubs, even though their overall dimensions were similar to nearby live shrubs. Smaller-diameter stems offered less structural rigidity, making them more susceptible to breakage and collapse over time. Soil texture likely reduced structural performance. The sandy, mobile substrate at the site provided limited anchoring support, contributing to the instability of vertical mulch and the gradual infilling of pits. In contrast, soils containing higher proportions of gravel, pebbles, or cobbles typically exhibit greater structural resistance (Poesen et al. 1994), which can enhance the persistence of microtopographic features and reduce collapse. Surface rock fragments also act as natural stabilizers that reduce sediment movement and erosion across multiple spatial scales (Poesen et al. 1994), and desert surfaces with greater rock cover experience lower wind-driven erosion compared to sandy soils (Goossens & Buck 2011). These substrate-dependent responses are consistent with observations that the effectiveness of pitting and other mechanical surface treatments varies across different soil and disturbance types (Eldridge & Ding 2023). Despite these limitations, the pits and vertical mulch maintained enough structural integrity to continue capturing organic debris, indicating that even partially degraded features limitedly function as resource traps or sinks in warm desert environments. In environments with highly mobile substrates or limited woody material to use for stabilizing structures, periodic maintenance may be necessary to sustain microhabitat structure until plants can colonize or additional restoration actions follow, and such maintenance is considerably less costly than installing and later removing manufactured infrastructure.

Recruitment Constraints and Seasonal Dependence

Recruitment in arid ecosystems is strongly influenced by microhabitat, soil texture, propagule supply, and rainfall pulses (Beatley 1974b; Eriksson & Ehrlén 1992; Clark et al. 2007). Shrubs often act as ecosystem engineers that create fertile islands and facilitate establishment through shading, resource capture, and microclimatic buffering (Flores and Jurado 2003; Filazzola & Lortie 2014). Fertile island effects vary across climatic gradients and plant patch types, often intensifying with increasing aridity (Ding & Eldridge 2021). The abiotic treatments in this study mimicked some of these physical attributes by creating depressions and aboveground structure capable of intercepting and trapping litter and seed. Under the dry conditions of the study period, these microsites functioned primarily as resource traps rather than recruitment hotspots, accumulating organic material even when emergence opportunities were limited.

The contrasting responses of exotic and native annuals further illustrate the importance of rainfall events that trigger plant germination (Beatley 1974a, 1974b). Exotic annual cover corresponded with treatment $\times$ litter combinations only in seasons with sufficient emergence, whereas native annuals remained uniformly low across treatments and seasons. Litter transfer may provide additional propagules when local seed production is high, although its usefulness will depend on the composition of the seed bank and the presence of exotic species. These

patterns suggest that abiotic structures may contribute to the physical foundation for future recruitment, while their ecological influence will depend on the timing and magnitude of favorable climatic conditions.

Management Implications

Treatment responses illustrate how abiotic bet-hedging approaches can help navigate the challenges of restoration in warm deserts. Restoration in arid environments is often constrained by propagule scarcity, unpredictable rainfall, and the logistical difficulty of seeding or planting (Clark et al. 2007; Abella & Newton 2009; Palma & Laurance 2015). Techniques that diversify microhabitat availability or mimic the physical aspects of fertile islands, such as vertical mulch, woody debris, rocks, or microtopographic features, have been used in other systems to promote establishment (Carlucci et al. 2011; Castiollo-Escrivà et al. 2019; Rader et al. 2022). The treatments in this study required only on-site materials, reducing the need for seed collection, propagation, irrigation infrastructure, or protective cages.

Evidence for a litter-addition effect was minimal during the study period. Supplemental litter may contribute to additional propagules during years with higher-quality seed rain (Rowe et al. 2022), but the ecological influence of litter transfer will depend strongly on seasonal conditions and seed bank composition (i.e., recent seed rain and integration into soil). Even though plant responses were weak, abiotic treatments created physical heterogeneity, reduced visual impacts of the decommissioned road, and accumulated organic material, all outcomes that can support future recruitment when climatic conditions improve.

The study finding suggested that the abiotic structures can promote the appearance of seedlings, while also providing further management and ecosystem functions. Abiotic structures provided shade by having persistent obstruction of sunlight and roughened the surface to reduce wind speed supporting organic deposition. While there was a known trespass vehicle disturbance during the study that we reported to Clark County, the structures provided soft impediments to trespass. This study provided baseline data showing that, even in highly mobile sandy soils, abiotic structures can persist through variable weather across multiple years, while also highlighting that periodic maintenance or augmentation management actions. To what extent and the time period for which maintenance of the abiotic structures is required may depend on the rate of desired plant establishment in and around the structures. During dry periods, continuing to periodically maintain the structures may be particularly important so that these structures can continue to provide their human use-disturbance management and ecological functions, including for facilitating plant recruitment when weather conditions improve. During wetter periods, maintenance could be reduced or ceased as plants establish.

Future Considerations

Future research should evaluate how abiotic structures perform across a broader range of desert soil types, plant communities, and disturbance contexts, and how their design, materials, or architecture can be optimized using native materials suited to local conditions. Anchoring methods appropriate for mobile soils, vertical mulch constructed from larger or bundled materials, or deeper pits may improve structural persistence and resource capture. Evaluating the

effect of abiotic treatments on soil properties across substrate types would clarify how soil parent material, soil texture, and surface substrates shape treatment efficacy. Pairing abiotic structures with targeted propagule additions, such as seeding, outplanting nursery-propagated, or transplanting, applying assisted natural regeneration treatments, could help determine whether these microsites facilitate establishment when climatic conditions vary. Additional work is needed to assess how seed bank or litter transfers can be used without inadvertently promoting exotic species, particularly in systems where invasive annuals dominate seed pools. As with other assisted recovery actions, exotic plant management may need to accompany abiotic treatments to reduce the influence of exotic plants on soil properties, developing soil seedbanks, and native plant establishment. Longer-term monitoring is essential to determine whether the resource accumulation observed here translates into increased recruitment during future favorable seasons and whether these treatments can contribute to the reestablishment of fertile island processes that support plant community recovery in desert ecosystems.

Evaluation of Project Goals and Objectives

Overall, the findings suggested attainment of most of the ecological and management goals. Abiotic structures persisted through dry periods, accumulated organic material, and maintained distinct microsite characteristics, demonstrating that simple, on-site materials can be used to create resource-trapping features. These outcomes confirm that treatments improved physical heterogeneity and reduced visual impacts of the unrestored, decommissioned road. Plant establishment remained limited, and evidence for a litter-addition ecological effect was minimal, reflecting low propagule availability and restricted emergence opportunities during the study period. Although biological processes were weak, the treatments fulfilled the primary objective of preparing the site for future recruitment by creating depressions and aboveground structures capable of capturing litter and seed. The project achieved its structural and preparatory objectives, while establishment-related outcomes will require more favorable climate conditions in subsequent years.

RECOMMENDATIONS

This case study suggests that simple abiotic structures constructed from on-site materials can persist through dry periods and accumulate organic material, even when plant establishment is limited and structures gradually degrade. These observations indicate that abiotic treatments may serve as supplemental tools that create physical heterogeneity and capture organic matter in years when biological responses are constrained by seasonal conditions. Their effectiveness depends on local soil texture, available woody material, and seasonal rainfall, and their contribution to plant establishment will likely vary across years with different emergence opportunities. In settings with sandy or mobile substrates, deeper pits or improved anchoring of vertical mulch may be needed to maintain structure, and periodic maintenance or reinstallation could help sustain microsite integrity. Because these treatments rely on local materials, such maintenance is far less costly than installing manufactured infrastructure that must be transported to remote sites and eventually removed.

These results also highlight how abiotic treatments can function as drought-adapted restoration approaches. In dry years, when propagule availability is low and conditions are not conducive to

seed germination or plant growth, establishing or reengineering physical microsites can serve as a bet-hedging strategy that prepares the site for future recruitment or propagule reintroduction. By creating depressions and aboveground structure that trap litter and seed, these treatments build on-site infrastructure that can accommodate seeding or planting when resources become available. This approach allows restoration to proceed in stages, adjusting to fluctuations in funding, labor, and climatic conditions. When wetter years occur or propagule resources are available, seeding or planting can be integrated into these pre-existing microsites, potentially improving establishment opportunities. Abiotic treatments offer a flexible, low-cost framework for restoration that can be adapted to resource availability and implemented opportunistically, while acknowledging that their ecological contribution will depend on future rainfall and propagule supply.

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