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Assessing Minimal-Input Restoration Strategies for Desert Soil and Vegetation Restoration

Audrey Jean Rader
audreyjeanrader@gmail.com

ASSESSING MINIMAL-INPUT RESTORATION STRATEGIES FOR DESERT SOIL AND VEGETATION RESTORATION

By

Audrey J. Rader

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Audrey J. Rader

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Scott Abella, Ph.D.
Examination Committee Chair

Lloyd Stark, Ph.D.
Examination Committee Member

Dale Devitt, Ph.D.
Examination Committee Member

Brenda Buck, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Dean

ABSTRACT

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By

Audrey J. Rader

Dr. Scott Abella, Examination Committee Chair
Assistant Professor
University of Nevada, Las Vegas

The Mojave and Sonoran Deserts have been negatively impacted by anthropogenic disturbances. Considering that these ecosystems may recover on millennial timescales, research has shown that restoration techniques can be fairly successful in initiating long-term recovery processes in these sensitive environments. However, uncertainty remains as to which techniques are effective in different circumstances, such as in different climates or across different soil properties, and which techniques may best avoid unintended consequences, such as facilitating non-native plants. To reduce fugitive dust as a human health hazard, increase soil stability, and enhance wildlife habitat, further work is necessary to develop restoration techniques for disturbed desert landscapes. The aims of this thesis were to examine the impacts of severe disturbances on soils of the Mojave and Sonoran Deserts and to investigate the efficacy of target restoration techniques within these ecoregions. Studies were conducted in the field, laboratory, and greenhouse to determine how anthropogenic disturbances impact soil characteristics and test the effectiveness of the three implemented restoration techniques.

The target restoration techniques chosen for this study span varying levels of effort and financial cost to better understand how effective minimal-input restoration strategies are in contrast to costlier, more intensive strategies. The minimal-input techniques examined here included vertical mulch (placing dead branches upright in the soil to simulate the appearance of

dead shrubs), soil surface manipulations (such as surface de-compaction and contouring the soil to create water catchments), outplanting, and seeding with litter. My research analyzes the effectiveness of vertical mulch treatments, surface de-compaction, and seeding with litter in the Dead Mountains Wilderness Area located 18 km northwest of Needles, CA in the Mojave Desert. I analyzed the influence of vertical mulch, water catchments, and outplanting in four distinct study sites south of Joshua Tree National Park along the Devers Palo II Transmission Corridor from Indio, CA to Blythe, CA. I conducted laboratory analyses of soil conditions at each of the sites. Before establishing restoration treatments in both regions, soil conditions were characterized by a lack of natural recovery of native perennial vegetation, and lower vegetation cover in disturbed sites in comparison to undisturbed sites.

Among the treatments at the Dead Mountains site, vertical mulch yielded the highest plant cover, soil moisture, soil stability, and lowest compaction in the Dead Mountains sites. During the wetter year of the survey, the surface de-compaction treatment had similar, less apparent results, indicating that surface de-compaction may be an alternative to vertical mulch if managers do not require vertical mulch structures to prevent public use of disturbed areas. These trends were not mirrored in the Devers Palo II Transmission Line sites, which had highly variable data, potentially due to the soil characteristics of each of the four sites. Each site had distinct bulk density, soil texture, pH, electrical conductivity, and C/N ratios that may have caused variability in the soil and plant responses to restoration treatments. The sites with the highest clay, silt, and organic matter had the highest plant cover and soil moisture whereas the site with the most mobile, well-drained soils had the lowest. Soil accumulation was highest in the vertical mulch treatments among all sites. Outplanting was largely unsuccessful due to the seedlings dying within four months of planting but may have had legacy effects, such as de-compacting the soil, inputting nutrients, and forming vertical mulch. These findings suggest that soil conditions may have been a stronger driver of soil and vegetation variation than restoration treatments.

The collected data suggest that the effects of vertical mulch surpass visual effects to include ecological ones. Vertical mulch and, to a lesser degree, soil de-compaction are a viable restoration treatments to reduce soil erosion and increase plant cover. However, the degree of restoration success depends upon soil conditions, indicating that a contextual understanding of study sites is necessary for overall success. This thesis can help inform restoration activities within arid lands, which are increasingly threatened by human-induced disturbances.

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DEDICATION

For Matt and Drake.

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CHAPTER 1
INTRODUCTION

Purpose of Study

In the Mojave and Sonoran Deserts of the southwestern United States, human disturbances are causing escalating, expanding degradation of arid landscapes. Off-road vehicle use, mining, extensive solar energy developments, and the construction of linear corridors, such as roadways and transmission lines, remove vegetation and topsoil and disturb biological soil communities. Land degradation associated with such land uses may reduce the ability of the ecosystem to provide ecosystem services and may be difficult or impossible to restore (Millennium Ecosystem Assessment, 2005). While natural vegetative recovery of total plant cover can occur within 50 years (Webb et al., 1987, 1988), natural recovery of species composition may take millennia (Web & Thomas, 2003). Confounding factors—including soil compaction retarding the establishment of perennial plants (Adams et al., 1982; Webb et al., 1988), increased fugitive dust ablating and burying native vegetation (Okin, et al. 2001), lowered infiltration rates in soils stripped of organic crusts and litter (Webb & Wilshire, 1983), and the lack of rainfall that typifies desert ecosystems—slow natural recovery in disturbed desert landscapes. Restoration practices can aid in initiating recovery of degraded desert ecosystems.

In many instances, the goal of restoration is not to restore an ecosystem for the sake of the ecosystem. Oftentimes, the over-arching goal of restoration is to protect off-site human populations from the adverse impacts of disturbance. One such goal from the Mojave and Sonoran Deserts is to reduce the incidence of airborne dust. Short-term exposure to dust particles negatively impacts human cardiovascular health and may have long-lasting respiratory health effects (U.S. EPA, 2009). Furthermore, Crooks et al. (2016) found that increases in non-accidental mortality are associated with dust storms in the states of Utah, Nevada, New Mexico, California, and Arizona. Stabilizing disturbed desert soils may eliminate sources of airborne dust (Pointing & Belnap, 2014). This is but one example of how restoration is applied to the benefit of adjacent human populations.

As evidenced by a lack of natural recovery in desert ecosystems and the adverse impact that disturbance has on human populations, restoration efforts are critical to salvage disturbed desert ecosystems. However, many restoration techniques, such as large-scale revegetation, are prohibitively expensive. An additional factor limiting the practice of some restoration techniques in desert ecosystems includes the amount of effort required for their success. Therefore, the development of minimal-input restoration techniques is necessary to effectively restore desert ecosystems. The objective of this research was to evaluate the success of minimal-input soil restoration techniques in restoring soil and vegetation function across diverse disturbances in the Mojave and Sonoran Deserts. This study also retroactively measured how mechanical manipulations of the soil (e.g., top soil removal, compaction fire, and pitting) affect soil properties to better inform restoration practices.

Opportunity for Research

The study areas addressed in this thesis are the Dead Mountains Wilderness Area (Mojave Desert) and the Devers Palo II Transmission Corridor between Blythe and Indio, California (Sonoran Desert). These sites span a biogeographic gradient from the Mojave and Sonoran Deserts that vary in climate, soils, and plant communities. Disturbances within these sites have included the construction of infrastructure such as roads and transmission lines, off-highway vehicular use, and recreational activities. The Dead Mountains Wilderness Area and Devers Palo II Transmission Line are characterized by a lack of natural recovery and disturbances have translated to soil compaction and a loss of soil stability, underscoring the need for soil restoration. Understanding the best techniques to restore the soils in these study sites is the goal of this research project. These study areas provide diverse settings for testing candidate restoration techniques on public lands.

Existing literature on ecological restoration techniques for the Mojave and Sonoran Desert landscapes are abundant and focus on techniques such as revegetation, biotic inoculations (surficial microbial communities also known as biological soil crusts or “biocrusts”), and emplacing abiotic materials (Abella & Smith, 2013; Bainbridge et al., 2009; Bashan et al., 2012; Belnap et al., 2001; Bowker, 2007; Elvidge & Iverson, 1983). However, soil restoration within this setting has been less studied, hindering the development of reliable soil restoration techniques especially in diverse landscape settings varying in soil conditions and climate. After an extensive literature search, few published papers were found that focus on soil restoration in North American deserts and little literature globally in drylands.

The objectives of this research were to test key soil restoration techniques in disturbed regions of the Mojave and Sonoran Deserts. These restoration techniques were vertical mulch, soil surface manipulations, and revegetation in the form of outplanting. Vertical mulch, a restoration technique that simulates the above-ground appearance of native shrubs, may aid restoring soil functions and plant recruitment processes, while being low-cost (Abella & Chiquoine, 2019). While vertical mulch is used broadly by land managers and non-profit organizations to curtail the recreational use of sensitive locations, few studies have examined the efficacy of vertical mulch as a restoration treatment. Soil surface manipulations have been used by human populations since the dawn of civilization in the form of altering surface hydrology for irrigation purposes (Butzer, 1976). Soil manipulations alter fundamental properties of soil, such as the distribution of particle size, nutrient content, and porosity (Wilkinson et al., 2009). For the purpose of this study, the soil surface manipulation techniques were (1) mounding the soil surface for increased organic material and water accumulation and (2) roughening the soil surface to lessen compaction and improve water availability for annual plants. Lastly, this study investigated the efficacy of outplanting in relation to the aforementioned techniques. In outplanting, plants are grown in the greenhouse and transplanted to disturbed sites. Outplanting is one of the major desert restoration techniques used to restore degraded soils.

Thesis Objectives

Understanding how best to restore disturbed desert soils is essential to reducing the incidence of airborne dust hazardous to human health, enhancing soil stability in drylands, and rehabilitating soils to provide vital ecosystem services to desert ecosystems. This research will evaluate the applicability of and extent to which key restoration techniques aid in restoring desert soils disturbed by compaction as well as top soil and vegetation removal. It will also address the impact of different disturbance types on soil physiochemical properties. Through field, laboratory, and greenhouse experiments, this thesis aimed to ameliorate the broad, disadvantageous impacts of disturbances within study sites of the Mojave and Sonoran Deserts. The following research questions drove the design and analysis of the study:

1. How effective are minimal-input restoration treatments in improving soil and vegetation function compared to more intensive treatments?
2. How do existing site conditions impact the relevance and success of restoration techniques?
3. Does vertical mulch provide ecological benefits to disturbed landscapes in addition to visual benefits?

Chapter 2 is a literature review identifying the effect of disturbance on soil properties of the Mojave and Sonoran Deserts as well as effective restoration techniques. Chapter 3 assesses vertical mulch and translocating O horizon material as a restoration technique in the Mojave Desert while Chapter 4 investigates restoration techniques of varying intensity across a gradient of study sites in the Sonoran Desert. Chapter 5 concludes the thesis and provides a summary as well as opportunity for future research.

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CHAPTER 2
LITERATURE REVIEW

Abstract

Drylands are simultaneously home to 33% of the human population and highly susceptible to human-induced disturbances. The Mojave and Sonoran Deserts have been deleteriously impacted by the construction of roads and utility corridors, urbanization, military use, agriculture and grazing, off-highway vehicle use, fire, climate change, and the introduction of invasive plants. Due to limited resources and harsh climatic factors, deserts are poorly suited to recovering from disturbance. Disturbances often result in loss of soil stability, reduction of soil fauna, imbalanced element ratios within the soil, poor organic matter content, soil compaction, altered hydrology, and vegetation loss. As a result, ecosystems of the Mojave and Sonoran deserts are subject to widespread, expanding degradation and increased rates of erosion. It is preferable on both temporal and fiscal scales to avoid and/or limit the extent of human-induced disturbance in the Mojave and Sonoran Desert. In many cases, such as with military exercises or off highway use, disturbance is difficult to prevent. Considering that these ecosystems are marked by slow natural recovery that may take decades to centuries, it is vital for humans to assist in recovery to expedite these processes. Restoration activities achieve the goal of initiating long term recovery processes in disturbed desert ecosystems. However, restoration in the Mojave and Sonoran Deserts also poses a problem. Typical restoration practices, such as outplanting, are costly and require much manual labor. Others, such as seeding, are likely to fail in deserts, which do not provide the same weather inputs as more temperate regions do. In response to the need for cost-effective, minimal-input restoration techniques, techniques such as vertical mulching have been developed in sensitive, arid landscapes.

Introduction

Deserts and the organisms that typify them are adapted to climatic and geographic extremes. The desert landscape consists of a wide range of adaptations, such as the pubescent leaves of brittlebush (*Encelia farinosa*) resisting UV radiation and water loss (Ehleringer et al. 1976). Biotic and abiotic components of the desert are resilient to factors that would negate the possibility of life in other ecoregions, such as extreme high temperatures, little to no reprieve from solar radiation, xerophytic and phreatophytic vegetation due to limited moisture availability, and high levels of herbivory by animals and invertebrates (Bainbridge 2001; Lovich & Bainbridge 1999; Bainbridge & Virginia 1990). While resilient to these limiting factors, deserts are fragile and are sensitive to human-induced disturbance (Belnap 2001).

Many soils of the Mojave and Sonoran deserts lack well-developed horizons and have thin A or V horizons sensitive to disturbance (McAuliffe 1994). Once disturbed, these soils may emit fugitive dust, have lowered plant productivity, and often lack diagnostic features of natural desert soils such as surface layers of biotic crusts and spatial patterning of islands of fertility, or the concentration of nutrient-enriched soils below shrubs (Bolling & Walker 2002). These disturbances may lead to negative impacts on human health, lessened resiliency to climate change, further susceptibility to disturbance and erosion, and loss of ecosystem services.

Drylands compose of 47% of the Earth's terrestrial surface and are a sink for 15% of the planet's soil organic carbon pool, which is declining rapidly with further disturbance and desertification (Lal 2004). Due to limiting factors typical of desert ecosystems, deserts recover from disturbance on the time scale of decades to centuries with complete ecosystem renewal occurring over thousands of years (Belnap 1995; Cortina et al. 2011). Restoration efforts may accelerate recovery of deserts and assist in preventing further erosion/disturbance. Information on the topic of desert restoration and rehabilitation is limited as it is a comparatively emergent field. Many restoration techniques that are successful in more temperate regions, such as large-scale revegetation, are less feasible in desert ecosystems. An additional factor limiting the practice of some restoration techniques in desert ecosystems includes the amount of effort required for their success. Cost-effective, minimal-input restoration techniques have been researched to determine best practices in desert landscapes. More research on this topic is necessary.

Human-induced disturbance in North American deserts has been extensively documented by government agencies and academic researchers. In this review, I summarize disturbance types and effects in the Mojave and Sonoran deserts. In addition, I consider methods of promoting the restoration of disturbed soil, including revegetation, nutrient amendments, abiotic amendments, and biotic inoculation.

Discussion

Impacts of human-induced disturbances in the Mojave and Sonoran Deserts

The history of human activities has been etched into North American deserts since Euro-American settlement. The Mojave and Sonoran Deserts have been bisected by linear disturbances through the construction of pipelines, roads, and transmission corridors. In World War II, these deserts were used for military operations including training exercises (Belnap & Patton 2002). European settlers introduced intensive grazing and agricultural practices to the arid landscape (Curtin et al. 2002). The Mojave and Sonoran Deserts have increased in impervious surfaces in large cities and through the construction and quick abandonment thereafter of towns during historical mining booms (Brown 2000). Invasive plants may increase in abundance in these desert ecosystems (Hunter 1991), as well as the potentially profound but poorly understood influences of contemporary climate change. Human-induced disturbance within North American deserts has been documented by numerous studies of past and present events.

Desert ecosystems deteriorate after human-induced disturbances have occurred. This deterioration can cause—and be amplified by—reduced soil fauna contribution to nutrient cycles, imbalance of element ratios, poor organic matter content, soil compaction, and water deficiency. Disturbances impact the landscape in different ways. The following sections overview these disturbances and their resultant effects on the environment.

Off-Highway Vehicles

Off-highway vehicles (OHV) have a multitude of far-reaching impacts on the environment. One of the predominate impacts of vehicles is soil compaction (Soane & Ouwerkerk 1998; Lei 2004; Nortje et al. 2012). Soil compaction is defined as: ‘‘the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density’’ (Soil Science Society of America 1996). The extent of compacted soil is estimated worldwide at 68 million hectares of land from vehicular traffic alone (Flowers and Lal 1998). Soil compaction may make soils more susceptible to erosion, increase loss of soil communities, and lower infiltration rates (Horn & Fleige 2009). Compaction decreases desert soil porosity (i.e. increases bulk density) and limits the transport of water. In turn, this lessens soil water availability to plants and causes increased run-off, leading to erosion in increasing severity (Webb et al. 1978; Webb 1982; Wilshire 1983). Severe soil compaction may prevent roots from penetrating through compacted soil layers, making them shorter and—in some cases—thicker (Nortje et al. 2012). Due to these changes in plant root physiology, plants may have poorer nutrient uptake rates (Bennie & Laker 1975). Soil macrofauna populations, such as earthworms, may also decrease with increased compaction rates in in semi-arid environments (Radford et al. 2001). Within the Mojave and Sonoran Deserts, continued OHV use of desert soils increases the compressional strength of soils and decreases soil permeability (Lovich and Bainbridge 1999). Desert soils are slow to recover after compaction has taken place because of decreased vegetation and low water availability.

Depending on soil type, consistent OHV use in arid landscapes may destroy key desert soil stabilizers. OHVs decimate soil biocrust, dislodge the rock fragments associated with desert pavement which exposes the vesicular horizons to erosion (especially eolian) (Wilshire 1988). Often erosion removes unconsolidated soil horizons, exposing the bare petrocalcic horizon to the surface. These actions remove and impede the growth of vascular plants, which cannot take root in this environment (Webb 1982). Belnap (2003) posited that biological soil crust communities covered nearly 70% of dryland landscapes. Biocrust communities stabilize soil, aid in the retention and accumulation of fine soil materials, and fix nitrogen in plant interspaces (Lange et al. 1992; Belnap 1996; Evans and Ehleringer 1993). The destruction of biological soil crusts by OHV use represents a major loss to desert ecosystems on many levels. Pointing and Belnap (2014) outline a multitude of ways in which the destruction of biological soil crusts and increase in airborne dust particulates results in desertification, biodiversity loss, and lowered evapotranspiration rates. The removal of rock fragments from the soil surface also has long-term impacts as these rocks typically enhance infiltration and soil moisture retention (Belnap and Gardner 1993). Contrarily, vesicular horizons associated with desert pavement lower infiltration rates and increase run-off to regions where shrubs grow downslope (Wood et al. 2005). The destruction of desert pavement and associated V horizons may therefore divert water flow and de-couple shrubs from their water source. Undisturbed soils in desert ecosystems are vital to limiting the incidence of airborne dust, debris flow run off, and in controlling water infiltration

(Iverson et al. 1981). When soil stabilizers are removed from the soil, rates of erosion and die-off may increase within the Mojave and Sonoran Deserts.

Agriculture and Grazing

Prior to the last two centuries, the Mojave and Sonoran Deserts were not extensively used for agriculture and grazing. In the late 1800s to early 1900s, these practices reached unsustainable levels (Archer 1994; Miller et al. 1994; Bahre 1995). For millennia, Southwestern United States Deserts (with the exception of the Chihuahuan Desert) evolved without grazing (Mack & Thompson 1982). Deserts are poorly adapted to the disturbances associated with grazing and agricultural practices, especially when grazing and agriculture are practiced unsustainably. Over-grazing combined with climatic factors, such as drought, cause lowered plant productivity and threaten plant growth (Stoddard 1946). These practices lower plant productivity and impede growth. Both of these impacts have long-lasting effects on the environment. For instance, Brooks (1995) found that previously grazed areas had a higher incidence of invasive plants in comparison to areas that had not been grazed. Lowered native plant cover and richness may ultimately result in poor habitat forage for native animals of the Mojave and Sonoran Deserts, such as the desert tortoise (*Gopherus agassizi*) (Brooks et al. 2006; Keith et al 2008).

Grazing also influences soil physiochemical properties and microbial communities. Heavy grazing may compact soils and remove surficial material/soil stabilizers (including desert pavement, algal crusts, lichens, fungi, and mechanical crusts as discussed in the OHV section) (Schlesinger et al. 1990). McGarry (2001) classified soil compaction as the most severe problem associated with agriculture. Within Mojave and Sonoran Deserts specifically, Lovich and Bainbridge (1999) found that regions with grazing had higher rates of soil compaction as compared to ungrazed areas. The loss of porosity within the soil alters infiltration rates and lowers the water available to plants in the soil. Therefore, soil compaction may impede plant establishment and growth. Disturbances originating from animal hooves remove soil crust and prevent soil communities from recolonizing (Pointing & Belnap 2014). In instances where biological soil crusts recovered from trampling, the biomass was still low (Petraisiak et al. 2011). Soil crusts are an integral component to maintaining soil stability and capturing airborne dust. These forms of disturbance also alter the hydrology of a region by promoting run off and erosional processes (Caldwell et al. 2006). The loss of natural hydrological regimes indicates that natural recovery of areas disturbed by agriculture and grazing is unlikely within the decadal or even century time scale relevant to near-term desert management and conservation.

Military

Military exercises negatively impact dryland ecosystems in a variety of ways. World War II training operations in the Mojave Desert represent a unique opportunity to review the long-standing influences of military exercises in arid landscapes (Prose & Metzger 1985). These operations typically included foot traffic, vehicular traffic, and tent living quarters (Kade & Warren 2002). The aforementioned activities may compact soil, denude the soil surface of vegetation and soil crusts, and increase erosion. The impacts of U.S. military exercises offer the unique opportunity to measure these impacts in the Mojave and Sonoran Deserts over time. In the 1940s, military training camps were erected in the Mojave Desert. After 54 years, the streams in one such camp had still not recovered due to roads, the disturbance of surficial rock fragments, soil compaction, and soil smoothing (Nichols & Bierman 2001). Similar training exercises in WWII occurred in the Sonoran Desert. In Camp Laguna of southwestern Arizona, vegetative recovery was low to absent and soils were compacted (Kade & Warren 2002). Van Donk et al.

(2003) posit that disturbances, such as the aforementioned case studies, leave desert ecosystems prone to wind erosion. Sediment discharge was comparatively higher at sites disturbed by military exercises in WWII than at undisturbed sites (van Donk et al. 2003). These sites provide researchers with the chance to investigate how desert landscapes respond on biologic and geomorphic levels to past military disturbance. The consensus appears to be an overall lack of recovery with higher rates of erosion.

Roads and Utility Corridors

In the states of Arizona, Nevada, and California (where the Mojave and Sonoran Deserts are primarily located within the United States), highways, high-voltage transmission lines, and pipelines account for a combined 45,131,590 hectares of the land (Federal Highway Administration 2010; Western Area Power Administration 2016; Pipeline Safety Stakeholder Communications 2011). This accounts for 4.9% of the total area of the contiguous United States. The construction of roads and utility corridors is highly destructive to natural ecosystems of the Mojave and Sonoran Deserts. In order to create roads, topsoil and vegetation must effectively be cleared from the landscape. This land is then replaced with an impermeable surface or severely compacted to the point of near impermeability in the instance of unpaved roads. For utility corridors, not only must the land be destroyed, but it may also be trenched for pipelines or the installation of power lines. Utility corridors have the additional, associated disturbance of access road establishment. Staging areas for the heavy equipment required for these activities and the movement of the equipment is also destructive to the landscape. There may also be long term exposure effects of electromagnetic radiation. Vian et al. (2016) found that high frequency electromagnetic radiation may elicit a stress response in adjacent plant communities. Other studies show that electromagnetic fields may impact plant development, such as oxidative damage to the roots of onions (*Allium cepa*) due to altered oxidative metabolisms (Chandel et al. 2017) and thinner cell walls, smaller chloroplasts, and mitochondria in aromatic plants (Soran et al. 2014).

The Mojave and Sonoran Deserts are susceptible to increased habitat fragmentation due to the construction of linear corridors. Linear corridors require the removal of plant populations, surround existing populations with impermeable surfaces or fully denuded ones, and may limit plant-pollinator interactions. Schlesinger and Jones (1984) implicitly recognized the importance of connectivity in desert ecosystems. Linear corridors (in the form of roads, utility corridors, or OHV trails that are often found adjacent to them) impede the distribution of resources across desert landscapes. They inhibit water transport across landscapes, often diverting it away from down-slope plant populations (Rowlands 1980). Fragmentation may also obstruct plant-pollinator relationships. Rathcke and Jules (1993) found that fragmentation resulted in a decline in pollinator abundance and diversity. As habitat is lost to fragmentation, so too are the animals that rely on those habitats. In the Sonoran Desert, the Baja California brush lizard (*Urosaurus nigricaudus*) went locally extinct due to their habitat growing increasingly fragmented (Munguia-Vega et al. 2013). With continued habitat loss, it is likely that the lizard will go extinct. Many animals of the Mojave and Sonoran Deserts face the same plight as the Baja California brush lizard as fragmentation impedes them from accessing vegetation, shade, and water.

Linear corridors may act as conduits for invasive species, lowering biodiversity in desert ecosystems. In a region of the Mojave Desert disturbed by an aqueduct pipeline, natural recovery of plants was higher with distance from disturbance and was nearly absent at the heart of the disturbance site (Berry et al. 2015). The disturbance from the linear corridor left the site vulnerable to invasive plants, which comprised 64-91% of the study site's plant biomass at the time of monitoring (Berry et al. 2005). Vasek et al. (1975) also recorded reduced native plant cover and increased invasive plant cover along roads and utility corridors of the Mojave Desert after 12 years. The invasibility of these regions is likely a result of the destruction of the above ground material, removal of top oil, and reduction of the seed bank.

Climate Change

Changing weather conditions due to climate change may represent a threat to desert ecosystems. With regards to the Mojave and Sonoran Deserts, climate change can cause lessened carbon sequestration productivity in deserts and transform inert carbon to atmospherically active carbon (Verburg et al. 2013). Deserts sequester carbon. Pedogenic carbonate, soil organic matter, and plant biomass remove carbon from the carbon cycle (Schlesinger et al. 2008; Schlesinger 1984). Climate change may alter precipitation patterns and lessen the ability of deserts to continue acting as carbon sinks. In the Mojave and Sonoran Deserts, vegetation and soil moisture are controlled by "pulses" of precipitation. Precipitation events are likely to increase in variability in coming decades (Fischer et al. 2013; Räisänen 2002). Plants of the Mojave Desert, well-adapted to current precipitation regimes, may not be able to survive with increasingly sporadic and irregular rain events. An overall lessened incidence of water input could likewise decrease soil functionality. Soil functionality, which includes the accumulation of fine particulates, is vital to other processes, such as soil respiration. Cable et al. (2008) found that soil respiration was higher on fine-textured soil as compared to coarse-textured soil and on vegetated versus bare soil. Biological soil crusts may also be significantly impacted by climate change. Increased, erratic summer precipitation patterns cause a lessened incidence of diversity and survival within biological soil crust communities (Barker et al., 2005; Ustin et al. 2009). As biological soil crusts are one of the predominant organisms responsible for stabilizing desert surfaces, the loss of these communities may result in feedback loops. Climate change may exacerbate many feedback loops similarly, posing a large challenge to land managers moving forward.

Invasive Plants

Due to the breadth of interactions between invasive plants and the ecosystems they invade, invasive plants are classified as one of the primary threats to native ecosystems, second only to habitat destruction (The Nature Conservancy 1996). In the United States, invasive plants—and threats related to invasive plants—have caused nearly half of all federally threatened or endangered plants to have been listed (Brooks & Pyke 2002). Introduced advertently and inadvertently through ranchers seeking to increase forage, soil stabilization, and as ornamentals, invasive plants are often capable of outcompeting native vegetation. The high reproductive potential and competitiveness of invasive plants as compared to native desert plants lowers biodiversity by outcompeting native vegetation, altering fire regimes, and changing surface hydrology within southwestern desert ecosystems.

In the Mojave and Sonoran Deserts, invasive grasses such as *Bromus rubens* (red brome) and *Schismus arabicus* (Arabian Mediterranean grass) exemplify how invasive plants alter the fire regime of desert ecosystems. *B. rubens* and *S. arabicus* grow densely across the typically mosaic scrubland landscape of the Mojave Desert (Brooks 1999; Brooks & Esque 2002; Brooks 2009; Abella et al 2009) . The grasses sprout early in the spring, grow quickly, and then die and dry out. The Mojave and Sonoran Deserts have sparse vegetation that is widely spaced which inhibits the spread and severity of fire. Dense monocultures of dried grasses act as a fuel for fire in desert landscapes. The altered fire regime associated with invasive grasses may force desert scrublands to becomegrasslands. While *B. rubens* and *S. arabicus* are prolific examples of how invasive plants alter natural ecosystems, issues related to invasive plants and changing fire regimes are common.

In addition to altering fire regimes, invasive plants also alter surface hydrology in the Mojave and Sonoran Deserts, where water is already a limited resource. The introduction of *Tamarix spp* (salt cedar) to riparian areas and washes of the Mojave and Sonoran Deserts resulted in a wide dispersal of *Tamarix* spp and in *Tamarix* spp outcompeting native vegetation. Within Arizona, Nevada, Southern California, Southern Utah, Southwestern Colorado, and Western New Mexico, it is estimated that nearly 21% of the streams they assessed had *Tamarix* spp present (Ringold et al. 2008). Research suggests that *Tamarix* spp groves may alter the structure and flow dynamics of streams by trapping and stabilizing sediments (Ringold et al. 2008). Trapping sediments increases overbank flooding and may create permanent sandbars in rivers. Sandbars, which reduce stream flow velocity, are often encouraged in heavily-channelized streams. In streams of the Mojave and Sonoran Desert, which often have more sediment than flow, additional sediment may decrease flow rate and the amount of water that reaches plants downstream. Less water may equate to less riparian vegetation and habitat.

When considering the aforementioned case studies, it is important to note that invasive plants frequently have multiple, compounding influences on the landscape. For instance, while altering surface hydrology was discussed in conjunction with *Tamarix* spp., this invasive plant also produces high levels of foliage that act as fuels for fire, aggressively outcompetes native riparian vegetation due to high reproductive potential, and alters soil salinity. The presence of invasive plants regularly amplify other forms of disturbance. Lastly, invasive plants may be promoted by increasing CO_2 levels in desert ecosystems during certain years in which water is less limiting (Smith et al. 2000, 2014). Enhanced CO_2 levels as a result of climate change may lend an even greater advantage to non-native invasive plants in outcompeting native vegetation. This may lead to further habitat degradation, less native biodiversity, and increased vegetative fuels for fire.

Fire

The Mojave and Sonoran Deserts are considered to be poorly adapted to fire. Due to a paucity of vegetation and relatively large distances between vegetation elements, deserts lack the requisite fuels for frequent fires. Within the last century, invasive plant cover and human encroachment have expanded in these deserts. As a result, the incidence and severity of fires have increased in deserts of the southwestern United States. Fire may lead to loss of plant material, reduction in canopy cover for the establishment of fertile islands, lessened soil stability, and a higher prevalence of invasive species cover (Abella et al. 2010; DeFalco et al. 2010; Lovich & Bainbridge 1999). These impacts may lead to further disturbance within the soil and plant community and positive feedback loops.

Fire may be interrelated with a higher incidence of invasive plants. Invasive plants are typically ruderal and highly competitive. In other words, they are well adapted to colonizing post-fire landscapes, which are commonly denuded. In comparison, native vegetation typically requires nurse plants for successful establishment (DeFalco 2010). Therefore, post-fire landscapes may become dominated by invasive plants. In the instances of the most ubiquitous plants in the Mojave Desert, *Schismus* spp and *Bromus rubens*, the landscape is densely covered by a monoculture of dry plant biomass by the height of fire season. In turn, these landscapes are more susceptible to future fires.

Increased fire frequency and severity may also deleteriously influence desert soils. In one study, fire was found to increase soil pH (Certini 2005). Another study found that soil pH of the Mojave Desert remained unchanged following fire (Abella & Engel 2013). Knoepp and Swank (1993) recorded increased N mineralization and the oxidation of organic soil nitrogen after exposure to elevated temperatures. However, the literature on this topic continues to be contradictory in that it indicates variable responses of desert soil C and total N in response to fire (Allen et al. 2011). Amongst burned and unburned regions, N, K, and S were more abundant under canopies than open spaces (Mudrak et al. 2014). However, these nutrients are depleted with time underneath burned shrubs. Increased nutrients in the soil post-fire may aid in invasive plant establishment. Beginning in the early 1980s, increased fire frequency has been correlated with grass-fire cycles (Brooks 2007). This is a pressing issue in deserts. The Mojave and Sonoran Deserts have mosaic soils related to what is termed “the fertile island effect,” where nutrients concentrate around shrubs. If the shrub landscape is converted to a grassland, nutrients in the soil may be homogenized (Soulard et al. 2013).

Fires caused by human activity and amplified by increased fuels in the form of invasive plants tend to have negative impacts on ecosystems due to disturbances related to fire. In particular, soil texture is consistently altered as a result of fire due to increased erosion and loss of structural support (Neary et al. 2005). Soil structural changes are not easily remedied. DeFalco et al. (2010) reports lessened compaction and higher infiltration (both resulting from structural changes) in surface soils due to erosional processes. Soils at a greater depth were still heavily compacted and exhibited low infiltration rates with little improvement, even decades later (DeFalco et al. 2010). Therefore, fire regimes may alter desert landscapes on a millennia scale.

The long-lasting impacts of altered fire regimes are compelling evidence for the need for restoration.

Impacts of human-induced disturbances on human populations

Nearly 40% of the human population lives in drylands, which are susceptible to degradation and recover slowly (Millennium Ecosystem Assessment 2005). The introduction of large human populations to the Mojave and Sonoran Deserts is one of stark contrasts. For instance, agricultural and ranching practices in the southwest (forever immortalized by the symbol of the cowboy) are both threatened by and cause desertification (Pointing and Belnap 2014). Off-road vehicular use is a common recreational activity in the Mojave and Sonoran Deserts, resulting in increased dust emissions, sometimes containing heavy metals harmful to human health, such as arsenic (Goossens et al. 2015). Human-induced disturbances cause a broad range of detrimental impacts outside of the ecological ones previously explored, including high economic costs and negative influences on human health.

The loss of desert ecosystems due to human-induced disturbance may represent a large economic loss. While the monetary valuation of ecosystem services is often subject to debate, it is generally acknowledged that all economic products are derived from natural materials or are the product of natural processes. Healthy ecosystems are essential to maintain our current standard of living and are not readily replaced by technology (Daily et al. 1997). The role of healthy ecosystems in the continued well-being of human populations is especially germane in arid lands, which are landscapes partially defined by limited resources.

The economic benefits of healthy ecosystems are difficult to quantify but provide compelling evidence for conserving and restoring these ecosystems. Functional dryland ecosystems provide suitable substrates for crop production, erosion control, remediation of heavy metals and other pollutants via soil microbial communities, and water provisioning (Millennium Ecosystem Assessment 2005). These ecosystem services would be extremely costly for humans to replicate. Some researchers attempt to estimate the beneficial cost of these services. Taylor et al. (2017) estimated that the Big Bend region of the Chihuahuan Desert provided over $1.6 billion annually in ecosystem services such as water remediation, which was markedly lower than adjacent areas. Analyses such as these are beneficial for both the better understanding the financial necessity of conserving, and also for restoring arid lands and analyzing the negative financial impacts that disturbances may have on the human populations that rely on these lands.

Natural areas are extraordinarily valuable to the tourism industry. Millions of tourists visit the Mojave and Sonoran Deserts on an annual basis. Le et al. (2004) found that, in 2003, visitors to Joshua Tree National Park (JOTR) typically spent $77 per person per day in and around the national park. There were over 1.2 million visitors to JOTR alone in 2003, indicating that over $98.8 million was spent in one park and its surrounding areas (Le et al. 2004). The conservation and maintenance of JOTR may be vital to sustaining the economy of towns adjacent to the park that rely on tourism. According to the National Park Service's Integrated Resource Management Application, JOTR was only the 55th most visited national park in 2003, with other desert national parks, such as Lake Mead National Recreation Area in the Mojave Desert, visited 500% more (IRMA NPS 2018). This suggests that there are likely many locations across the desert that rely on natural, undisturbed landscapes for economic benefit. Additionally, the number of tourists in eco-tourism may be increasing. From 2003 to 2017, the number of park visitors to JOTR has more than doubled (IRMA NPS 2018). Statistics such as these emphasize the economic benefit of conserving and restoring natural spaces in order to continue promoting eco-tourism. This information also provides a compelling argument to conserve more natural landscapes by designating more wilderness areas. Loomis and Richardson (2001) posited that the U.S. wilderness system generated $634 million of consumer surplus. These researchers observed that designating just one additional 4,000-ha wilderness area could yield an additional $436,000 of surplus (Loomis and Richardson 2001). By merely minimizing human activities in a given natural area, it is possible that the United States could see economic benefits of hundreds of thousands of dollars. This economic surplus does not take into account the supplementary benefits of designating wilderness areas, such as air quality or biodiversity preservation mentioned in the prior paragraph. Desert landscapes economically benefit human populations through multiple avenues.

The impact of fugitive dust from disturbed desert landscapes is especially germane to human health. According to Pointing & Belnap (2014), nearly all airborne dust is derived from deserts disturbed by human activities. Airborne particulate matter, such as the aforementioned fine dust particulates, may cause grave health problems for humans. For instance, approximately 1.7% of deaths by lung cancer and cardio-pulmonary disease is caused by continued exposure to airborne desert dust (Giannadaki et al. 2013). Another study by Cao et al. (2016) similarly noted associations among dust, respiratory disease, and cancer. These studies indicate that populations continually subjected to dust storms may be at an amplified risk of death and disease. The relationship between human health problems and dust storms may be further exacerbated by proximity to the dust storm sources. In the states of Arizona, California, Nevada, New Mexico, and Utah, vehicular mortality increase by 7% and cardio-vascular mortality increase by 4% during dust storms (Chen et al. 2016). These statistics indicate a combined 11% increase in deaths associated with airborne dust events in the states that span the Mojave, Sonoran, and Chihuahuan Deserts. In addition to increased mortality, populations routinely exposed to dust storms may contract diseases that lower their quality of life. Kanatani et al (2010) related higher incidences of asthma and asthma-related hospitalization in children to continued dust exposure. While not fatal, asthma can be a debilitating disease and is life-threatening without treatment. Even with treatment, those with asthma may face challenges navigating their daily lives when continually exposed to airborne dust. These statistics underscore the need for limiting activities that increase airborne dust in disturbed desert landscapes. Mitigating disturbed soils may also be a viable approach to preserving human life.

Adverse effects associated with dust exposure may be augmented by dust acting as a vector for toxic metals and bacteria. Increased airborne particulates are of extreme interest in regions where concentrations of harmful minerals are present. Harmful minerals in dust, such as amphibolite (an asbestos mineral), may be responsible for further incidences of cancer, lung damage, or poisoning in humans (DeWitt et al. 2017). The presence of damaging minerals in dust multiplies the risk to human life. Airborne dust may also act as a vector for biotic materials. Bacteria and fungi are correspondingly capable of dust transport. An increased incidence of airborne dust may simultaneously increase the threat of the infectious diseases spreading (Griffin 2007). It is important to stabilize soils so as to prevent them from transporting harmful materials from one population to the next. Conserving arid landscapes is significantly less costly than restoring them, but the cost of losing these landscapes to human-induced disturbance is the costliest option regarding human and economical welfare.

Soil Restoration Techniques in Desert Environments

The defining characteristics of desert landscapes, such as high temperatures, low water availability, and little reprieve from solar radiation, limit natural recovery in deserts. After severe disturbances have taken place, natural recovery will likely occur on a decadal to century scale and may not result in desired functional benefits that undisturbed desert ecosystems provide (Lovich & Bainbridge 1999; Belnap 2002). In these instances, restoration must be considered a necessary practice. Restoration efforts aid in counterbalancing the severity of disturbance in North American Deserts. However, the same factors that limit natural recovery also tend to limit restoration success. While existing literature conveys that ecological restoration enhances recovery rates in desert regions, not all restoration techniques are financially feasible. The remainder of this review explores restoration techniques previously implemented in desert ecosystems, with emphasis being placed on the cost-effectiveness and effort required of said techniques. Some investigation into how these techniques influence soil properties will also be conducted.

The primary methods of restoration in the Mojave, Sonoran, and Mojave-Sonoran transition zone deserts vary depending upon the fiscal resources available, extent of disturbance, geographic and climatic limitations, and type of disturbance. Regardless, the primary goals of soil restoration are generally to 1) stabilize the soil and 2) return functionality to the soil in order to provide ecosystem services to the landscape.

Abiotic Materials

One method to aid in stabilizing disturbed soils is to add abiotic materials, such as a straw checkerboard or rock cover. Abiotic materials have been implemented on a broad scale to great success with “checkerboards” 1 m^2 in area with straw of 10-20 cm in height in China (Guo et al. 2014). The checkerboards aided in fine dust accumulation and dune stability (Guo et al. 2014). The aboveground structure may trap airborne soil, acting as a seed source, and stabilizing the slope of the dune they were installed in. However, this technique may fragment the landscape. By creating a uniform array of aboveground structures, animals and seeds may be prevented from traveling or dispersing through them. More research may be necessary to determine if stabilizing the soil to prevent aerosolized dust outweighs this potential harm to the habitat.

Returning rock cover is another generally beneficial restoration technique. Rock cover requires little input after initial installment and utilizes on-site material. A study spanning the Mojave and Sonoran Deserts found that surface rock fragment cover reduced the probability of slope failure (Simanton et al. 1994). Rock fragments are an inexpensive option that generally uses material from donor sites. Re-introducing rock fragments into a degraded landscape has an additional benefit of not requiring ancillary efforts such as watering, as would revegetation. There is also precedent for re-introducing rock cover in regions reliant on prevalent surficial rock cover for hydrology prior to disturbance (Abrahams & Parsons 1990). In undisturbed desert landscapes, rock fragment cover lowers infiltration rates and diverts water downslope to patches of vegetation. Re-introducing rock fragment cover may aid in returning the landscape to a trajectory of recovery.

Vertical Mulch

Vertical mulching is placing dead and down woody plant material upright in the soil surface to simulate the appearance of defoliated shrubs (Bainbridge 1998). Oftentimes, this practice is used by land managers to dissuade public use of sensitive areas. It may also be implemented to act as a pseudo-fertile island by providing shade to plants, aiding in seed accumulation, and stabilizing soils. Recent research has revealed that vertical mulch may also have positive influences on annual plant abundance (Abella & Chiquoine 2019).

In Joshua Tree National Park, vertical mulch was successfully installed as a restoration technique to promote the recovery of annual plants in denuded road-side study sites (Abella & Chiquoine 2019). Vertical mulch was one of the treatments used to restore roadside sites disturbed by vehicles. While not as effective as outplanting, the vertical mulch treatment facilitated more native plant abundance than in interspaces (Abella & Chiquoine 2019). In this instance, vertical mulch is a viable, minimal-input approach to restoration. Unfortunately, the vertical mulch treatment also aided in the growth of non-native species (Abella & Chiquoine 2019). It may be possible to limit the vertical mulch's facilitation of non-native plants by applying herbicide early in the season to target *B. rubens* and *S. arabicus* or perhaps by mechanically removing the non-native species.

Vertical mulch may also aid in returning soil functionality to disturbed desert sites. Ghidey & Alberts (1997) indicate that dead roots have a positive impact on soil stability. Perhaps the belowground structure of the "planted" vertical mulch branches may correspondingly promote soil stability. Vertical mulch has also been used in the past with a goal of aerating the soil, lessening compaction, and inoculating the root zone of plants with mycorrhizae (Bainbridge et al. 1996). This technique has been found to increase soil moisture and lessen temperature, although it has not been investigated within the realm of the Mojave and Sonoran Deserts (Bristow 1988). Vertical mulch likely lowers soil temperature by providing shade cover. Soil moisture may be increased by de-compacting the soil to "plant" the vertical mulch's dead branches, allowing for water infiltration. Further work is necessary to fully determine the mechanisms by which vertical mulch improves these soil characteristics. In other cases, the restorative role of vertical mulch in the Mojave and Sonoran Deserts is clear. Mechanical manipulation in combination with vertical mulch both maximized vegetation establishment and reduced the rate of erosion in disturbed arid lands (Beggy 2016). This indicates that vertical mulch is a successful technique for future studies to address restoring soil and plant functionality in disturbed ecosystems.

Other mulches include wood chips or other abiotic materials, which may similarly benefit disturbed ecosystems. In a study involving restoring biological soil crusts, Chiquoine et al. (2016) found that the addition of wood chips likely stimulated the growth of soil crust communities. This methodology may have increased C content within the soil. In contrast, another study found that the addition of saw dust did little to aid in the restoration of a disturbed desert study site. Granted, this study was focused on vascular plants and found that saw dust did not impact the establishment of native over non-native vegetation (Corbin & D'Antonio 2004). The varied results of mulch amendments in these study sites illuminate the need to determine what the project's restoration goals are in order to delineate best practices to get there. Studies conducted by Evenari et al. (1982) emphasize the benefit of using a combination of different soil mulch amendments. It may be beneficial to incorporate multiple techniques to attain a series of goals within the site. This multi-faceted approach is made easier when using on-site or inexpensive materials as is customary for abiotic materials. Mulching treatments are beneficial from an economic standpoint as they generally use on-site materials and do not require multiple trips for watering or additional adjustments.

Soil Surface Manipulations

The addition of organic amendments, nutrient amendments, and soil contouring may improve soil stability and functionality in disturbed, desert soils (Bowker 2007). Soil organic amendments incorporated into disturbed soils aid in lowering bulk density and compaction while promoting higher water retention and N and P contents. In a sandy soil site denuded for nearly 30 years, the addition of sewage-sludge compost and manure greatly improved soil properties, ideally making the soil more beneficial to sustaining vegetation (Tester 1989). Organic amendments are commonly used in polluted or heavily degraded landscapes, such as quarries.

The addition of carbon may promote vegetation establishment. Other nutrient amendments focus on N, P, and K. Hobbs and Atkins (1988) found that nutrient addition significantly increased the incidence of native plants in disturbed communities and also increased plant establishment. In contrast, an earlier study found that the addition of N had no significance on the soil and that leaching likely did not occur in any treatment attempted (Westerman 1979). Therefore, further studies are necessary to constrain how nutrient amendments impact vegetation, especially in desert landscapes. Nutrient additions could benefit non-native plants as much as or more than native plants, as many non-native species thrive in nutrient-rich environments. Therefore, land managers should be cautious of incorporating nutrients such as N into a disturbed soil with non-native vegetation or the potential of being exposed to non-native vegetation. Other nutrient amendments, such as the addition of carbon, allow for soil microbes to fix nitrogen, potentially preventing nonnative plants from out-competing native vegetation (Blumenthal et al. 2003). C amendments may therefore benefit both soil communities and vascular plants. As this method could be achieved by simply incorporating sugar into the soil, it is both cost effective and low input. There is also potential for it to be broadcast from a helicopter as a sweeping restoration technique for non-native plant species.

Soil contouring has long been used by human populations to stabilize soils and influence surface hydrology. Contouring soil may also assist in de-compacting the soil. Liu et al. (2014) investigated factors that cause slope failure and erosion, discovering that rainfall intensity and ridge height are the primary contributors to ridge failure. Contouring soils, such as in the case of water catchments, may alter surface hydrology and promote preferential water and litter accumulation. As soil contouring simply utilizes soil of the study site, it is relatively inexpensive aside from establishing it.

Revegetation

Revegetation efforts are highly beneficial to degraded landscapes. Outplanting shrubs may initiate the process of the fertile island effect and facilitate annual plant cover (Abella & Chiquoine 2019; Grantz et al. 1998). Fertile islands are a characteristic feature of the desert wherein higher levels of soil moisture, soil nutrients, annual plants, and animal habitats are centered around shrubs (Bolling & Walker 2002). Promoting the establishment of fertile islands may initiate recovery on a landscape scale. Revegetation has also long been shown to prevent erosion by promoting soil stability (Burri et al. 2009). Outplanting increases soil aggregate stability and prevents shallow landslides via the structural support of the plant root systems. Additional benefits to disturbed desert landscapes may include increased seed input from successful outplantings (Abella et al. 2012). However, revegetation efforts in desert landscapes can be difficult. The lack of water availability and high UV insolation is prohibitive to plant establishment and growth. Around 50% survival in out-planting treatments is considered a success in desert ecosystems (Abella & Newton 2009). In addition, outplanting treatments often require protection from herbivory and supplemental watering, which increase costs and effort.

The source of the outplants can be an economic challenge for land managers. Plants used for restoration efforts may either be salvaged from soon-to-be-disturbed areas or grown in greenhouses. Unless they are transplanted immediately, the salvaged plants will need to be stored and watered in a nursery or greenhouse until they may be planted. For plants grown in greenhouses or nurseries, resources that the plant will use while growing, such as soil, water, and overhead costs associated with a greenhouse or nursery must also be taken into account.

In order to ensure the highest rate of survivability possible in outplants, land managers may employ certain tactics in tandem with planting. The age of the plant prior to planting can influence the success or failure of the restoration treatment. Bean et al. (2004) determined that greenhouse plants should be allowed to grow for a year at minimum for best. This duration may allow for optimum root growth, which is necessary for the survival of many plants in desert landscapes with scarce water. Another way to promote root growth is by using taller containers. Lighter colored containers may lower the temperature of the soil in a warm, desert greenhouse and may promote roots and root symbionts (Bainbridge et al. 1995). Encouraging the growth of root symbionts may encourage plant growth and survival. Research on one such symbiont, mycorrhizae, has shown that it increases surface area of the root and encourages carbon storage. Incorporating rocks and protective structures such as plant collars are additional ways in which the success of re-vegetation efforts may be improved (Bainbridge et al. 1995; Allen 1989).

With a relatively high success rate for facilitating annual plant growth and stabilizing soils, revegetation is an optimal restoration technique. However, the effort and money required for the success of this treatment may be prohibitive to some land managers. Growing and storing outplants is an initial, costly step. After establishing the plants, the plants will likely require repeat-watering. There are multiple options for this. One option is to install irrigation, which is very costly and requires maintenance. Another option is to water the plants using a volunteer force. While it may be cheaper to send volunteers to regularly water the outplants, this does take a lot of time and effort on the part of an unpaid work force. A final option is to use Driwater. Driwater is water held together in gel form by food grade ingredients (Newton 2001). Unfortunately, the company that produces it is now out of business. Some land managers may have Driwater stockpiled. For most, this option is eliminated. Therefore, the cost and effort required for successful revegetation efforts may outweigh the benefits of this treatment.

Seeding

Seeding is the practice of introducing seeds to a denuded area in the hopes of restoring native plant cover. Seeding has been a successful restoration technique in the Mojave (Abella et al. 2009) and Sonoran Deserts (Cox et al. 1984), but has also failed completely, especially in the warm and dry climate (Abella et al. 2012). Seeding may also be a beneficial restoration technique when used in conjunction with other treatments. For instance, seeding in conjunction with vertical mulch may restore annual plants to a disturbed desert location. In general, however, seeding treatments are less successful in desert ecosystems than other restoration techniques (Abella et al. 2012). This may be due to the reliance of seeds on precipitation events and low granivory, both of which are variable and difficult to prevent in desert ecosystems. Typical methods of seeding include hydro-seeding, creating seed balls, and broadcasting the seed by hand or, occasionally, by plane. Some techniques to aid in the success of this restoration treatment are to time seeding events with rain events and to use protective materials such as mulches, as discussed in previous sections (Brown et al. 1979). The protective materials may both protect the seed from granivores and assist in retaining moisture should precipitation events be few and far between (Jones et al. 2014). Should the timing be right, seeding may be a minimal-input restoration technique that may prove effective in optimal conditions.

Biological Soil Crusts

Biological soil crusts (biocrusts) are communities of fungi, lichens, cyanobacteria, mosses, and algae that compose about 70% of dryland soil surface (Belnap 2003). These soil communities fulfill various ecological and functional roles in desert ecosystems. Biocrusts, which inhabit only the upper several mm of the soil surface, promote soil stability (Pointing & Belnap 2012), sequester carbon (Maestre & Cortina 2003), fix nitrogen (Belnap 2002; Castillo-

Monroy et al. 2020), and have mixed influences on runoff and infiltration, depending on the aridity of the region (Belnap 2006). These soil communities are ubiquitous across the desert soil surface and are integral to arid landscapes. Biocrusts inoculated on the soil surface eventually coalesce and form a cohesive structure (McKenna Neuman et al. 1996). The thin surface that biocrusts form across the landscape aids in reducing the incidence of air borne dust particulates and promotes stability. Consequently, biocrusts may be an excellent initial approach to restoring a disturbed landscape. Biocrusts may also aid in initiating successional processes for vascular plants (Bowker 2007). These findings encourage the use of biocrusts as a restoration technique as they may catalyze long-term recovery processes in the desert. Experimental disturbance treatments reveal that biocrusts are highly sensitive to disturbance. Faist et al. (2017) recorded biocrust response to trampling and scraping in comparison to undisturbed biocrusts. After disturbance, the biocrusts had lower biomass, lower stability, and higher runoff (Faist et al, 2017). Therefore, it is desirable to restore biocrusts where possible to further the resiliency of not only the soil community but the entire ecosystem for desert sites where biocrusts form a major natural soil component.

Best practices for biocrust inoculation treatments are still being researched. The process generally involves salvaging and storing biocrusts or propagating biocrusts in the greenhouse. The biocrust is then incorporated with the soil surface, ideally to encourage biocrust recovery and soil fertility and stability thereafter (Chiquoine et al. 2016). The biocrust inoculant treatments were successful in increasing the rate of recovery for biocrusts in disturbed areas, returning to them nearly to pre-disturbance levels (Chiquoine et al. 2016). Other studies demonstrate the success of biocrust restoration for utilities such as increasing soil stability and fertility (Maestre et al. 2006; Bowker 2007; Delgado-Baquerizo 2018). This is a minimal-input, cost-effective restoration technique. It utilizes salvaged, native materials that do not have high storage or upkeep requirements, does not require high effort to inoculate in disturbed areas, and does not require consistent watering after establishment.

Conclusion

The body of work investigating human-induced disturbance within the Mojave and Sonoran Deserts is broad. There is a wide range of literature that details the disturbances that have occurred within the Mojave and Sonoran Deserts, as well as the influence of these disturbances on their respective ecosystems. Findings have consistently shown that 1) desert ecosystems recover from severe disturbances on decadal to centurial scales without intervention, 2) human-induced disturbance is primarily responsible for the degradation of these systems, and 3) restoration techniques may aid these landscapes in a recovery trajectory and potentially prevent feedback loops. Techniques for the ecological restoration that have been used in Mojave and Sonoran desert landscapes are multitudinous and include abiotic materials, vertical mulch, soil surface manipulations, revegetation, seeding, and biocrust inoculations.

In general, soils recover on time scales outside of the average human lifespan. While some restoration methods can kick-start long term recovery processes, it is difficult to quantify the efficacy of soil restoration techniques due to time constraints. Even so, little research examining short-term results and retrospective analyses have been published on the topic. The lack of studies centering on soil restoration has hindered the development of reliable soil restoration techniques, especially in diverse desert landscape settings varying in soil conditions and climate. Few published papers focus solely on soil restoration in North American deserts.

Restoration techniques, and the influence of these techniques on the soil, should be evaluated further in arid lands. Optimal techniques may include vertical mulch or revegetation using native desert plants to restore fertile island structure, inoculation with biocrust materials to improve soil stability, contouring the soil surface, and the emplacement of abiotic materials such as rock cover to restore ecological structure related to soil formation processes. Specific emphasis should be placed on the soil responses to these treatments, such as soil temperature, soil moisture, soil accumulation, soil stability, and recruitment of native annual plants to determine success. These variables are useful as they can change quickly during restoration and indicate initiation of longer-term processes of ecosystem recovery in disturbed desert landscapes.

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CHAPTER 3

ASSESSING VERTICAL MULCH AND TRANSLOCATED ORGANIC MATERIAL AS A MINIMAL-INPUT RESTORATION TECHNIQUE

Abstract

To reduce fugitive dust as a human health hazard, increase soil stability, and enhance wildlife habitat, further work is necessary to develop restoration techniques for disturbed desert landscapes. Human-induced disturbances can degrade soil integrity, especially in arid lands with weakly developed soil horizons. Vertical mulch, a low-cost restoration technique that simulates the above-ground appearance of native shrubs, may help restore soil function and plant recruitment. My research analyzed the effectiveness of vertical mulch in the Dead Mountains Wilderness Area located 18 km from Needles, California in the Mojave Desert. Large-scale disturbances compacted the soil and removed top soil and vegetation. The Bureau of Land Management conducted pitting, seeding, and vertical mulching activities in the area two years before this study, presenting the opportunity to research the effect of microsite and seeding with litter more specifically. In 2017, I installed experimental plots testing the effect of surface de-compaction with and without vertical mulch treatments in two blocks. One block also received a organic material addition gathered from 90 shrubs up to 1 km from the study area. Native plant cover was six times higher under vertical mulch structures than in control interspaces both observation periods. Non-native cover also increased under vertical mulch. These trends were mirrored in the BLM restoration site. Soil properties were also altered by the installation of vertical mulch, with significant decreases in compaction and increases in both soil moisture and soil stability. Results suggest that vertical mulch is a useful technique to enhance annual vegetation cover and promote soil function, although considerations must be made to limit non-

native plant response. Combining vertical mulch with additional restoration treatments, such as litter addition, would be a viable approach, and should be further studied.

Introduction

As human-induced disturbances continue to degrade desert landscapes, effective restoration techniques must be developed to return landscapes to trajectories of recovery. Once disturbed, desert ecosystems may emit fugitive dust, have lowered plant productivity, and often lack diagnostic desert features such as surface layers of biotic crusts and spatial patterning of "islands of fertility," or nutrient-enriched soils below shrubs (Belnap, 1995; Abella et al., 2012; Maestre et al., 2012). These disturbances may lead to negative impacts on human health by increasing the harmful release of dust and allergens (Pointing & Belnap, 2014), lessened resiliency to climate change (Maestre et al., 2012), further susceptibility to disturbance and erosion (Belnap, 1995; Bainbridge, 2007), and loss of ecosystem services (Cortina et al., 2011). Restoration efforts may aid in ecosystem recovery. Due to extreme environmental conditions, the amount of cost and effort often preclude the practice of some restoration techniques in desert ecosystems. Cost-effective, minimal-input restoration techniques are vital to efficiently restoring desert landscapes.

Developing restoration techniques is challenging in arid regions as high temperatures and limited water often impede cost-effective restoration efforts. Revegetation is costly and is generally considered successful if 50% of outplants (greenhouse-grown seedlings placed at field sites) survive (Abella & Newton, 2009). While less costly than revegetation, seeding treatments yield a lower success rate and may not germinate at all in years with low rainfall and in areas with intensive granivory (Abella et al., 2012; Maestre et al., 2012). In spite of limiting factors, seeding has been successful in the Mojave (Abella et al., 2009) and Sonoran (Cox et al., 1984)

Deserts. In some circumstances, using litter from surrounding areas may enhance vegetative cover without a high degree of effort or expense. Translocating O horizon material into disturbed areas introduces seeds and organic matter with minimal expense as it uses on-site materials. Other techniques, such as mechanically manipulating the soil of disturbed areas, can be expensive and may permanently alter the appearance of the landscape. As a result, alternative restoration techniques such as vertical mulch are increasingly viewed as a visually acceptable, cost-effective option for restoration. Vertical mulch, the “planting” of dead woody material to simulate the aboveground appearance of plants, is increasingly used by governmental, private, and non-profit agencies as a cost-effective, minimal-input solution to human-induced disturbance (Figure 1). Most commonly, vertical mulch is installed to dissuade public use of sensitive areas as it acts as a visual and physical barrier (Bainbridge, 1996). Ecosystem functional benefits, such as improved annual plant recruitment (Abella & Chiquoine, 2018), increased water retention, seedling protection, and seed accumulation (Bainbridge 1996), have been less explored. In the semi-arid to arid Iberian Peninsula, branch piles increased seed rain by attracting frugivorous birds (Castillo-Escrivà et al., 2018). Some of these ecosystem functional benefits, such as seed accumulation and de-compaction, may arise from roughening the soil surface to install the vertical mulch structures. There is also evidence to suggest that vertical mulch may not be as effective for restoring ecosystem functions. For instance, studies have found that vertical mulch has little to no impact on soil moisture (Jalota & Prihar, 1998) and little influence on plant recruitment during years with low water availability (Bainbridge, 2001). More research is necessary to understand the ecological influence of vertical mulch as a restoration technique.

At the Dead Mountains Wilderness Area (Bureau of Land Management 1994) in the Mojave Desert, a former unpaved road was decommissioned in 1994 when this area was designated as wilderness and later treated in 2015. For treatment, the road was pitted mechanically and a portion of the former road received a vertical mulch and seeding with litter treatment. To better understand the effects of de-compaction, vertical mulch, and seeding using litter, I conducted a focused study in an adjacent, disturbed area. I hypothesized that: (1) de-compacting compacted surface material, vertical mulch, and translocating organic material would all independently result in greater plant recruitment, and (2) the combination of these treatments would result in the greatest plant recruitment.

Materials & Methods

Study Area

I conducted this study in the Dead Mountains Wilderness Area (35° 2'1.82"N 114°41'56.27"W; Bureau of Land Management; BLM,), 18 km northwest of Needles, San Bernardino County, California, USA. Prior to the area's wilderness designation in 1994, the site was used as a recreational vehicle area and RV campground. A road (~1000 m in length) led from a powerline corridor to the RV campground. In 2015, to dissuade unauthorized use of the area and this road, the BLM ripped and pitted (0.5 m × 0.5 m × 0.5 m depressions) along the entire length of the road to the campground using large earth-moving equipment, then installed vertical mulch along the approximately the first 500 m of the pitted treatment. Vertical mulch consisted of dead and down *Larrea tridentata* (DC.) Coville (creosote bush) branches inserted to mimic the structure of a creosote bush. Additionally, in the area that received a vertical mulch treatment, litter was incorporated into the surface area around the vertical mulch. Litter was collected from adjacent undisturbed creosote microsites where litter, which contained seed, accumulated. A spur road to the west of these restoration treatments was not restored and presented the opportunity to test the effects vertical mulch in a scientifically rigorous manner.

The Dead Mountains Wilderness Area is a granitic mountain range bordered by the Colorado River to the east and Piute Valley to the west. Topography of the region includes jagged mountains and sweeping bajadas with pristine desert pavement surfaces. The soil parent materials are granite, gneiss, and schist. Soil profiles are skeletal and show weak differentiation throughout (personal observations). Vegetation consists of *L. tridentata* and *Ambrosia dumosa* (A. Gray) Payne (white bursage with sparse stands of *Senegalia greggii* (A. Gray) (catclaw acacia) Britton & Rose and *Hyptus emoryi* (Torr.) (desert lavender) in surrounding washes. Portions of the area provide critical habitat to the desert tortoise (*Gopherus agassizi*).

The nearest weather station (Needles, CA, 18 km from the study site) reported average high temperatures of 43°C in July 2018 and a low of 11°C in February 2019 over the course of the study. Precipitation ranged around 24 mm for the 2017-2018 hydrologic year (November 2017-April 2018) and 33 mm for the 2018-2019 hydrologic year (November 2019-April 2019) (2017-2019; Needles, CA, 271.3 m in elevation, 34°46'3" N, 114°37'7.68" W, 18 km from the study site; data from National Oceanic and Atmospheric Administration). During this study period, there was 57% of the average precipitation in 2018 and 66% of the average precipitation in 2019 (Figure 2). Conditions were abnormally dry for the study area, especially in 2018.

Implementation

I installed two 48 m × 3 m experimental blocks with one designated as a litter addition block (Figure 3). Within blocks, three microsite treatments were installed, N=8, (1) surface de-compaction (SD), (2) surface de-compaction with vertical mulch (VM), and (3) no treatment control (CON), for a total of 24 microsites per block, or 48 total microsites among blocks (Figure 3). Microsites were 1 m × 1 m, evenly spaced across blocks with microsite types alternating across blocks, and at least 1 m from any other microsite. Surface de-compaction treatments consisted of using rock hammers and hand rakes to loosen the top 5-10-cm of compacted surface material. Vertical mulch consisted of inserting at least ten dead creosote branches per microsite at least 10-cm deep into the soil in the center of microsites to appear as erect dead shrubs. Dead branches were collected from beneath live creosote individuals from nearby sites. After microsites were constructed, in the seeding block only, litter collected from beneath 90 shrubs (*Larrea tridentata, Encelia farinosa*) in a 0.5 km radius around blocks, and homogenized was to incorporate in the upper 10-cm of soil in the SD and VM microsites. To determine viability of seeds in litter, we conducted an assay with a portion of the litter material over the course of three months using the emergence method (Thompson et al., 1997). Using the same volume of litter per microsite (3785 cm^3), litter was applied 5 cm deep onto sterilized soil in 15-cm diameter 1-gal nursery pots. Pots were watered three times a day and monitored weekly. As seedlings were identified to species, seedlings were removed.

Data Collection

To determine how vertical mulch influenced environmental factors and soil properties, I measured air and soil temperature, soil stability, soil compaction, and soil moisture. To monitor soil temperatures, in March 2018 (three months after treatment) I installed eight Onset U23-004 HOBO Pro v2 Temperature/6 ft External Temperature Climate Sensors (Bourne, Massachusetts, USA) with the external probe 5 cm below the surface soil with a secondary probe set at 25 cm above surface to monitor air temperatures. The internal soil sensors were buried 5 cm below the soil surface to capture annual plant and perennial seedling root-zone temperatures. In January 2019, 13 months after installing the treatments, I measured compaction using an AMS G 281 E-280 Pocket Penetrometer (American Falls, Idaho, USA). Following Herrick et al. (2001) soil stability was measured using 3 peds per microsite. Soil moisture was measured gravimetrically in

March 2019, 15 months after treatment. Vegetation was monitored within experimental microsites in both blocks in April 2018 (four months after treatments) and March 2019 (sixteen months after treatments). The areal cover per species was estimated using cover classes: 1= 0-1%, 2 = 1-2%, 3 = 2-5%, 4 = 5-10%, 5 = 10-25%, 6 = 25-50%, 7 = 50-75%, 8 =75-95%, and 9 = >95% (modified from Peet et al. 1998). Within 0.5 km radius from experimental blocks, I also sampled undisturbed interspace microsites (areas >1 m or more away from perennial plant canopy) and below mature *L. tridentata* shrubs using the same cover class and quadrat size (1 m × 1 m) to use as reference to compare with experimental treatment microsites. Undisturbed microsites were measured at the same time as experimental blocks.

To compare the 2015 de-commissioned road treatment to experimental treatments, microsites were assessed along the two different treatment section of the decommissioned and treated road. Along the treated road and adjacent undisturbed area (<100 m from road), random points were generated in ArcGIS v9.4. In the two road treatment blocks, (1) the pitted and vertical mulch treatment block and (2) the pitted only treatment block, the closest interspace (pitted only), live *Larrea*, or vertical mulch (where applicable) microsite to the random point were selected for survey within a 1 m x 1 m quadrat. Twelve of each applicable microsites were sampled per the two treatment blocks (pitted only, N=12 pitted interspace, N=12 live Larrea; pitted with vertical mulch, N=12 vertical mulch, N=12 pitted interspace, N=12 live Larrea). On either side of the road, along the entire length, twelve live Larrea and twelve interspace microsites were also surveyed. Areal cover for all species present were estimated using cover classes as described above. All *Larrea* plants were expected to have been established after the 2015 road treatments, but the year the plants germinated since 2015 is uncertain.

Data Analysis

The experimental design for the 2017 site was a repeated measures (two years) factorial, two-factor, randomized complete block, with microsite type (three levels: surface de-compaction, surface de-compaction with vertical mulch and no treatment control) and organic material addition (two levels, present or absent) and their interaction set as fixed effects. Vegetation and soil analyses were performed using PROC MIXED in SAS version 9.4. I also regressed each environmental variable (soil stability, soil compaction, and gravimetric soil moisture), averaged for each sampled microsite, with 2018 and 2019 native plant cover. The relationship between soil properties and native plant cover varied with r^2 values of 0.98 (stability), 0.88 (moisture) and 0.73 (compaction) (CI=95%). The 2015 road restoration treatment vegetation surveys data were analyzed using a similar design above.

Results

Plant response to 2017 experimental treatment

Compared to disturbed but un-manipulated and surface de-compacted microsites, the vertical mulch microsite type yielded higher plant cover percentages. Plant cover in the vertical mulch microsites was higher in all categories: exotic annual cover, native annual cover, and native perennial cover (Figure 4a-d). However, through microsite × year interactions, exotic and native perennial cover were higher in 2019 in the vertical mulch microsite than in 2018 (Figure 4a-d). Native perennial plant cover and exotic annual cover were significantly higher in the vertical mulch microsite type as compared to surface de-compaction microsite types and control sites (Figure 4a,b). While there were interactions in native annual plant cover between microsite type and year, this relationship was not as strong in exotic plant cover. Both native and exotic plant cover were significantly higher in 2019 than 2018.

Retrospective assessment of 2015 restoration treatments

The 2015 microsites supported the general trends shown in the experimental restoration plots (Figure 5a). Exotic cover was significantly higher below vertical mulch as compared to interspaces (Figure 5b). Cover for native plants was not significantly higher in vertical mulch treatments, although cover was significantly higher in 2019 than 2018.

For the 2015 restoration treatments, microsites differed between years and among treatments or between treatments and undisturbed microsites (Figure 5). In pitted only microsites, interspace and *Larrea* microsites did not differ within year from each other but did differ between years. Native annual cover was greater in 2019. In pitted with vertical mulch microsites, in 2018 *Larrea* microsites did not differ from vertical mulch microsites, but did differ from interspace microsites. *Larrea* microsites had the lowest native annual cover in 2018. In 2019, *Larrea* microsites in the pitted with vertical mulch sites also had the lowest cover of the three microsites surveyed, similar to 2018 results. Interspace and vertical mulch microsites did not differ from each other in 2019. Compared to undisturbed microsites, treatment microsites tended not to significantly differ in 2018 in most cases. However, in 2019, undisturbed microsites had significantly higher native annual cover compared to all treatment microsites. Exotic plant cover, which primarily consisted of *Schismus* cover, did not differ among any of the microsite types or between years. Among microsites each year, exotic annuals contributed <1 % cover among all plots. Both perennial forbs and shrubs were analyzed separately because *Larrea* was expected to contribute significantly to both shrub and total perennial cover. Perennial forbs differed between years, although only contributed to <1 % cover both years. For shrubs, as expected, *Larrea* microsites had the highest shrub cover among microsites both years and undisturbed microsites also had the highest shrub cover both years.

Soil response to 2017 experimental treatment

The restoration treatments also influenced soil properties. Soil stability, soil compaction, and soil moisture had strong interactions among microsite types (Figure 6a-c). Soil in the vertical mulch microsite was 3.5 times more stable than the experimental control sites and significantly more stable than both the experimental control and surface de-compaction microsite types. Both the vertical mulch and surface de-compaction microsite types had significantly greater gravimetric soil moisture than the experimental control microsite types across both the seeded and non-seeded blocks (Figure 6a). The experimental control sites were significantly more compacted than the vertical mulch and surface de-compaction microsite types. Air and soil temperatures also differed among the microsites (Figure 7). Vertical mulch had temperatures averaging 2-4°C lower than the other microsite types in both categories.

Discussion

In this study, I found that vertical mulch is a beneficial technique for restoring disturbed desert landscapes. Vertical mulch significantly increased native cover and altered soil properties in ways that appear favorable to plant establishment. The relationships between vertical mulch, plant abundance, and erosion control investigated in this study indicate that vertical mulch is not only a visual aid but also an ecological one. Adding organic material to vertical mulch treatments was a low effort way to increase plant cover to reference conditions, although there was no significant difference in cover between seeded and non-seeded vertical mulch sites. To a lesser degree, de-compaction also aided in enhancing plant cover and may be a lower effort alternative to vertical mulch depending on management goals.

The response of annual plants and soil to vertical mulch structures indicates that vertical mulch may behave similarly to a dead fertile island. Across all plant categories, vertical mulch had significantly higher plant cover percentages than experimental control sites. I also found that vertical mulch sites had higher soil moisture, greater soil stability, and were the least compacted, which likely provided preferable conditions for plant establishment. The aboveground structure of vertical mulch may be providing canopy protection and aid in seed accumulation. This increased accumulation may be a mechanism by which seeds and nutrients accrete in the vertical mulch treatment. Both the canopy protection and increased accumulation are features of fertile islands in desert systems. As temperatures were lower in vertical mulch microsites than the other microsites, vertical mulch also appears to buffer microsite conditions, especially during the hottest months of the year (Figure 7).

The lack of significant differences in plant cover between the surface de-compaction microsite and the vertical mulch microsite suggests that the act of installing vertical mulch is not solely responsible for vegetation and soil response. During years of higher precipitation, de-compacting the soil alone may increase plant cover.

Translocating the O horizon material had less of an influence on plant cover than the microsites, suggesting that it may not be worth the extra effort. For instance, there was no significant difference between the vertical mulch treatments with and without translocated O horizon material. However, when compared to the undisturbed reference sites, the vertical mulch treatments with translocated O horizon material yielded plant cover percentages more similar to the reference sites than vertical mulch treatments without translocated O horizon material. Vertical mulch microsites with translocated O horizon material yielded ratios of 97% (2019) and 59% (2018) of native plant cover to reference interspace whereas the vertical mulch structures without it had ratios of 79% (2019) and 22% (2018) (Figure 8). In comparison to the control sites, both vertical mulch structures with and without translocated O horizon material had much higher native plant cover relative to the reference sites (control site cover ratios were closer to 22% [2019] and 2% [2018], respectively). Translocating O horizon material may be a beneficial extra step to promote higher cover (up to twice as much plant cover in dry years as compared to wet years).

The significant difference in native plant cover between 2018 and 2019 may have been driven by environmental factors. In the hydrologic year (November 2017-April 2018) preceding the 2018 growing season, Needles, CA received 15 mm of precipitation. In the hydrologic year preceding the 2019 data collection (November 2018-March 2019), Needles, CA received 89 mm of precipitation. The lower plant response during the drier year is consistent with findings of Bainbridge (2001) that vertical mulch is less effective in drought years. The vertical mulch may also have increased cover by buffering seedlings from extreme temperatures. During the hottest months of the year, the vertical mulch microsites had air and soil temperatures several degrees lower than the other microsite types (Figure 7). This may have aided in keeping perennial plants alive over the summer, as perennial plant cover was significantly higher in 2019 than 2018. The less severe temperatures may have also aided in plant recruitment.

The variation in precipitation had less influence on exotic plant cover. Exotic grasses had strong interactions between microsite types in both years of the study. In 2018, the drier of the two study years, vertical mulch had five times as much native plant cover as control sites (Figure 4a). During the wetter year of 2019, exotic plants utilized the vertical mulch significantly more than the control sites (Figure 4c). Therefore, precipitation may not have as strong of an effect on exotic plants as native plants with regards to vertical mulch treatments. The increased abundance of both native and non-native vegetation supports the findings of Abella & Chiquoine (2019). Vertical mulch may have the unintended consequence of facilitating exotic species. Additional exotic plant treatments in conjunction with vertical mulch may be necessary to provide opportunity for native plants to establish and compete. Based on these findings, we propose that, while vertical mulch is a beneficial technique for enhancing vegetative recovery, exotic plants warrant consideration.

The longer-term plant response of the 2015 restoration sites support the apparent trends in the shorter-term experimental data. The vertical mulch sites had 33% (2019) and 36% (2018) of the native cover of undisturbed reference interspaces whereas the microsites with no vertical mulch had ratios of 48% (2018) and 17% (2019). There was more variability in the 2015 restoration sites during the drier study year likely due to longer establishment. As evidenced by both the experimental vertical mulch established in 2017 and the 2015 restoration site, vertical mulch and de-compaction have both immediate and long-term influences on plant response. Considering that the vertical mulch structures of this study have remained upright for the duration of the study period, it may be concluded that the vertical mulch treatments will continue to have long-lasting influences on an ecosystem. In their study, Abella and Chiquoine (2019) found that their vertical mulch persisted for nearly a decade with minimal structures breaking or tipping over, unless the structures were outright removed by humans. Given that woody material in the deserts have been found to disintegrate on decadal scales (e.g. Ebert & Ebert 2006), vertical mulch may be a viable restoration technique on longer time scales.

My findings indicate that vertical mulch is a suitable restoration technique to ameliorate soil disturbance. Bainbridge (1996) suggested that vertical mulch improved soil stability and may improve seed and soil accumulation. This study bolsters this conjecture as vertical mulching and soil de-compaction activities improved soil stability, soil moisture, and soil compaction. The soil of vertical mulch microsites was over three-fold more stable than the soil of control sites.

Both the installation of vertical mulch and soil surface de-compactions de-compacted soil significantly more than control sites. Contrary to the findings of Jalota and Prihar (1998), soil moisture was higher in vertical mulch sites than control sites. This may be due to geographic differences between this study site and Jalota and Prihar's study site, which was located in the central Great Plains of North America. Considering that the vertical mulch sites also had lower air and soil temperatures by up to 5°C, structures could have enhanced moisture retention (Figure 7). This may be investigated further with humidity sensors and soil moisture meters.

Future research is necessary to assess the efficacy of vertical mulch in simulating the fertile island effect. While this study addressed the ability of vertical mulch to enhance plant recruitment, determining the mechanisms by which vertical mulch may have interacted with plant recruitment processes, such as trapping seeds or protecting seedlings, was beyond the scope of this study and warrants further research. Continuing to track environmental processes around the vertical mulch structures may provide insight into potential longer-term dynamics. For example, in their study examining seed accumulation in branch piles, Castillo-Escrivà et al. (2018) noted less litter cover under the branch piles than under shrubs after four years. Understanding which mechanisms (wind, etc.) drive seed accumulation under vertical mulch structures would further analogs between vertical mulch and simulating a fertile island effect. Understanding how vertical mulch influences these longer-term properties may further illuminate the factors underlying increased cover beneath vertical mulch as compared to control sites and how vertical mulch may compare to other, more costly treatments.

This study illuminated the need to study vertical mulch further. Our findings suggest that incorporating O horizon material with vertical mulch structures resulted in comparatively high percentages of plant cover. Vertical mulch can likely be paired with other treatments for different management goals. For instance, pairing vertical mulch with treatments to lower non-native plant cover may prove viable. This may eliminate the apparent downside of vertical mulch facilitating these species. Herbicide may be one such treatment, especially considering that typical considerations of applying herbicide around nurse plants may not be a concern for the already dead vertical mulch material. Applying Fusilade II eliminated non-native grasses and shrubs from a burned portion of the Sonoran Desert and doubled native plant cover (Schutzenhofer & Valone, 2006; Steers & Allen, 2010). Scoles-Sculla et al. (2014) found minimal impact on outplanted shrubs after their four year study on herbicide application on annuals surrounding outplants. These findings may also be influenced by application timing, weather, and secondary invasion. Another approach to limiting non-native cover may be manually removing non-native plant species in specific microsites and at specific times to strategically employ this labor-intensive but potentially effective strategy. Brooks (2000) found that thinning non-native grasses did not change native biomass in a dry year but doubled it in a wet year. Similarly, removing *Erodium circutarium*, a non-native forb, nearly doubled native annual cover and richness in the Chihuauan Desert (Schutzenhofer & Valone, 2006). These treatment combinations may be modified to yield the highest native plant cover and lowest exotic plant cover. Other treatments may be combined to potentially increase percentages of plant cover. Amending the soil surface with organic material may promote higher plant cover beneath vertical mulch. In the Mojave Desert, killing a shrub and placing the canopy on fertile soil yielded annual plant biomass similar to that of below live shrubs (Holzapfel & Mahall, 1999). Given the success of incorporating native litter to this study, it may also be beneficial to study seeding with regard to vertical mulch.

Our study indicates that vertical mulch is a promising restoration technique for both vegetation and soil, particularly if combined with another treatment that may suppress non-native plant. In some cases, merely manipulating the soil surface can yield good results. Environmental variables, such as precipitation, compaction, and soil moisture, may drive trends in abundance and facilitate higher cover. Exotic plants appeared to thrive in years of both above and below average precipitation. As desert ecosystems are increasingly threatened by human use and plant invasion, it is vital to develop effective restoration techniques. Many restoration projects lack ample funding and rely on volunteer work to carry out restoration projects. Vertical mulch is a cost-effective, minimal-input technique that may promote annual and perennial plant recruitment in denuded areas, promote plant retention through improved soil moisture, stabilize disturbed soils, and de-compact heavily compacted soils such as the ones in this study.

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Figure 1. An example of the vertical mulch (VM), surface de-compaction (SD), and control (CON) microsite types along 48 m × 3 m Block 2 of the 2017 experiment, which received a litter treatment. The photo on the left is from March 2018 and the photo on the right was taken one year later in March 2019. Note the large perennial shrub *Encelia farinosa* in the first vertical mulch structure of the right-hand photo. Photos by A. J. Rader.

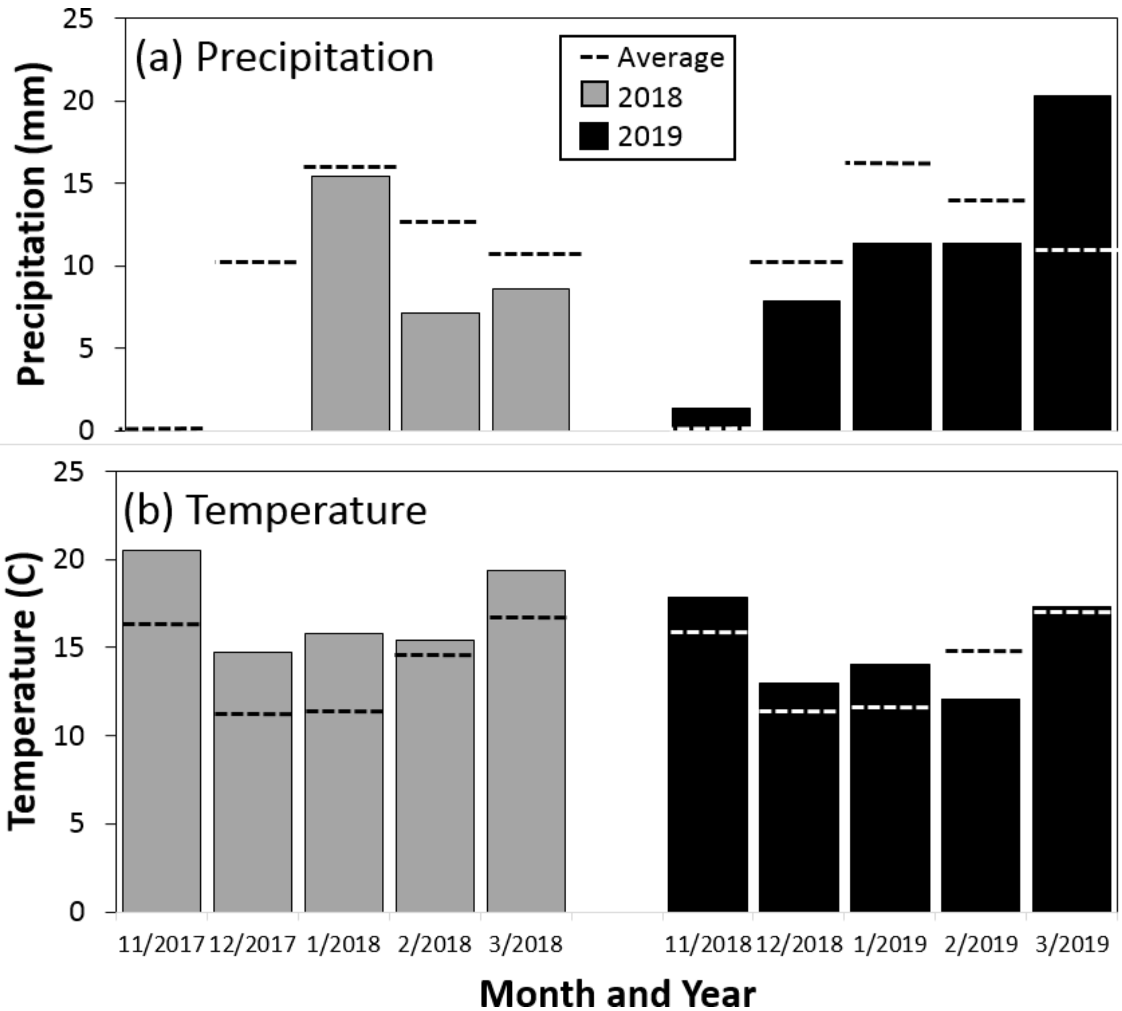

Figure 2. Precipitation and temperature data at the study sites in the 2017-2018 and 2018-2019 hydrologic years. Actual data from the National Oceanic and Atmospheric Administration Needles, CA and average data from Western Regional Climate Center.

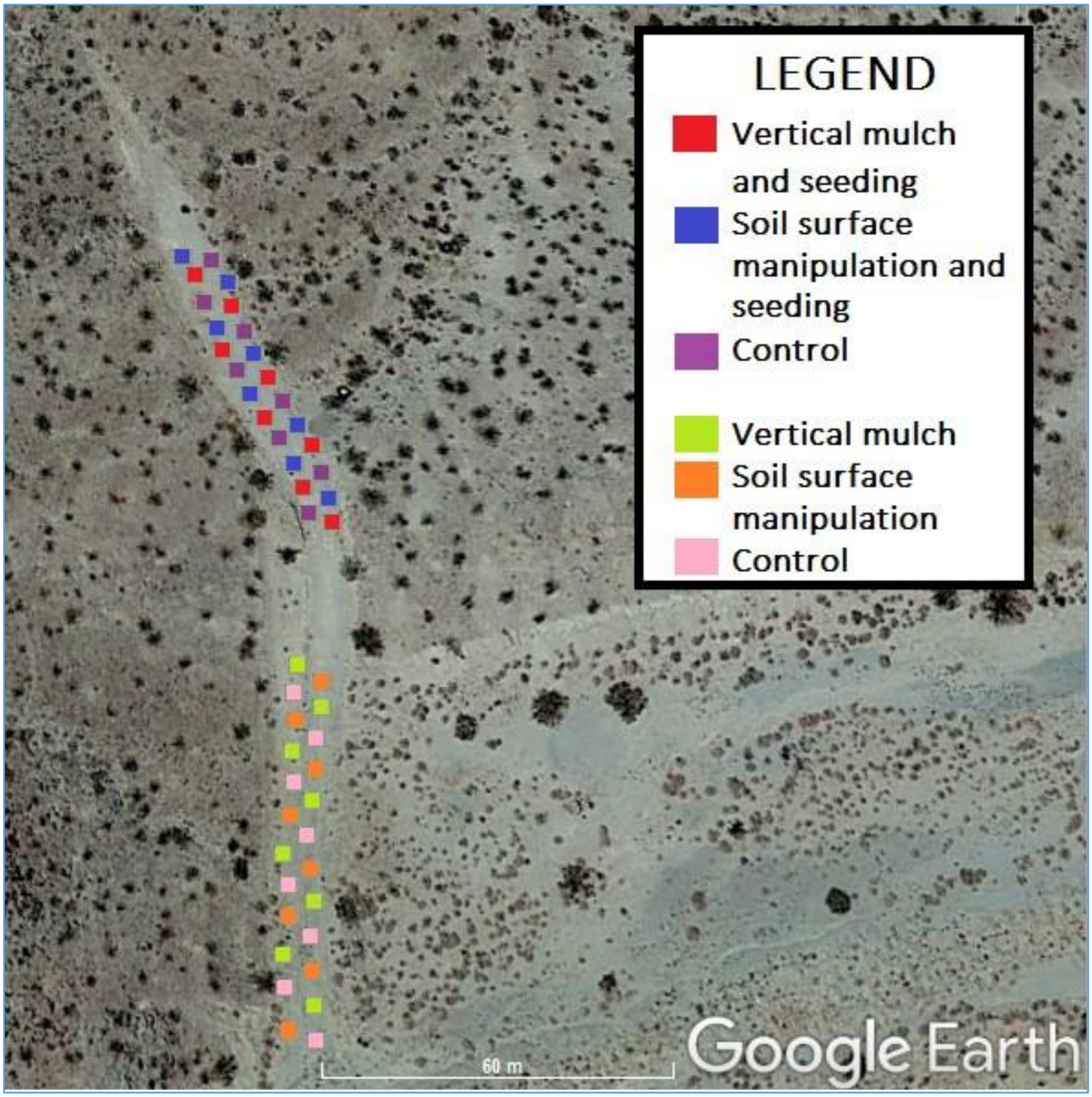

Figure 3. The study design for the experimental 2017 restoration blocks. Each block is 48 m x 3 m in size. Three microsite treatments (n=8) are in each plot: the vertical mulch microsite type, the surface de-compaction microsite type, and the control microsite type. Block 2, the northernmost block, also received a litter with seeding treatment wherein translocated O horizon material was incorporated into the microsite soil surfaces.

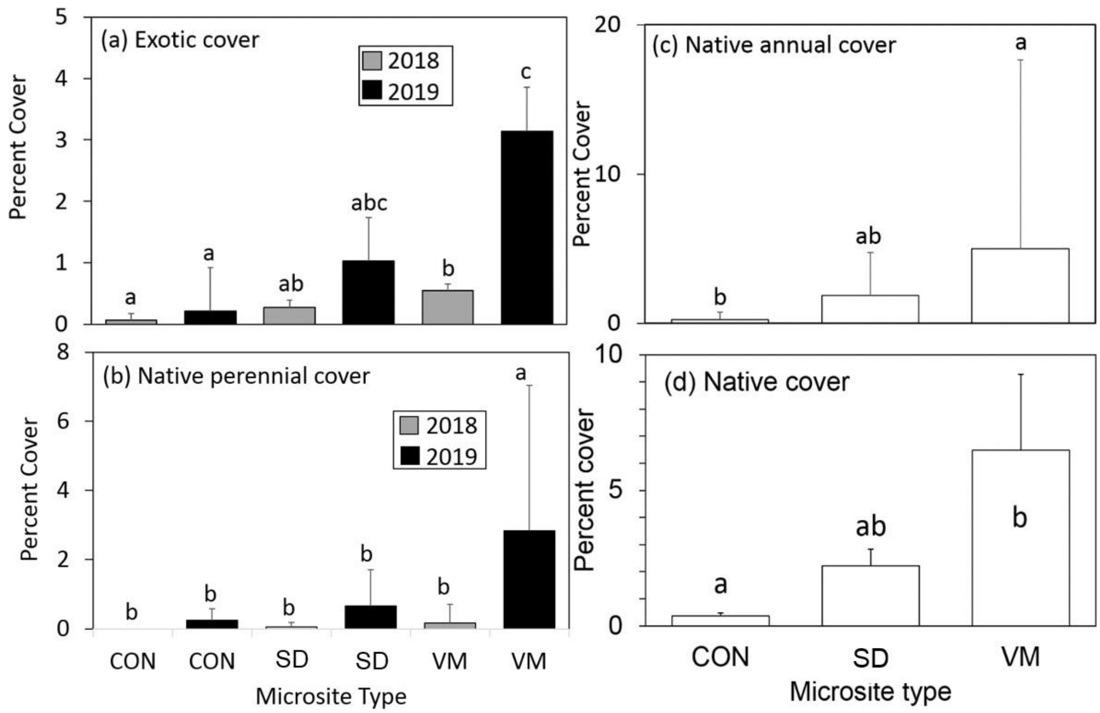

Figure 4. Significant effects for mean (a) exotic annual plant cover, (b) native perennial cover, (c) native annual cover, and (d) total native cover among microsite types (CON=control, SD=surface de-compaction, VM=vertical mulch) among seeded and non-seeded experimental blocks in the 2017 experiment. Data are shown according to whether year × microsite or microsite were significant. Error bars are one SEM. Letters indicate statistically significant groups ($p<0.05$).

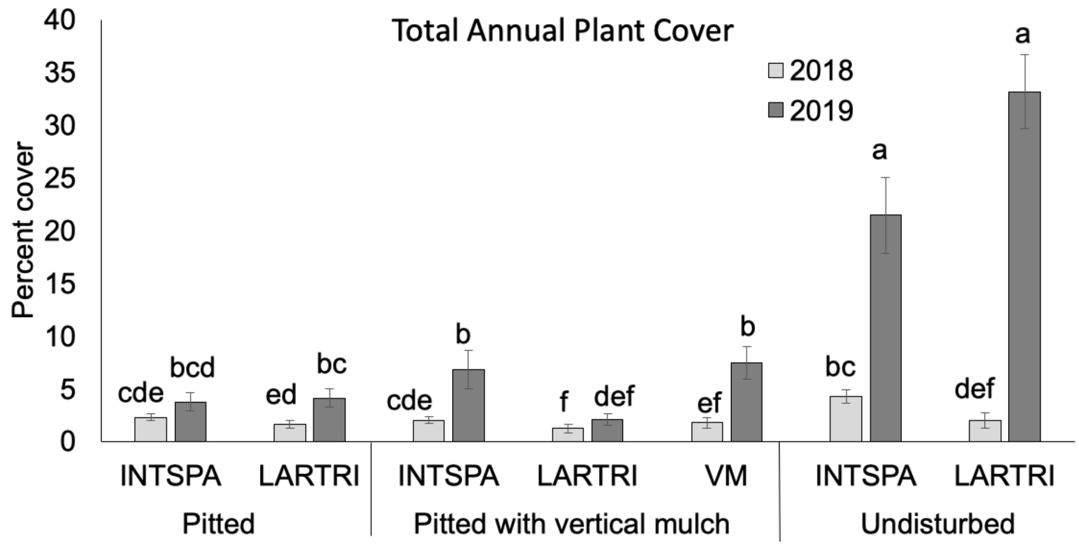

Figure 5. Significant treatment effects on (a) native annual cover and (b) exotic annual cover in the 2015 restoration microsites in the Dead Mountains Wilderness Area, Mojave Desert, California. The microsite types are PITT INTSPA= pitted interspace, PITT LARTR= pitted Larrea tridentata, PITTVM INTSPA=pitted vertical mulch interspace, PITTVM LARTRI=pitted vertical mulch with Larrea tridentata, PITTVM VM= pitted vertical mulch with vertical mulch, UND INTSPA=undisturbed interspace, and UND LARTRI=undisturbed Larrea tridentata. Values are means and error bars are one standard error of

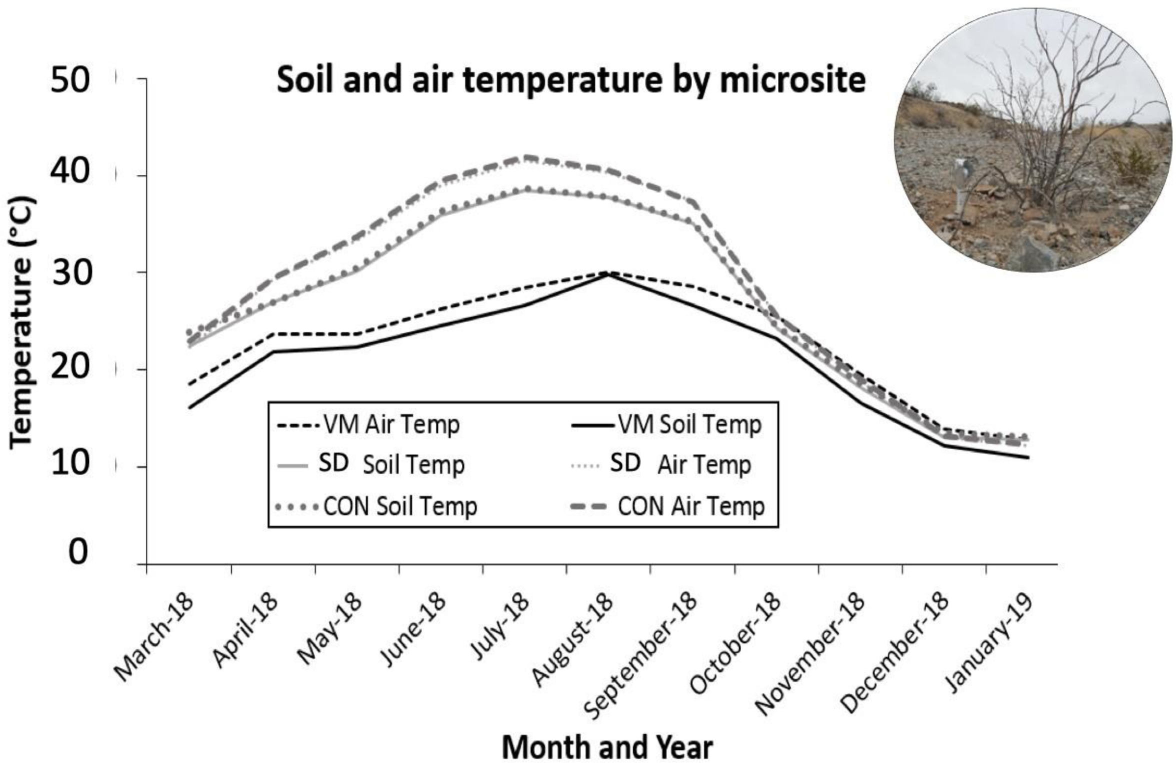

Figure 6. Monthly values for air temperature and soil temperature in vertical mulch (VM), surface de-compaction (SD), and control (CON) microsites during eleven months of the study during 2018 and early 2019 in the Dead Mountains Wilderness Area, Mojave Desert, California. Values are averaged from data points taken every thirty minutes.

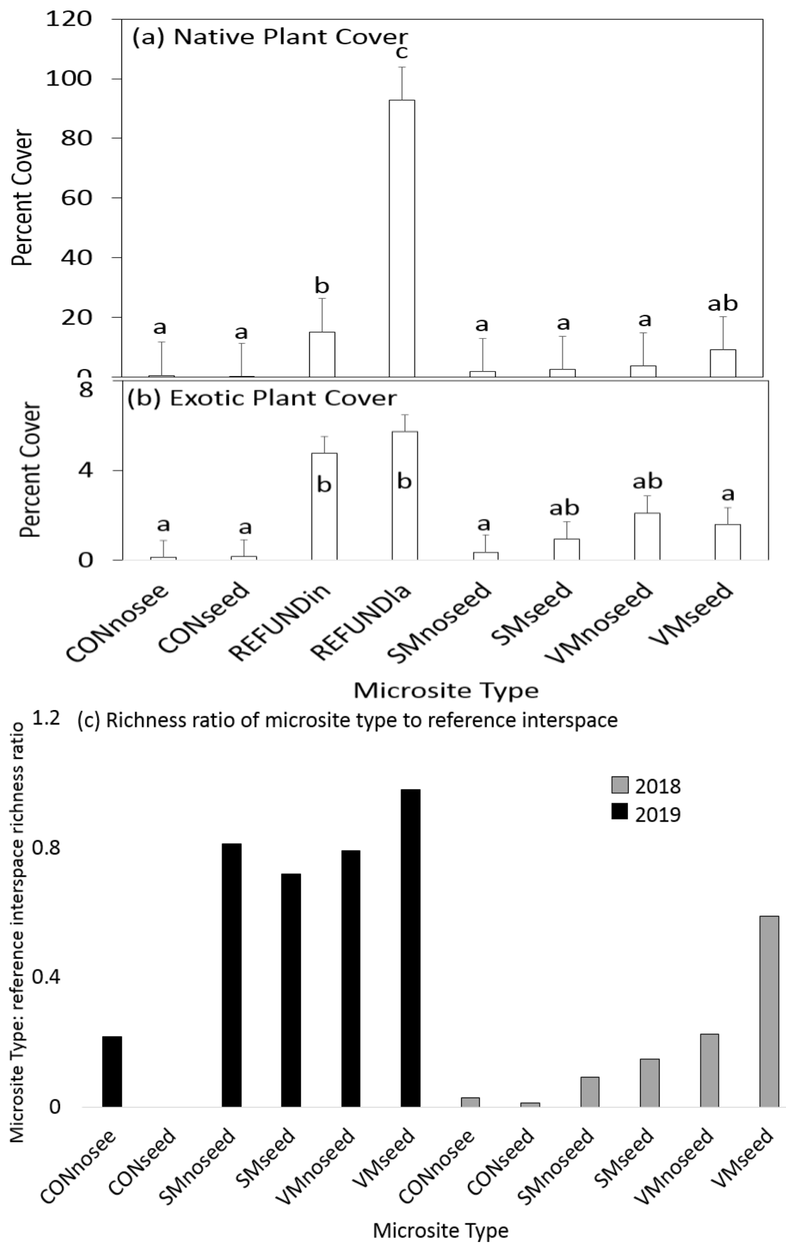

Figure 7. Dissimilarity in native (a) and exotic (b) plant cover between the seeded, non-seeded, and reference sites in the 2017 experiment. Different letters indicate statistically significant differences for the variable (P<0.05). Part c shows the relative ratio of each microsite type's native plant cover to reference interspace native plant cover, divided by year (CONnosee=control microsite without litter addition, CONsee=control microsite with litter addition, SMnoseed=surface de-compaction microsite without litter addition, SMseed=surface de-cmpaction microsite with litter addition, VMnoseed=vertical mulch microsite without litter addition, VMseed=vertical mulch microsite with litter addition). The closer the ratio is to 1, the more similar the cover between the microsite types. If the ratios are less than 1, there is indication that the treated areas have lower richness than the undisturbed areas.

CHAPTER 4

ASSESSING RESTORATION TECHNIQUES ACROSS VARYING SOIL CONDITIONS OF THE SONORAN DESERT

Abstract

Ecological restoration mitigates the impacts of human-induced disturbances in deserts with varying levels of success. To determine how site characteristics may influence restoration success, I measured plant cover, soil moisture, soil compaction, soil stability, and soil accumulation in response to three restoration-created microsite types—outplanting, vertical mulch, and water catchments—across four Sonoran Desert study sites with different soil properties and degrees of disturbance. I hypothesized that restoration techniques would enhance vegetative cover and improve soil functional properties (stability, moisture, de-compaction, and accumulation) across all study sites, with the level of success dependent upon soil substrate and extent of disturbance. The microsite type influence was not as evident as predicted. Plant cover was consistently highest in the study site with the most favorable soil conditions, regardless of microsite type. Soil stability and moisture yielded similar trends whereas soil accumulation was significantly highest in the vertical mulch microsite type, regardless of study site. Soil compaction was lower in microsite types with outplanting than within microsite types without. These findings suggest that returning disturbed landscapes to trajectories of recovery is highly dependent on existing soil characteristics. Developing a contextual understanding of how certain site conditions influence restoration success is essential to developing effective projects and predicting their success.

Introduction

Arid desert ecosystems are increasingly imperiled by human development and recreational use. Disturbances such as the construction transmission lines and off-highway vehicle use remove vegetation and soil, compact soil, and introduce invasive plant species (Webb & Wilshire, 1983; Wilshire, 1983). In desert dune systems, transmission corridors may also act as a ground-level boundary that prevents soil transport (Yu et al., 2004). As a consequence, dune systems lose more soil than they accumulate. Adjacent human populations experience the undesirable repercussions of these disturbances. According to Pointing & Belnap (2014), most airborne dust is derived from deserts disturbed by human activities. Human populations living adjacent to sources of airborne sand may be at a higher risk for vehicular and cardiovascular death during dust storms (Crooks et al., 2016). Continued exposure to dust may result in higher incidences of asthma and asthma-related hospitalization in children (Kantani et al., 2010). It is vital to stabilize soils and prevent soil loss in disturbed desert systems. Land managers and researchers have developed restoration techniques to mitigate the impacts of human-caused land degradation. The success of these restoration treatments varies, and it is often difficult to pinpoint reasons for this variation.

Common restoration techniques range from soil contouring such as water catchments, vertical mulch, and using on-site materials to protect plants to more intensive treatments such as revegetation efforts via outplanting (greenhouse-grown seedlings placed at field sites) or transplanting (relocating plants from one area to the area of interest) (Abella & Newton, 2009; Bainbridge, 2007). In the Mojave and Sonoran Deserts, vertical mulch treatments may enhance annual plant cover (Abella & Chiquoine, 2019), promote seed accumulation (Castillo-Escrivà et al., 2018), and stabilize soils (Bainbridge, 1996). Contrarily, vertical mulch treatments may also be ineffective in years of low water availability (Bainbridge, 2001), facilitate non-native plant cover (Abella & Chiquoine, 2019), and have little to no impact on soil moisture (Jalota & Prihar, 1998). In the arid Southwest of the United States of America, revegetation efforts are considered successful if 50% of the outplants survive (Abella & Newton, 2009).

The limited success of these treatments is largely due to the limiting factors typical of desert systems: climactic variability and the extreme environmental conditions (Ehleringer, 1985; Smith et al., 1997; Abella et al., 2012; Maestre et al., 2012) but existing site conditions may be an additional, but less understood, factor. The spatial heterogeneity of soils has long been linked to the plant distribution in desert systems (McAuliffe, 1994; McAuliffe, 1999). In the Mojave Desert, *Ambrosia dumosa* density increased with soil horizon development whereas *Larrea tridentata* shrubs were more prevalent and longer lived on younger soils (Hamerlynck et al., 2002). McAuliffe & Hamerlynck (2010) found that soil texture and parent material influenced plant response to multi-year drought in the Mojave and Sonoran Deserts. Similarly, site conditions determined the recovery of soil and vegetation of Mojave Desert ghost towns (Webb & Newman, 1982). The well documented relationship between soil, water, and plants in arid landscapes may be mirrored in how plants and soils respond to restoration treatments.

In the 1980-90s, the installation of a transmission corridor between Blythe, California and Indio, California in the Sonoran Desert resulted in severe surface disturbances, including the removal of the top layer of soil and vegetation. These disturbances rendered these areas vulnerable to further loss of surface materials. The purpose of this study was to understand how a range of candidate restoration treatments varying in cost and resources influence soil and plant response in different soil substrates and disturbance levels. I installed vertical mulch, water catchments, and outplants in four sites along the transmission line. I hypothesized that: (1) the target restoration treatments would improve soil conditions across the four distinct study sites, (2) the target restoration treatments would have the highest plant cover compared to control sites, and (3) the degree of success of these treatments would fluctuate in accordance with the existing soil condition of the sites.

Materials and Methods

Study Area

I conducted this study along 64 km of the Devers-Palo Verde II Transmission Corridor (33°39’55.422”, 115°39’,15.3664” through 33°35’37.9176”, 114°59’33.4959”). The installation of the transmission corridor during the 1980s-1990s resulted in severe surface disturbances, including the removal of the top layer of soil and vegetation. Prior to study installation, site conditions were characterized by a lack of natural recovery of native perennial vegetation and lower vegetation in disturbed sites compared to undisturbed sites. The area supports a series of sand dune habitats reliant upon aeolian and—to a lesser extent—fluvial sources. When the transmission line was constructed, it is possible that the dunes were decoupled from their soil source. Some dune systems show evidence of being deflated but it is hard to discern the validity of this observation without repeat photography. Airborne dust particulates from the transmission line area limit visibility during dust storms, often resulting in air quality and traffic warnings for the nearby I-10 freeway. The right-of-way provided for transmission line maintenance is frequently used by off-highway-vehicle use (OHV).

The study area has relatively flat topography, possibly due to the ground being leveled for the construction of the transmission corridor, with an average slope of 4 to 6 degrees. Elevation ranges around 200 m. The soils of these regions are composed of granite and gneiss alluvium, weakly developed (lacked the presence of V horizons and petrocalcic layers), and somewhat excessively drained. Predominant vegetation types were creosote bush (*Larrea* *tridentata*) shrubland which frequently form coppice dunes. The washes are dominated by big galleta (*Hilaria rigida)*.

The nearest weather station reported an average precipitation of 5.3 mm/year for the duration of the study period (2017-March 2019; Desert Center, CA, 200 m in elevation, 69.2 km from study areas; data from National Oceanic and Atmospheric Administration, Desert Center, California) (Figure 8). This was 5% of the average precipitation (1913-2016; WRCC accessed 7 April 2019). During this study period, the annual maximum temperature was 29°C, which was cooler than the historic annual maximum temperature of 31°C whereas the annual minimum temperature was 14 °C was hotter than the historic annual minimum temperature of 13°C (Figure 8).

In December 2017, restoration treatments were installed in four blocks along the transmission line with varied soil properties (Table 1, Table 2a,b, Figure 9). Blocks were labelled Block 1, Block 2, Block 3, and Block 4 in accordance with severity of disturbance (1 being the most severe and 4 being the least, with all transmission line construction disturbances approximately 25 year old). At all blocks, vegetation was absent. Block 1 (33°39'55.422", 115°39',15.3664") was a staging area for the transmission line and was used for unauthorized off-highway vehicle use for the duration of the study. After the construction of the transmission line, the study area was ripped (mechanically breaking up soil layers tines that penetrate 35-50 cm), which churned up cobble-sized clasts and may have broken up subsoil layers, preventing the retention of subsoil moisture. Block 2 (33°39'57.2760", 155°36'11.3346") had the highest biological soil crust and surface clast cover. Distinct vehicle tracks bisected this plot, removing the biological soil crust cover. Evidence of consistent OHV use was also consistent in Block 3 (33°40'9.1848", 115°34'11.7830") throughout the study, including two-tracks adjacent to the microsites and directions to the freeway in the soil. Unlike in Block 2, these disturbances were not observed to interact with microsites. Block 4 (33°35’37.9176”, 114°59’33.4959”) had the most mobile soils, making it difficult to determine what disturbances, if any, had occurred.

Implementation

I installed four 24 m × 14 m experimental blocks in disturbed plots in the transmission line staging area (Block 1) or adjacent to the transmission line (Blocks 2-4) (Figure 9). Within blocks, six microsite treatments were installed, N=4, (1) water catchment with outplanting, (2) water catchment without outplanting, (3) vertical mulch with outplanting, (4) vertical mulch without outplanting, (5) no treatment with outplanting, and (6) no treatment, for a total of 24 microsites per block, or 96 total microsites among blocks (Figure 9). Microsites were 0.5 m × 0.5 m, and randomly placed throughout the blocks on a grid, with at least 2 m between each microsite. Water catchment treatments consisted of contouring the soil surface into a circle with a diameter of 0.5 m. The center of the catchment was lower than the contoured surface to potentially accumulate water, soil, and seed. Vertical mulch consisted of digging a moat 0.5 m in diameter, pressing shoots of big galleta (*Hilaria rigida)* collected from nearby washes into the moat, and backfilling the moat to ensure the big galleta shoots remained upright. After microsites were constructed, three target species of plants were installed in the outplanting microsite types. The species were: brittlebush (*Encelia farinosa*), cheesebush (*Bebbia juncea*), and big galleta (*Hilaria rigida).* The outplantings were watered one liter of water at the time of planting and once two months later to simulate a low-cost treatment.

Data Collection

Plant cover

I monitored the vegetation response to the treatment combinations in each of the 96 microsite types sixteen months after microsite installation. Using a 0.5 × 0.5 quadrat centered on each microsite, I estimated areal percent cover of annual, perennial, native, and exotic plant species using cover classes 1 = 0-1%, 2 = 1-2%, 3 = 2-5%, 4 = 5-10%, 5 = 10-25%, 6 = 25-50%, 7 = 50-75%, 8 = 75-95%, and 9 = > 95% (modified from Peet et al. 1998). Outplants were monitored by survival one, three, and six months after installation, at which time monitoring stopped because all outplants had died by the third month (confirmed at the six month monitoring mark).

Soil properties

I collected and analyzed soils from each of the four blocks to characterize the existing soil conditions. Prior to installing treatments, I obtained four soil samples (10-cm diameter; 5-cm deep) from the four corners of each block and composited them. I analyzed these samples for bulk density by weighing oven-dry soil with volume determined via water displacement (Grossman & Reinsch, 2002), texture using the hydrometer method (Gee & Or, 2002), electrical conductivity using the saturated paste method (Rhoades et al., 1989), pH using a glass electrode in a 1:1 soil: water and 1:0.25 soil: $CaCl_2$ suspension (Sims, 1996; Sikora, 2006), and soil organic carbon using a dry combustion analyzer (Nelson & Sommers, 1996).

Sixteen months after treatment installation, I also measured soil response to the treatments at a microsite level. I measured compressive soil strength with an AMS G 281 E-280 Pocket Penetrometer (American Falls, Idaho, USA). I took three compaction measurements at each microsite and averaged them. To measure soil accumulation, I placed a ruler at each cardinal direction of each microsite type and measured the accumulated soil over time. The values of the four rulers were averaged per microsite. I measured soil aggregate stability using a Jornada soil stability kit (Herrick et al., 2001). Three peds were gathered from each microsite, placed in individual sieves, and dipped in water. The percentage of the ped remaining on the sieve correlated to the aggregate strength, with higher strength correlated to higher values on a scale of 1-6. Median values were taken for the three peds taken at each microsite. Soil moisture samples were collected from each microsite type in March 2019 (10-cm diameter; 5-cm deep) and measured using the gravimetric method via oven drying the sample at 105°C for 24 hours. The percentage of soil moisture within the sample was calculated with the following formula:

$$\%\ Soil\ Water = \frac{weight\ of\ wet\ soil\ (g) -\ weight\ of\ dry\ soil\ (g)}{weight\ of\ dry\ soil\ (g)} \times 100$$

Data Analysis

The experimental design was a factorial, two factor, randomized complete block, with microsite type (water catchment, vertical mulch, and no treatment control) and outplanting (two levels, present or absent) and their interaction as fixed effects. Vegetation and soil analyses were performed using PROC GLIMMIX (SAS Institute 2009).

Results

Plant cover and outplanting

Plant cover varied significantly among the different study blocks. Block 3 (site with the highest silt, clay, and total organic material) had the highest exotic plant cover by 30-fold, exotic annual forb cover by 25-fold, and native perennial cover by six-fold (Figure 10b, d, e). Native plant cover, native annual cover, and native annual forb cover were highest in Blocks 2 (site with the highest biological soil crust and surficial gravel cover) and 3 (Figure 10a, c, f). Blocks 1 (site with the highest degree of disturbance and most coarse clast fragments) and 4 (site with the most mobile, sandy soils) had the lowest native plant cover, native annual cover, exotic annual forb cover, native perennial cover, and native annual forb cover among all the blocks (Figure 10a-f).

Blocks 2 and 3 also had the most cover when examining block × microsite type interactions. Native annual cover was highest among all microsite types in Blocks 2 and 3 (Figure 11b). While there was no significance between microsite types within blocks, general trends of the data show that native annual cover and shrub cover was higher in either the water catchment or the vertical mulch microsite types than the control (Figure 11b, c). However, whether the water catchment microsite type or vertical mulch microsite type had higher cover than the control microsite type was not consistent (Figure 11b, c). This trend is mirrored in the percentages of exotic annual graminoid cover among microsite types and blocks, aside from Block 4 (Figure 11a). Block 4 had higher exotic annual graminoid cover in control microsite types (Figure 11c). The outplants did not survive past three months regardless of block or microsite type.

Soil response

Soil responses and properties also varied across the study blocks (Table 2). The two geographically closest sites, Blocks 2 and 3, were sandy loams with bulk densities of 1.5 and 1.0 gm/cm^3 and pH of 8 and 7.7, respectively (Table 1). Blocks 1 and 4 were dissimilar from both Blocks 2 and 3 and each other (Table 1). Block 1, a loamy sand, had the highest bulk density and electrical conductivity of all of the sites (Table 1). The soils of Block 4 were sand, had the lowest electrical conductivity, pH, and a bulk density of 1.7 gm/cm^3, which is common in coarse-grained, sandy soils (Table 1).

Similar to vegetation, the soil response to restoration treatments was varied strongly among blocks. Blocks 2 and 3 had the highest median stability values and Block 4, the dune site, was the least (Figure 12a). This trend was mirrored in the soil moisture data (Figure 12b). Compaction had block × microsite type × outplanting interactions (Figure 14a, b). Despite 100% mortality, outplanting decreased compaction across all microsite types and blocks but this finding was not significant (Figure 14b). The control microsite types had the highest compaction in Blocks 1 and 4. Among the microsite types that did not have outplanting, vertical much had less compaction than both water catchment and control microsite types (Figure 14a). This trend was not as clear in the outplant microsite types.

Contrary to the other soil measurements, soil accumulation was significantly different across the main effect of microsite (Figure 13). Vertical mulch accumulated significantly more soil than the control and water catchment microsite types. The control microsite type lost 0.5 cm of soil on average whereas the vertical mulch microsite type gained on average 2.3 cm/16 months of soil.

Discussion

Plant response to restoration treatments

The variation in plant response to the restoration treatments deviated from my prediction that restoration treatments would increase vegetative cover. Plant cover trends among microsite type varied depending upon the plant category of interest. For Block 4, the dune site, plant cover was only significantly higher in the vertical mulch microsite type in the shrub category (Figure 11c). This trend was reflected in Block 3 but not to a significant degree (Figure 11c). While not significant owing to high variability among blocks, there were trends that indicated that the water catchment and vertical mulch microsite types had higher plant cover in the native annual plant cover and exotic annual graminoid categories (Figure 11a, b). Conversely, plant cover had significant trends among blocks (Figure 10a-e). Blocks 2 and 3 had the most native plant cover, native annual cover, and native annual forb cover (Figure 11a, c, f). Block 3 had the most native perennial cover, exotic plant cover, and exotic annual forb cover (Figure 11b, d, e). These data do not support the hypothesis that vertical mulch and water catchment microsite types enhance vegetative cover but do indicate that plant response varies markedly between different soils.

Much of the variability in plant cover may be understood in terms of different soil conditions and disturbances among the blocks. For instance, the greater *Ambrosia dumosa* seedling colonization at the vertical mulch microsite type of Block 4 may be attributed to the vertical mulch treatment capturing wind-blown material at this highly mobile sand sheet site. It is likely that Block 4's sandy, well-drained soils were less suitable for plant establishment than the soils of the other blocks. Conversely, the preferable soil conditions of Block 2 and 3 may be responsible for the higher plant cover. These sites are geographically closest and have a balance of sand, silt, clay, and organic material (Table 1, Table 2) more desirable for plant establishment and growth. The higher soil moisture and stability likely made these sites more conducive to native plant establishment. Block 1 yielded the lowest cover percentages of all of the blocks. Block 1 also had a higher amount of cobble sized clasts at the soil surface and throughout the profile, perhaps as a result of the clasts being churned up with ripping activities. The continual, harsh disturbances may have caused a structural crust (5-10 mm in thickness, common across the study site) atop the soil surface that was difficult to penetrate. These combined soil qualities may have restricted root penetration and plant establishment in Block 1.

While all of the outplants died within the first three months of planting regardless of microsite type pairing, the outplanting treatment may have had legacy effects. The greenhouse-grown outplants had soil with higher organic matter than that of the study sites, which could have contributed nutrients in the soil. Installing the outplants likely aided in further de-compacting the microsite types, as evidenced by the lower compaction levels in microsite types with outplants than those without.

Soil response to restoration treatments

The site conditions and degree of disturbance also influenced soil response. As with plant response, Blocks 2 and 3 largely had the most preferable soil responses. Median stability was significantly higher in Blocks 2 and 3 than Blocks 1 and 4, indicating that these sites have stronger soil aggregate strength and are more resilient to further degradation (Figure 12a). Considering that Block 2 had both the highest biological soil crust cover and surficial gravel cover, it is perhaps unsurprising that this site had the most stable soils after restoration treatment installation. Correspondingly, Block 3 soils had higher silt and clay content and higher organic matter content than the other blocks, all of which are properties that promote soil aggregate strength. The continued OHV use nearby Block 1 and the mobile, sandy soils of Block 4 likely lowered the lower median stability of these sites. Soil moisture followed the same trend as stability, likely for the same reasons (Figure 12b). The biological soil crusts and surface clasts at Block 2 may prevent the depletion of shallow soil moisture, making it more available to annual plants and perennial seedlings. The sandy loam soils and high organic matter content of Block 3 could retain more water than the sandier soils of Blocks 1 and 4. Due to the ripping in Block 1 and the dry condition of the study years, it is also possible that there was no stored subsoil moisture. Of all the measured soil responses, none exemplified the variance among blocks and microsite type as much as compaction. The primary trend evident among blocks was that outplanted microsite types were less compacted than the microsite types without an outplant

(Figure 14a-b). No other trends were clear among blocks although there were some trends within blocks. The vertical mulch and water catchment microsite types lowered compaction in Block 1 more than the control microsite type (Figure 14a-b). Block 4 also had lower compaction in the vertical mulch and water catchment microsite types that did not receive an outplant, although neither of these trends were significant (Figure 14a). In both Blocks 2 and 3, the water catchment microsite type had the highest compaction followed by control (Figure 14a). This trend did not hold in the outplanting microsite types (Figure 14b).

Implications for restoration

The variation of both plant and soil response among microsite types and blocks indicate that site conditions and level of disturbance have a large role in restoration success. Depending upon the study site's starting conditions, desired level of effort, and goals, this may be used to researcher's and land manager's advantage. For example, Block 1 was continually subjected to harsh disturbances and showed the least amount of natural recovery. The soil conditions were poor and potentially limiting to plant establishment. While Block 1 had some of the lowest cover percentages compared to other blocks, installing the restoration treatments lead to higher plant cover (when compared to controls). The installation of restoration treatments also lowered compaction and prevented soil loss. For a site with very little cover and poor existing soil conditions, this is not insignificant. Restoration treatments can also be modified for best success. In Block 3, native annual cover was not significantly influenced among microsite types. However, exotic annual graminoid cover was significantly different among microsite types. Disturbances caused by installing the restoration treatments may have enhanced exotic cover. If managers desired to use the treatments to promote soil accumulation and stability without also increasing exotic plant cover, the vertical mulch or water catchment treatments may be used in conjunction with an herbicide. Steers & Allen (2010) found that herbicide application within the Sonoran Desert would promote native cover and lower non-native cover if applied at the optimal time. A thorough understanding of the environmental factors influencing the study site will result in a more informed approach to restoration treatments and a more accurate understanding of final results.

My findings indicate that plant and soil response to restoration practices are strongly dependent on soil conditions. Understanding pertinent landscape characteristics and soil properties of a given restoration site lends a framework to both decipher results and install the most successful treatments. It may also indicate that treatments may not be successful in certain sites without additional effort. Future studies pairing soil properties and restoration treatments may further illuminate the role of site conditions in restoration success.

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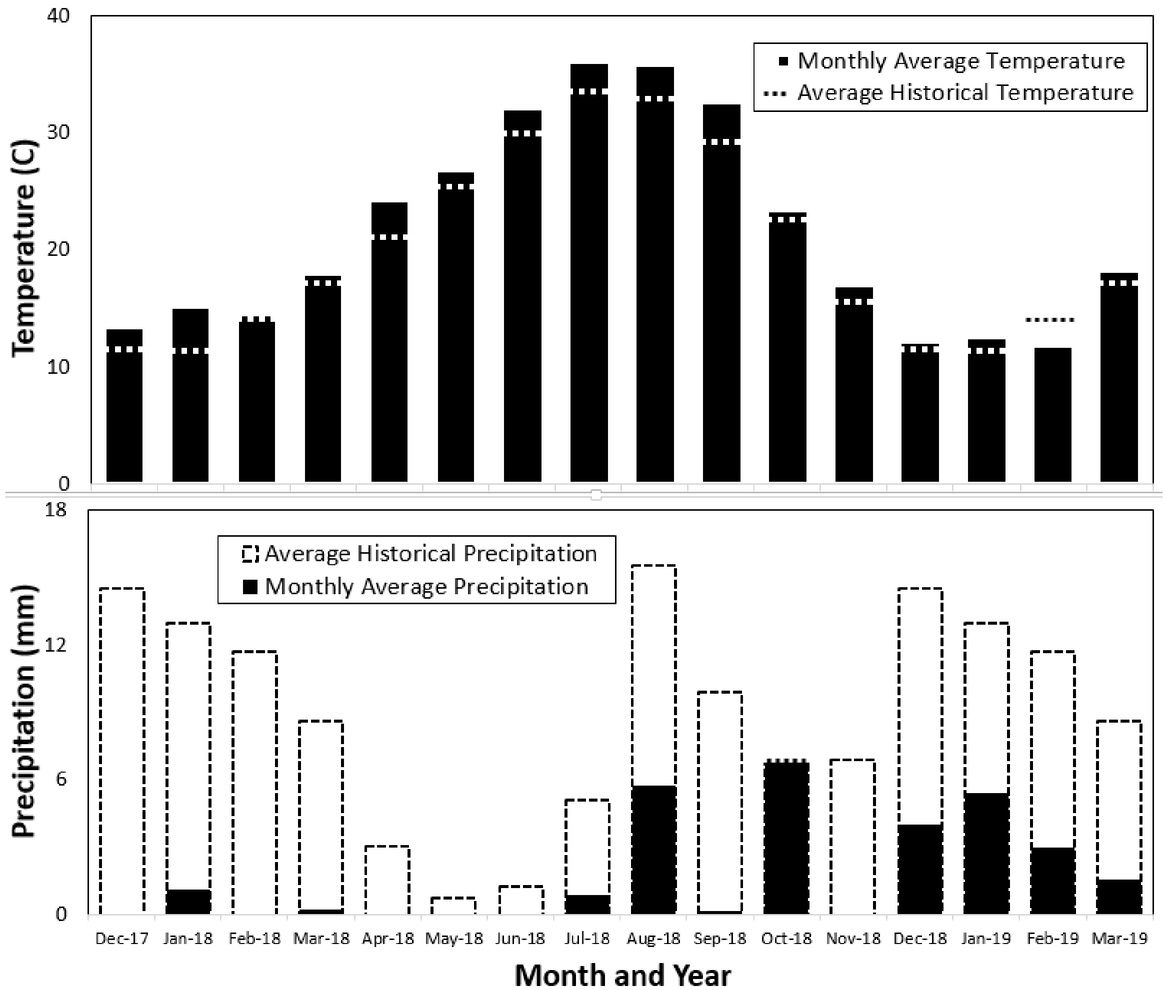

Figure 8. Precipitation and temperature data at the study sites in the 2017-2018 and 2018-2019 hydrologic years. Actual data from the National Oceanic and Atmospheric Administration Desert Center, CA and average data from Western Regional Climate Center.

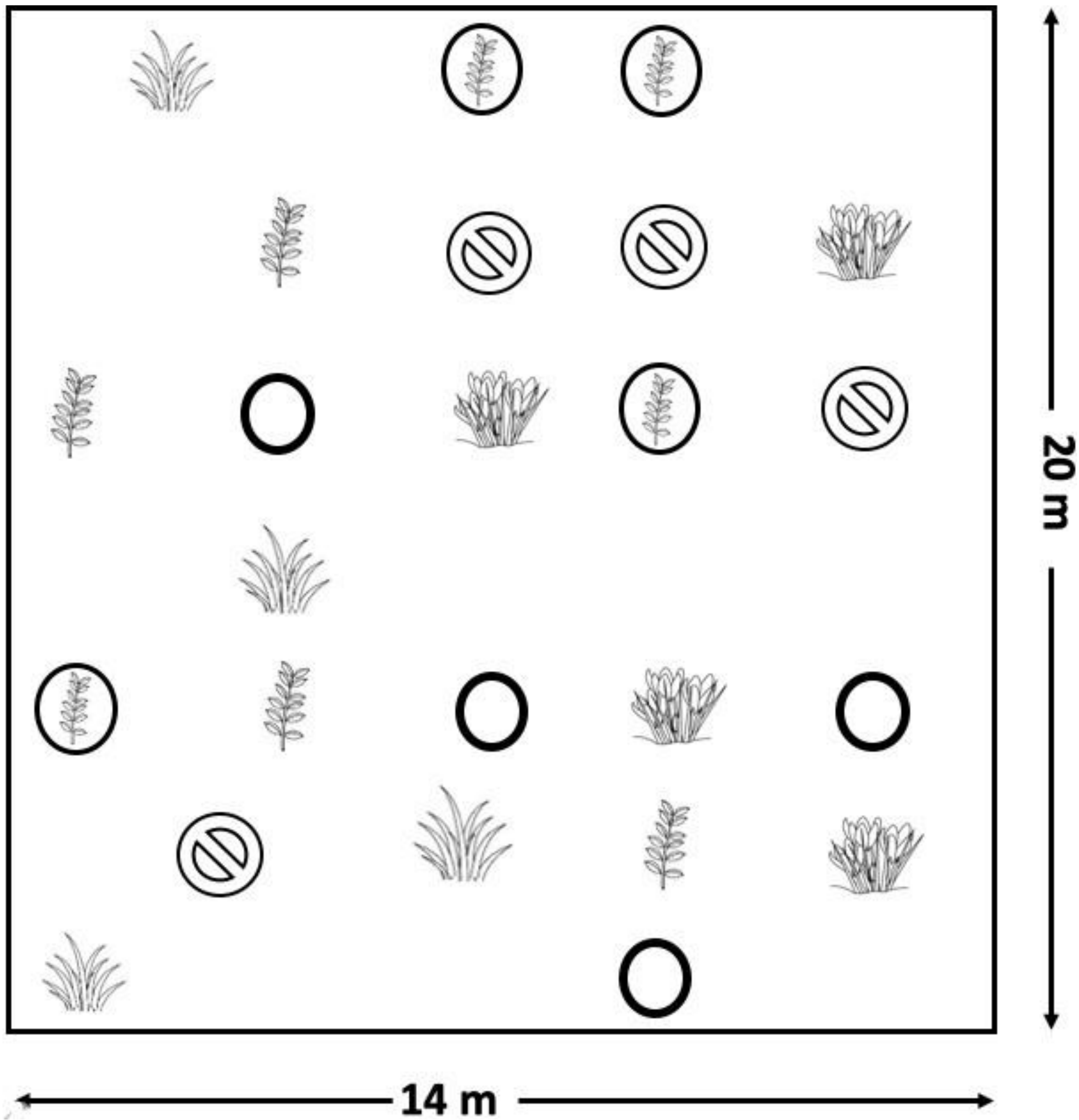

Figure 9. The study design for the restoration study blocks. Each block is 14 m x 20 m in size. Six microsite types were randomly placed throughout the block on a standardized grid. The microsite treatments (n=4) were outplant only, control, water catchment with outplant, water catchment only, vertical mulch with outplant, and vertical mulch only.

Block	Percent Sand	Percent Silt	Percent Clay	Electrical Conductivity (uS/cm)	Total Nitrogen (%)	Total Carbon (%)	pH	Bulk Density (g/cm^3)
Block 1	84.9	15.1	0	895	0.01671	0.24727	7.9	1.8
Block 2	77.4	19	3.6	701	0.01709	0.15857	8.0	1.5
Block 3	71.3	13.2	15.5	881	0.02801	0.4062	7.7	1.0
Block 4	94.2	5.7	0.1	537	0.01894	0.22183	7.8	1.7

Table 1. Raw values for soil properties at the disturbed study blocks in which ecological restoration treatments were implemented to stabilize soils and enhance habitat in the Sonoran Desert, USA. Soil values represent the 0-5 cm mineral soil.

Block	Date	UTM E	UTM N	Vegetation	Parent material	Geomorphic Surface	Slope	Description
Block 1	Dec-18	624765	3725869	Absent	Alluvium from gneiss or granitoid	Alluvial fan	4	Anthropogenic disturbed sand surface. Physical crust overlying sandy, rocky subsoil
Block 2	Dec-18	629504	3725989	Absent	Alluvium from gneiss or granitoid	Alluvial fan	4	Anthropogenic disturbed sandy loam with biological crust and gravel cover
Block 3	Dec-18	632578	3726398	Absent	Alluvium from gneiss or granitoid	Alluvial fan	5	Anthropogenic disturbed sandy loam with loose sand overlying silty subsoil
Block 4	Dec-18	686268	3718932	Absent	Alluvium from gneiss or granitoid	Alluvial fan	4	Anthropogenic disturbed sand sheet. Decimeters thick. Surrounding, reference area had coppice dunes <50 cm present.

Block	Depth (cm)	Color (moist)	Structure	Gravel %	Cobble %	Stone %	Texture	Crust	$CaCO_3$ %
Block 1	0-5	10YR 6/4	Single Grain	10	10	0	Loamy sand		
	5-60	10YR 6/4	Single Grain	10	20	5	Cobbley coarse sand	Physical	0
	60-100	10YR 6/4	Single Grain	10	20	2	Gravelly coarse sand		
Block 2	0-4	10YR 6/3	Single Grain	15	0	0	Gravelly loamy fine sand		
	4-23	10YR 6/4	Single Grain	5	0	0	Gravelly fine sand	Biological	0
	23-62	10YR 6/4	Single Grain	33	0	0	Gravelly sand		
	62-100	10YR 4/4	Single Grain	5	0	0	Gravelly coarse sand		
Block 3	0-4	10YR 4/4	Single Grain	10	0	0	Sandy loam	Absent	
	4-31	10YR 4/4	Single Grain	15	0	0	Gravelly loamy sand		0
	31-100	10YR 6/3	Single Grain	30	0	0	Very gravelly coarse sand		
Block 4	0-38	10YR 6/4	Single Grain	8	0	0	Medium sand	Absent	0
	38-100	10YR 6/4	Single Grain	8	0	0	Gravelly coarse sand		

Table 2. Soil pit characterizations for the study blocks. Site descriptions were conducted for each of the study blocks. Pits were dug to one meter depth and characterized for moist color, structure, rock fragment percentage, texture, presence of soil crusts, and effervescence.

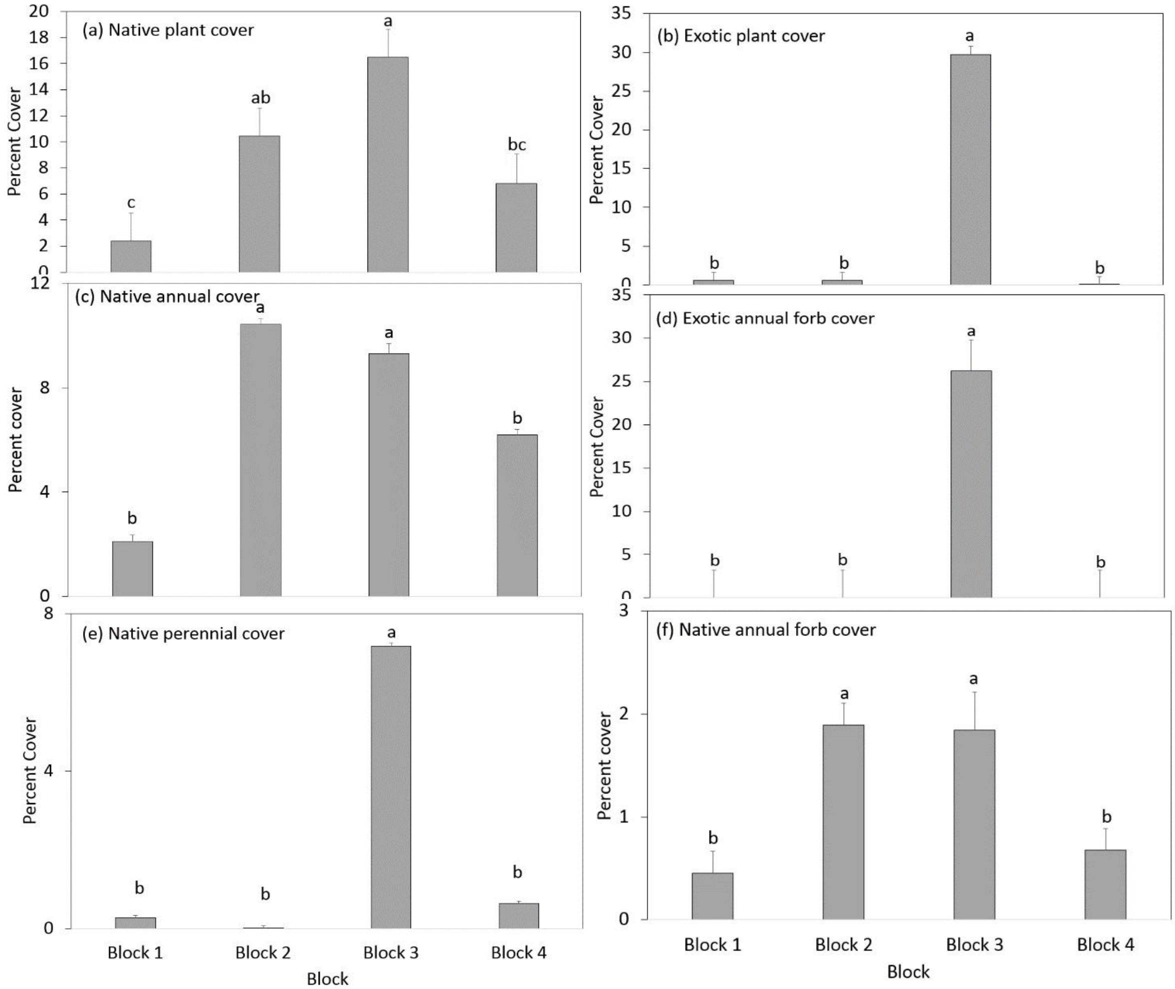

Figure 10. Significant effects for mean (a) native plant cover, (b) exotic plant cover, (c) native annual cover, (d) exotic annual forb cover, (e) native perennial cover, and (f) native annual forb cover among blocks. Letters indicate statistically significant groups ($p<0.05$). Error bars +1 SEM.

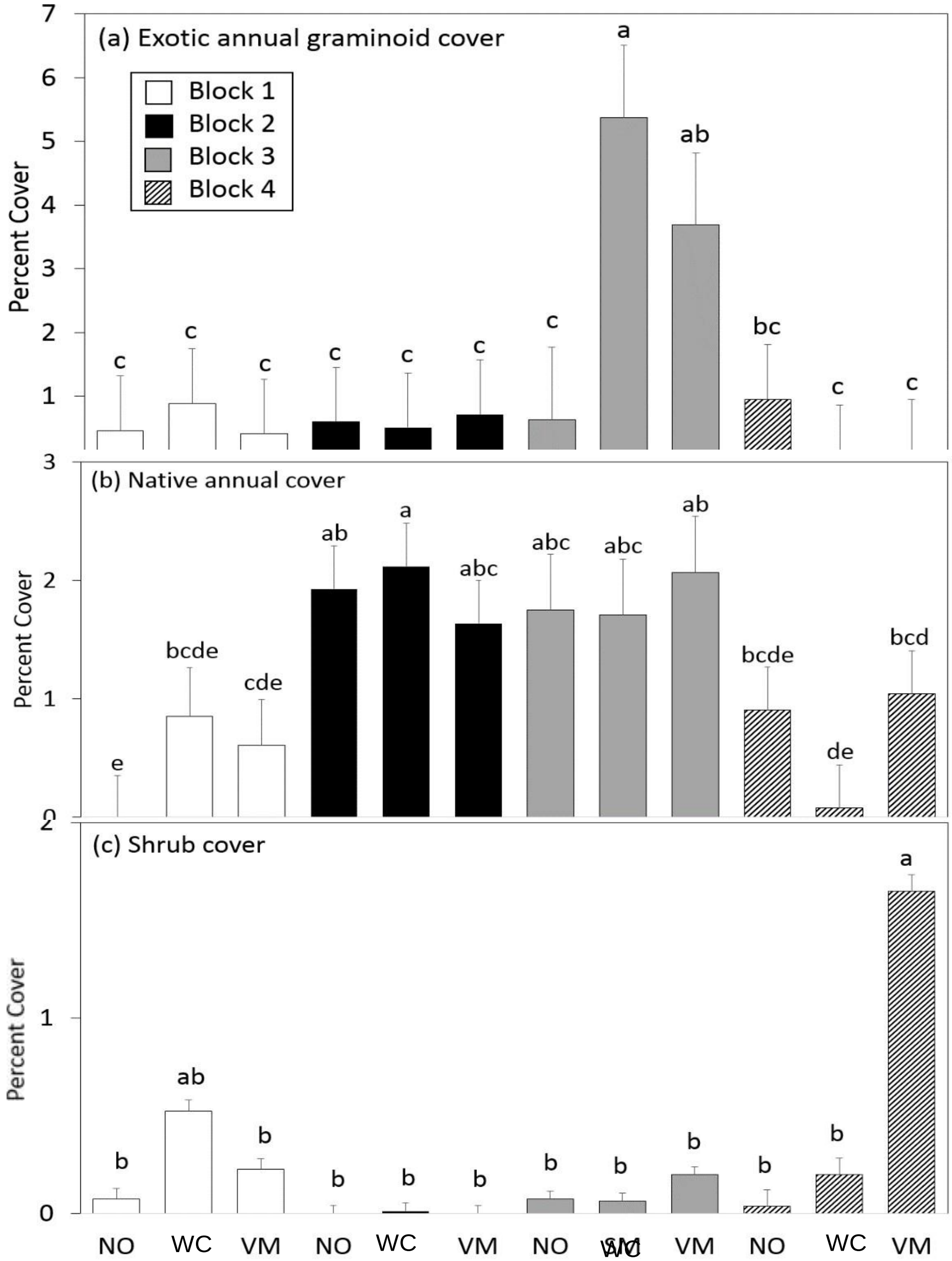

Figure 11. Significant block × microsite type interactions on (a) exotic annual graminoid cover, (b) native annual cover, and (c) shrub cover. The microsite types are No=no treatment, WC=water catchment, VM=vertical mulch. Values are means and error bars +1 SEM. Letters indicate statistically significant groups (p<0.05).

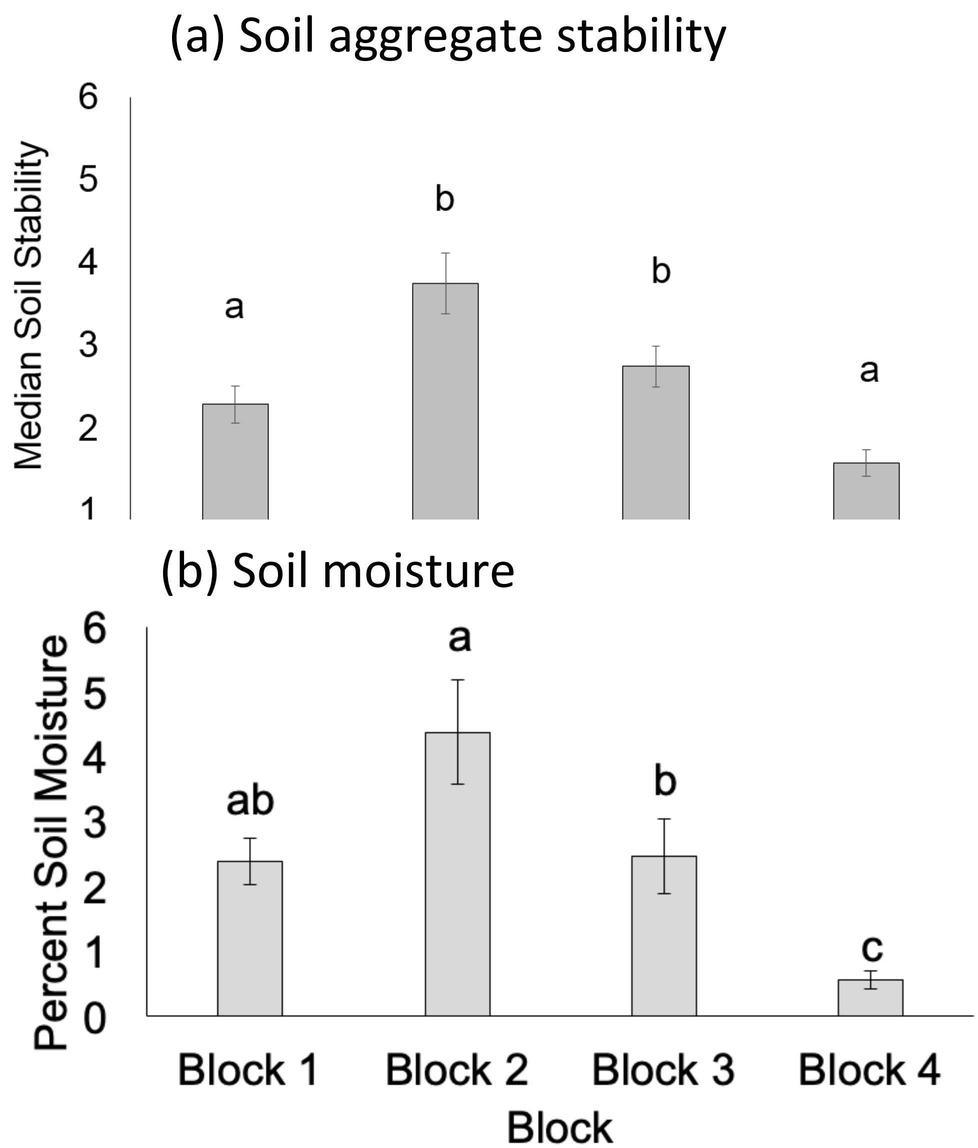

Figure 12. Significant effects for median stability (a) and mean soil moisture percent (b) organized by block. Error bars are Error bars ±1 SEM. Letters indicate statistically significant groups ($p<0.05$).

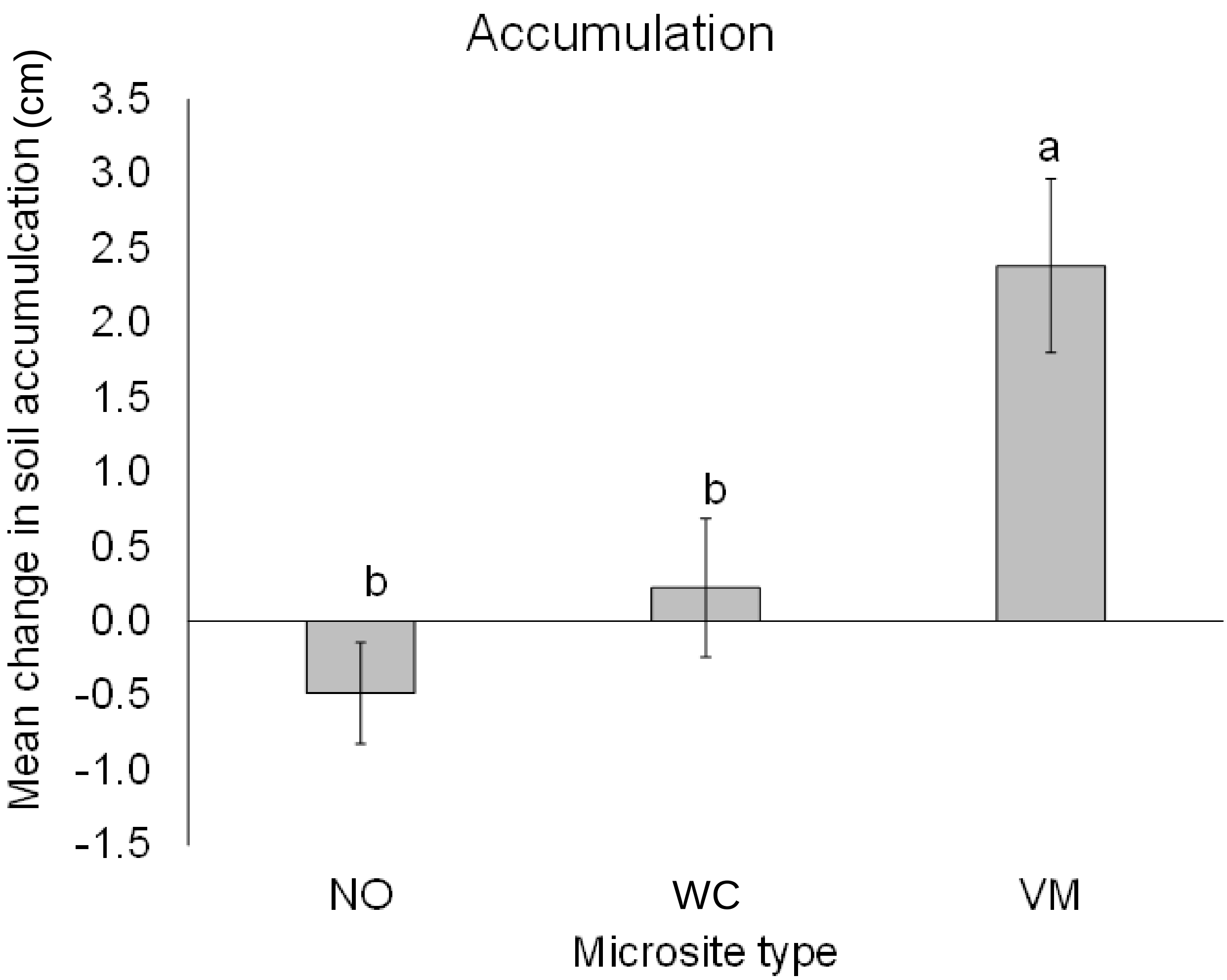

Figure 13. Significant effects for mean soil accumulation among microsite types (NO=no treatment, WC=water catchment, VM=vertical mulch). Error bars ±1 SEM. Letters indicate statistically significant groups ($p<0.05$).

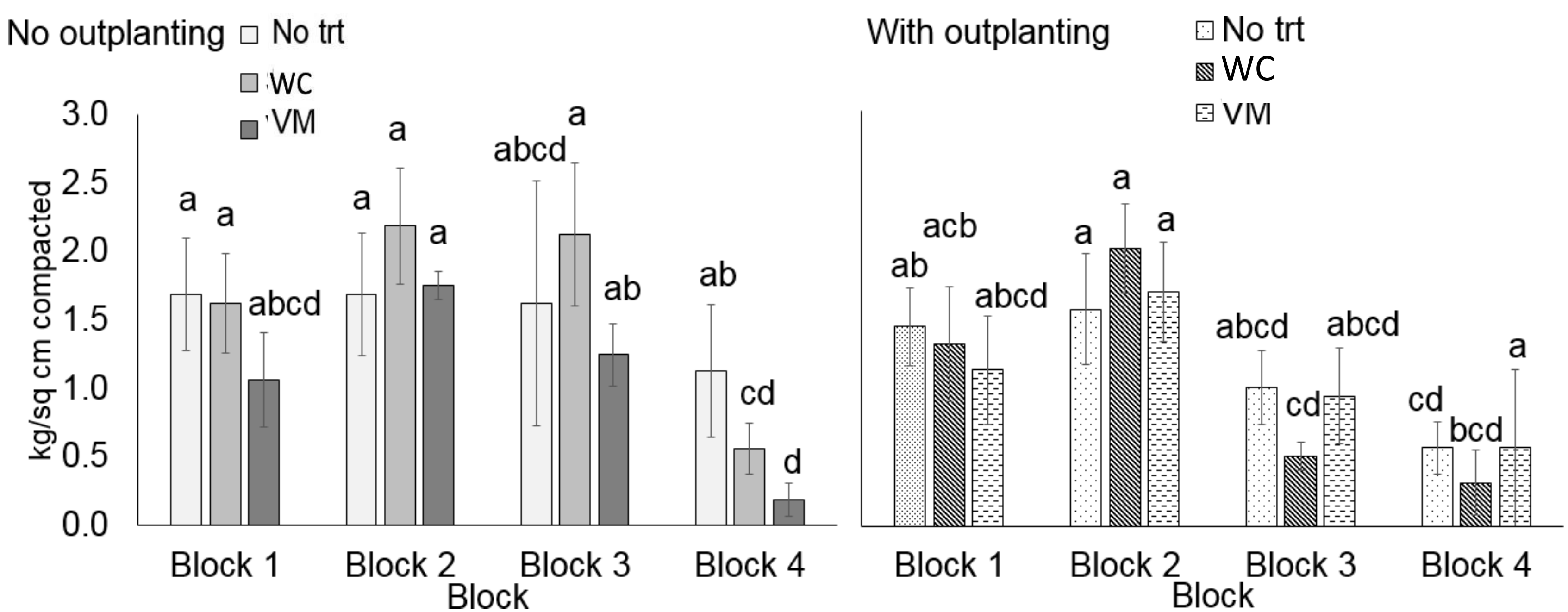

Figure 14. Significant treatment effects on compaction on microsite types (a) without outplanting and (b) with outplanting. The microsite types are No trt=no treatment, WC=water catchment, and VM=vertical mulch. Values are mean kg/cm^2 of soil compressional strength. Error bars ±1 SEM. Letters indicate statistically significant groups ($p<0.05$).

CHAPTER 5
CONCLUSION

Healthy desert ecosystems are vital to erosion resistance, the native flora and fauna, carbon sequestration, and the 33% of human populations that live and thrive there. Due to limiting factors such as low levels of precipitation, depauperate vegetation, and high temperatures, desert ecosystems are sensitive to human-induced disturbances. In addition, desert ecosystems may take centuries to millennia to recover naturally after severe disturbances. As a result, there is high incentive for land managers to effectively restore disturbed desert ecosystems. Revegetation, seeding, and soil surface manipulations are all viable options for restoration efforts with varying levels of success.

This thesis developed and investigated cost-effective restoration techniques to address the need for minimal-input restoration techniques in disturbed desert ecosystems. My study found that vertical mulch enhanced plant cover, soil moisture, and soil stability. De-compacting the soil also followed these trends in comparison to the experimental controls during the wet study year, meaning that it may also be a viable restoration technique. However, solely de-compacting the soil would provide none of the visual benefits of vertical mulch. The vertical mulch structure also lowered soil compaction and ambient air and soil temperatures. Therefore, vertical mulch may have a buffer effect on microsites. Vertical mulch may potentially behave as a dead fertile island shrub. Seeding with litter in conjunction with vertical mulch did not yield significantly higher plant cover than in non-seeded sites. However, the seeded vertical mulch sites had plant cover values more similar to reference sites. Combining vertical mulch with other treatments may yield the best results, depending upon restoration goals. The results of this study suggest that vertical mulch is a viable restoration treatment and should be investigated further.

This thesis also aimed to determine the most successful restoration techniques across a gradient of soil types and disturbances. Whereas soil accumulation was highest at the vertical mulch microsite type, plant cover, soil compaction, soil stability, and soil moisture mostly had significant trends on a block level. These findings suggest that soil and site conditions may have a larger role in restoration success than previously thought. Plant and soil responses were more favorable in sites with higher silt and clay content and C/N ratios. Where disturbances were more severe and continued, plant cover and stability were lower. However, in the most disturbed site, the restoration treatments had the most distinct influence. This is most evident in the compaction levels, which was significant on a microsite level. Thus, while restoration treatment success varies greatly among different soil types and disturbance levels, it still improved site conditions. Further developing this contextual framework for restoration practices may assist in understanding variability in restoration success and developing optimal restoration techniques.

The data suggest that vertical mulch provides both visual and ecological benefits to disturbed ecosystems. Vertical mulch and, to a lesser degree, soil de-compaction are viable restoration treatments to improve soil's ability to resist erosion and provide ecosystem services to vegetation over time. Vertical mulch may be combined with other minimal-input restoration treatments, such as seeding with litter, or more intensive treatments, such as applying herbicide, to achieve desired goals for the area of interest. Before installing restoration treatments, it may be beneficial to first investigate the conditions of the site of interest. In order to fully understand how minimal input restoration techniques such as vertical mulch influence soil properties and perennial vegetation, long term monitoring of vertical mulch is necessary. While the studies associated with this thesis investigated short term responses that indicate the initiation of long term recovery, it found short-term results within two years, which encapsulated different weather conditions. Further research should be conducted on seeding with litter, de-compacting the soil surface, and vertical mulch across a series of soil and disturbance gradients to determine the ecological role of these techniques in disturbed soils.

CURRICULUM VITAE

Audrey Rader
Email: audreyjeanrader@gmail.com

EDUCATION

University of Nevada, Las Vegas Aug 2017 – May 2019
MSc Biology-Ecology and Evolution 4.0 GPA
University of Nevada, Las Vegas Aug 2012 – May 2017
BSc Geoscience

PROFESSIONAL EXPERIENCE

Graduate Research Assistant Aug 2017 – May 2019
University of Nevada, Las Vegas
- ➢ Designed, established, and monitored restoration projects to address anthropogenic disturbance concerns
- ➢ Conducted greenhouse studies, laboratory analyses, literature reviews, and outreach to educate public
- ➢ Published research findings and scientific data at conferences and in peer-reviewed journals

Research Associate/Ecological Monitoring Technician May 2018 – Aug 2018
Great Basin Institute (GBI) and Bureau of Land Management (BLM)
- ➢ Made observations and recorded botanical and soil data using federal protocols; performed computer data entry, quality assurance/quality control, editing, and retrieval tasks to verify scientific data.
- ➢ Prepared weekly and monthly reports for scientific data information requests for BLM and GBI
- ➢ Used GIS, ENVI, and Google Earth to create maps to navigate to randomly generated plot coordinates

Research Assistant May 2016 –Aug 2017
University of Nevada, Las Vegas
- ➢ Assisted in the implementation and monitoring of restoration projects in the Sonoran and Mojave Deserts; analyzed soils collected from the research group’s study sites; analyzed findings
- ➢ Assisted with soil media inoculation studies for the purpose of developing treatments for restoring biological soil crusts and stabilizing soils; propagated microbial soil communities in the greenhouse

Research Assistant Mar 2016 –May 2017
University of Nevada, Las Vegas
- ➢ Used geospatial imaging software to better understand the geologic sources and distribution of natural background radiation

- Mapped radiation, elevation, and drainage elevation models using ArcGIS, ENVI, and remote imaging sources; digitized maps and produced quarterly reports for the Department of Energy

Student Worker Mar 2015 –May 2016
USDA-FS & Forest Inventory and Analysis Program
- Conducted research and developed user documentation for a national forest and grassland monitoring and analysis program
- Gained proficiency in the suite of Design and Analysis Toolkit for Inventory and Monitoring (DATIM) programs, including Spatial Intersection Tool plugin for ArcGIS, Analysis Tool for Inventory and Monitoring, and DATIM Compilation System

PUBLICATIONS

Rader, A., Abella, S. Assessing vertical mulch as a minimal-input strategy for restoring desert soil functions. [abstract]. Proceedings of Ecological Restoration Conference; Sept 12-14; Flagstaff (AZ): SER; 2018.

Rader, A., Are we getting hotter with age?: Correlating land development and temperature in the Las Vegas Valley. [abstract]. University of Nevada, Las Vegas Geosymposium Conference; April 28; Las Vegas (NV): Geosymposium; UNLV; 2017.

David, W.; Andrew, G.; Pollard, J.; Brand, G.; **Rader, A.**; Negovschi, M. 2017. Design and Analysis Toolkit for Inventory and Monitoring (DATIM): User Guide version 7.0.1. U.S. Department of Agriculture, Forest Service. 308 p.

Rader, A., Chiquoine L, Abella, S. Comparing disturbed and undisturbed soils as a basis for developing soil rehabilitation techniques in arid landscapes. [abstract]. Proceedings of the Society of Ecological Restoration Conference; Nov 9-11; Las Vegas (NV): SER; 2016. Abstract nr 9.

VOLUNTEER WORK

2018| Glen Canyon National Recreation Area Volunteer (applied restoration ecology), Clark County Wetlands Park Volunteer (educational outreach), Meow or Never Cat Rescue Volunteer
2017| Spring Monitoring Volunteer (data collection), Keep Las Vegas Beautiful Clean Up Volunteer (homelessness outreach), Clark County Wetlands Park Volunteer (outreach), Meow or Never Cat Rescue Volunteer
2016| Keep Las Vegas Beautiful Clean Up Volunteer (homelessness outreach)
2015|Grand Canyon National Park Service Conservation Volunteer (restoration), Habitat for Humanity ReStore Volunteer

TRAININGS AND SKILLS

- Proficient in the Spanish language

- Three months of experience with Assessment, Inventory, and Monitoring (AIM) and Habitat Assessment Framework (HAF) Protocols.
- Wilderness First Aid Certified through the National Outdoor Leadership School (NOLS)
- Possess working knowledge of soil taxonomy, soil morphology, soil chemistry, botany of North American plant families and genera and the species of the Intermountain West and Desert Southwest
- Trained in experimental design, data collection QA/QC, navigating and logging points using GPS, field safety, off-road driving, backcountry camping, Leave No Trace principles, and integrated pest control
- Experience in drafting reports, statistical analyses, and writing manuscripts
- Proficient in Microsoft Office Suite (Excel, Access, Word, PowerPoint), MiniTab, R, SPSS, SAS, ENVI, GPS, Google Earth Pro, BaseCamp, ArcMap products, and Adobe Illustrator

GRANTS AND AWARDS

University of Nevada, Las Vegas

- Alumni Association Scholarship, 2018, 2019
- Farouk El-Baz Scholarship, 2019
- First Place: Geosymposium Conference Poster Presentation Contest, 2017
- UNLV Grant, 2013, 2014, 2015, 2016, 2017
- Bernarda French Grant, 2015, 2016, 2017
- Anne Fenton Wyman Scholarship, 2016, 2017
- Rebel Achievement Scholarship, 20
- Second Place: Society for Ecological Restoration Conference Poster Presentation Contest, 2016
- Bob Davis Scholarship, 2013, 2014, 2015
- Honorary Commendation for Academic Excellence, 2014
- Nevada Gear Up Grant, 2012, 2013, 2014, 2015, 2016, 2017

MEMBERSHIPS

2017-2018| Founder of the UNLV Botany Club (2017-2018)
2016-2017| Secretary of the UNLV GeoClub (2016-2017)
2016-2019| Member of Sigma Xi Scientific Research Honor Society, Society for Ecological Restoration, Association of Environmental & Engineering Geologists- Southern Nevada Chapter, American Society of Agronomy, Geological Society of America, Soil Science Society of America, UNLV Wilderness Club