

**INCREASING WATER RETENTION IN ARID SOILS THROUGH BIOLOGICAL
AMENDMENTS: ADAPTIVE ROTATIONAL GRAZING, CYANOBACTERIA INOCULATION,
AND COMPOST EXTRACT**

by

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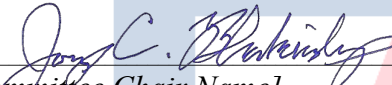
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LAND ACKNOWLEDGEMENT

We respectfully acknowledge the University of Arizona is on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, with Tucson being home to the O'odham and the Yaqui. Committed to diversity and inclusion, the University strives to build sustainable relationships with sovereign Native Nations and Indigenous communities through education offerings, partnerships, and community service.

DEDICATION

To Julie. This success is as much yours as mine.

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ABSTRACT

If drought conditions continue, as expected, how can land managers prepare their fields to endure ongoing water rationing? Often adding biodiversity to land is seen as a liability to water resources, but perhaps biodiverse soil treatments can be a cost-effective tool for land managers. This research and literature review will synthesize experiments using compost extract and cyanobacteria inoculations as soil amendments to improve water retention and compare those results with experiments using adaptive rotational grazing (ARG) of livestock as a biological soil amendment positively impacting water retention. The experiment will also compare one year of ARG to three years of ARG. Data show that neither microbial inoculation helped to create more soil organic carbon, lower soil bulk density, or increase soil water infiltration. However, ARG did significantly increase soil organic carbon and marginally significantly decrease soil bulk density in the short term. Longer term increases were smaller. Based on these results, we suggest ARG is a more effective treatment for affecting soil hydrology compared to microbial treatments in hot arid systems.

Review of Biological Treatments for Improving Arid Land Soil Health: Rotational grazing and Cyanobacteria

1. Introduction

Drylands cover over 40% of Earth's landmass and in 2019 The United Nations prioritized dryland restoration on its list of sustainable development goals (United Nations Sustainable Development Goals, 2019; Antoninka et al., 2020). Each year, roughly 12 million hectares of land are newly classified as degraded (IPBES, 2018). An estimated 50-700 million people of the more than 2 billion people that currently live in arid regions are likely to migrate due to land degradation and climate change by 2050 (IPBES, 2018; Berdugo et al., 2020). These ecosystems are being degraded through human activity, with the "unsustainable management of croplands and grazing lands [...] currently the most extensive direct driver of land degradation," and global climate change exacerbating land degradation impacts while complicating current solutions (Kemp & Michalk, 2007; IPBES, 2018, p. 3; Antoninka et. al., 2020, Berdugo et. al., 2020).

Abundant research points toward greater biodiversity as a requirement for stable arid ecosystems (Hector & Bagchi, 2007; Maestre et al., 2012; Zavaleta et al., 2010; Bowker et al., 2013). Arid landscapes are a punishing environment for soil, plant, and animal species not well-adapted to the extremes of temperature and water availability often present. Therefore, encouraging greater biodiversity is often a major challenge. Increasing the amount of water held in the landscape would help mitigate some of these challenges. Soil health is a keystone metric for arid lands and healthy soils hold more water, which creates a more suitable environment for plants to thrive and reduces dust (a contributor to poor human health in arid regions). To improve soil health in these challenging arid environments, this literature review aims to assess and compare two land treatment approaches that focus on increasing biodiversity: macrofauna and microfauna.

First, adaptive rotational grazing (ARG), otherwise known as high-intensity multi-paddock grazing, is a method of grazing livestock (macrofauna), especially cows, goats, and/or sheep. Scientists and practitioners of ARG hypothesize that by keeping the animals densely stocked in small paddocks and moving the animals regularly to new paddocks of fresh pasture, land managers can protect the health of their animals, vegetation, and soils. The animals experience less parasite pressure from being around their own waste, and the soils and grasses have time to recover from the animal impact before being grazed again (Prasad et al., 2019). Some studies point to perennial grasses returning to fields from the disturbed seedbank in the soil and existing grasses growing more vigorously after ARG (Gosnell et al., 2020). As many drylands are already in use as rangeland, and unsuitable for many other purposes, ARG could be a relatively inexpensive option for land managers who would like to improve the health of their soils while also keeping the land in production.

The second arid land treatment approach being assessed in this review is inoculation of soils with cyanobacterial cultures. Cyanobacteria are photosynthesizing prokaryotes (microfauna) commonly found near the surface of most soils and are particularly important to desert soil crusts. Many scientific trials are attempting to find ways to inoculate degraded soils with cyanobacteria soil crusts as a soil restoration method. To inoculate soils, cyanobacteria communities can be harvested from healthy biocrusts, and in many cases, grown in liquid solutions to be applied to degraded areas (Bowker, 2007). In healthy

communities, cyanobacteria produce biological soil crusts that bind the top few millimeters of soil together into aggregates (Belnap et al., 2016; Antoninka et al., 2020). In arid lands cyanobacterial crusts can perform crucial ecosystem services including mitigating soil erosion and fixing and releasing carbon, nitrogen, and other micronutrients in the soil (Bethany et al., 2019). Effective inoculations for depleted arid soils exist but implementing them is the challenge now being faced. Therefore, research into nurturing cyanobacteria populations in arid ecosystems has the potential to improve arid soil health.

This literature review synthesizes research from 63 published articles that address two approaches to improve arid lands through enhancing biodiversity: adaptive rotational grazing of macrofauna above ground, and microfauna cyanobacterial inoculations below ground. Sources were found using the University of Arizona library website (lib.arizona.edu) and the following keywords: arid land, biological soil crust, cyanobacteria, rotational grazing, soil carbon, soil water storage, and water infiltration. Articles were selected for topic relevance particularly within arid landscapes. Some articles cited in articles from our initial search were also referenced in this review. First, by identifying the benefits of each of these treatments to soil health, when and how these techniques are most effectively used, and why land managers might choose to implement them, this review can inform future land management on new strategies. Second, by identifying the uncertainties and the “known unknowns” in the literature, this review can help land managers implement these biological treatments successfully.

2. Adaptive rotational grazing

Adaptive rotational grazing (ARG) has potential to be an effective tool in arid land ecological restoration. In their own review of ARG practices and benefits, Gosnell et al., (2020) highlighted positive ecological outcomes of ARG: reduced bare ground, increased soil moisture, improved soil respiration and topsoil depth, and more organic matter.

2.1. Reduced bare ground and increased soil moisture

Reducing bare ground in arid environments has many benefits. During rain events, plants and plant litter (i.e., the fallen leaves and other plant matter that create a mulch on the soil surface) slow down water to prevent rainwater from rushing across the surface and allowing it more time to infiltrate into the soil (Teague et al, 2011; Xu et al., 2018). Arid lands, by definition, have minimal precipitation, so holding the water that *does* come through the system *in* the system is key to supplying water to soil and plant biodiversity. Bare ground is also exposed to the sun and therefore gets hotter than less exposed areas. Hotter soils lead to increased evaporation, which means that not only does bare ground infiltrate less water, but water also evaporates from the soil more quickly. ARG has repeatedly shown to reduce bare ground (Allen, 2007; Leake et al., 2004; Teague et al, 2011; Xu et al., 2018; Hawkins et al, 2021). The benefits to soils retaining extra water are highlighted in Table 1 with improved plant growing conditions being particularly meaningful.

In their 2001 review of grazing approaches and their impact on soils, Greenwood and McKenzie highlight several environmental factors that affect soils moisture including greater plant cover, living and decaying roots increasing infiltration rates, and greater swelling/shrinking and freeze/thaw effects associated with soils of higher clay content. They highlighted the complex effects of grazing on soil moisture depending on the existing conditions—that is, observed soils with greater plant cover could retain more soil moisture

with minimal grazing due to higher infiltration rates and lower soil evaporation, while fields grazed more heavily may have had higher soil moisture due to lower levels of plant transpiration (Greenwood & McKenzie, 2001).

Our research did yield studies in which grazing benefits to increased plant cover were not observed. In their 2018 study of grazing management approaches across 17 farms in Wyoming and Colorado, Wilmer et al. found that ecological outcomes such as ground cover and plant species composition were minimally affected by the grazing management approaches studied. More mixed results were found in a four-year study in Argentina—soil plant cover remained unchanged in continuous grazing and in rotational grazing regimes, but changes in plant species densities were observed with rotational grazing (i.e. C3 grass populations increased, while C4 grass populations decreased, causing no overall change in soil cover) (Jacobo et al., 2006). The authors noted the hilly topography in the region was the largest contributing factor to differences observed, as the well-draining soils of the mid- slope (“Hapludols” and “Argiudols”) experienced a gradual change in plant species population densities over the four years, while wetter soils in the lowlands only experienced these effects during the drier years of the study (Jacobo et al., 2006). Thus, drier soils benefited more from ARG in this study. These results indicate plant species and soil drainage may impact the observed results of ARG, and that cool arid landscapes may not benefit from ARG as much as hot drylands do.

2.2. Improved soil respiration and topsoil thickness

A defining characteristic of ARG is that the grazing animals are moved to fresh ground regularly. This frequent animal movement is intended to allow plants and soils time to recover. Several studies have found multiple benefits in soils given these recovery periods. In years two and three of an ARG study, researchers found significant increases in soil macroporosity in fields treated with ARG compared to control fields (Cattle & Southorn, 2010). Macroporosity means a greater number of “larger pores” (>80 μm) in the soil, which create spaces for more oxygen, organic matter, and water within the soil, thus leading to increased microbial activity and increased water retention (Cattle & Southorn, 2010). Increased macroporosity and the resulting benefits were also found to stabilize soil structure and quality more so than soils not exposed to ARG (Cattle & Southorn, 2010). In a similar study, these stable soil structures led to thicker topsoil over time (Teague et al., 2011). ARG-treated fields also stimulated the growth of higher-quality grasses with deeper root zones, meaning the plants had access to an increased volume of soil (and soil nutrients) compared to those of control fields (Teague et al., 2011). These benefits to soil structure and topsoil thickness indicate ARG can lead to meaningful impacts in arid soils.

However, some studies did yield contrary results. In their 2001 review of grazing approaches and their impact on soils, Greenwood and McKenzie did not find published evidence of recovery of soils after the removal of animals. Rather than treatments, their review found higher soil organic matter, lower initial bulk density and, higher clay content, were associated with greater soil recovery under any treatment type (Greenwood & McKenzie, 2001). Greenwood and McKenzie also indicated no significant difference in topsoil bulk density between treatment types, meaning soil respiration was not increased (Cattle & Southorn, 2010).

2.3. Increased soil organic carbon

Grazing animals can add carbon and other organic matter to soils through several mechanisms. First, grazers can stimulate increased plant growth, particularly by increasing root biomass. Second, their

trampling can increase litter incorporation below the soil surface (Xu et al., 2018). Studies show ARG can multiply these benefits and consequently increase plant productivity by 30% in the top 30 cm of the soil profile as compared to conventional grazing (Xu et al., 2018). One study involving grazing goats – notable in their ability to eat woody shrubs in addition to grass while browsing – found even greater increases in soil organic carbon, showing the type of vegetation available may indicate which browsing/grazing animal could be most effective in that landscape (Hawkins et al., 2021). The presence of browsing livestock reduced shrub encroachment in pastures and helped transfer that woody material into soil organic carbon (Venter et al., 2018; Hawkins et al., 2021). This study also found that the organic carbon gains found during ARG treatments were more likely and more pronounced in arid rangelands (Sanderson et al., 2020; Hawkins et al., 2021). The overall benefits of soil organic carbon to arid soils are indicated in Table 2.

Tempering the above results are the findings from Henderson et al. (2015) who used modelling to estimate changes in global soil carbon as a result of changing traditional grazing to ARG. They calculated the SOC gains at 0.13–0.32 t C ha⁻¹ yr⁻¹, which are very small gains, especially compared to some of the claims proponents of ARG make concerning SOC (Hawkins et al., 2021).

2.4. Regional differences

Proponents of ARG point to many of the above claims as proof that the method works. But many of these claims have been contested. Briske et al. (2013) did a study in which very little soil organic carbon was added under ARG treatments. Their main conclusion was that the benefit of ARG seems to be in the adaptive nature of the management strategy and planning, in other words that the benefits were social, not ecological (Briske et al., 2013; Gosnell et al., 2020). In fact, there are many studies refuting the claims of ARG because the ecosystems being studied are complex and many factors (not just ARG) may influence the improvement of soils (Hawkins et al., 2021). But Hawkins and Gosnell both point out that these differing results seem to be regionally grouped—there are more contradictory results from the wetter temperate regions of Europe and North and South America, whereas more confirmatory results in drier landscapes in Oceania and Southern Africa (Gosnell et al., 2020; Hawkins et al., 2021). Sherren & Kent (2017) also identify this regional discrepancy and provide a potential explanation for this geographical pattern: they hypothesize that ARG is more successful in “brittle ecosystems.” They define brittle ecosystems as “those with prolonged dry periods that challenge plant growth and where low soil biota makes for slow nutrient cycling” (Sherren & Kent, 2017). Many of these studies seem to point toward ARG as a viable option in hot arid regions, but not in cooler or wetter regions. Brittle ecosystems may be another way of describing Walker and Salt’s (2006) idea of systems near their resilience threshold (low resilience), where seemingly small changes can push a system into an “alternate regime.” Fischer’s (2009) results from arid Australia seem especially compelling that ARG has merits in hot arid climates. They found that land regeneration (defined in this study as increasing tree canopy cover over time measured with remote sensing) was up to four times more probable using ARG than by using conventional grazing techniques (Fischer et al., 2009). They concluded “reducing nutrient inputs and applying [ARG] can substantially enhance regeneration” (Fischer et al., 2009). This study, and others previously mentioned, indicate that dominant vegetation may be a compounding factor in the effectiveness (or lack thereof) of ARG. Topography and how well soils drain also seem to contribute to this equation. Clearly the ecosystems in which ARG is implemented will always be complex, but drier systems seem to be closer to their resilience thresholds and therefore more likely to benefit from ARG.

3. Soil cyanobacterial amendment

Another arid land treatment approach is inoculating soils with cyanobacteria species that can emulate biocrusts. Bowker et al. (2014) describe biocrusts as “miniature ecosystems, performing all the vital functions of larger ecosystems, but at a smaller scale.” Cyanobacteria are photosynthesizing microbes common in arid soils (Belnap et al., 2016; Antoninka et al., 2020). Many cyanobacteria species are filamentous in structure (i.e. genera *Microcoleus* and *Hydrocoleum*) forming long threads, sometimes called “rope-building” (Garcia-Pichel & Wojciechowski, 2009). These macroscopic threads, usually 50–200 µm in size, help to bind soil particles together, thus contributing to the formation of biological soil crusts often found in the interspaces between plants in arid environments (Garcia-Pichel & Wojciechowski, 2009; Bethany et al., 2019). This behavior allows cyanobacteria to colonize unstable sedimentary soils, providing a pioneering bio-stabilization effect in the soil (Garcia-Pichel & Wojciechowski, 2009). For these reasons cyanobacterial biocrusts have caught the attention of many scientists for their potential to improve ecosystem functions in arid environments (Bowker et al., 2013). Many ecosystems naturally contain surface biocrusts, including drylands (Antoninka et al., 2020). But biocrusts are particularly sensitive to human disturbance causing communities of biocrusts to suffer huge population declines due to tilling, trampling, and a warming and drying climate (Antoninka et al., 2020). Adding cyanobacterial biocrusts in arid lands is an attempt to reverse some of this damage, introducing biodiversity that belongs in the ecosystem *and* can participate in restoring the ecosystem. Because cyanobacterial biocrusts perform many ecosystem services (Table 3), many experiments have been performed using biocrusts to inoculate arid land soils in order to quantify benefits. What follows are the results from the reviewed literature.

3.1. *Reduced bare ground.*

Biocrusts reduce bare ground via an entirely different mechanism compared to ARG. Rather than protecting the ground through plant establishment, microbes in biocrusts bind soil particles together into aggregates and form a literal crust on top of the soil (Chaudhary et al., 2009). The ground may even still appear to be bare, but the living organisms in biocrusts reduce soil loss from wind and water erosion and minimize evaporation (Chaudhary et al., 2009). Biocrusts can protect the soil like an armor and may keep seeds from penetrating the soil surface, however, if seeds manage to break through the crust, the armor works to protect the seed to promote germination and plant establishment (Ferrenberg et al., 2018; Slate et al., 2019; Antoninka et al., 2020). As an example, several studies found the presence of biocrusts correlated with decreased plant cover (Condon & Pyke, 2018; Slate et al., 2019), while others found that the plants that germinated under biocrusts had greater biomass than those that germinated in bare soils (Ferrenberg et al., 2018). This effect may be the result of biocrust effects increasing soil nutrients, contributing to soil fertility (Darby et al., 2007; Maestre et al., 2012b).

3.2. *Increased organic matter*

Studies show that biocrusts are crucial for increasing soil organic matter in drylands. Rodriguez-Caballero et al. (2018) calculated that in total biocrusts store 0.58 Pg carbon and 0.024 Pg nitrogen in soils annually. Three months after initial inoculation, Roman et al. (2018) found “significant gains” in soil organic carbon and total soil nitrogen compared to controls. This increased organic matter can benefit the entire soil food web as a food source for bacteria, fungi, and various fauna, as well as a source of nutrients for plants (Darby et al., 2007; Maestre et al., 2012; Antoninka et al., 2020). Six et al. (2004) also found cyanobacterial inoculation in particularly poor soils caused an increase in organic matter that improved

soil structure and water retention (Roman et al., 2018). These are crucial conditions for other organisms in the community to thrive, thus improving biodiversity in arid ecosystems (Antoninka et al., 2020; Tosi et al., 2020).

3.3. Ineffective inoculation techniques

To inoculate soils, cyanobacterial communities are harvested from healthy biocrusts, and, in many cases, lab-grown in liquid solutions to be easily applied to degraded areas. But as Chen et al. (2006) notes, “techniques to cultivate and reestablish biocrusts are in an early stage.” Cyanobacteria are placed in liquid solution to produce ample cells for field-scale application, but applying this liquid solution in the field and seeing populations establish in soils has not yet produced effective restoration at scale (Chen et al., 2006; Doherty et al., 2015; Bowker et al., 2018; Bowker et al., 2019; Faist et al., 2020; Zhou et al., 2020; Antoninka et al., 2020). Bu et al. (2018) were able to transplant biocrusts and see them established, but this is not a scalable solution because transplanting means disturbing a healthy area to restore a degraded area; and even this success was contingent on adequate levels of shade and inoculating during the proper season. Most success in liquid inoculation research has happened at the plot scale. However, methods do not yet exist to scale up production and treat soils at a scale relevant to the needed restoration (Antoninka et al., 2020). Van Veen et al. stated, back in 1997, that introduced bacteria decline rapidly in natural soils, and “growth of introduced populations in microbiologically undisturbed soils is a rare phenomenon.” Twenty-five years later, this is still the case. As Antoninka et al. (2020) notes, “determining the causes for failure and success needs to be addressed by studying the biology and ecology of these organisms.”

3.4. Challenges to inoculation success

There are actually many challenges to successfully inoculating soils with cyanobacterial biocrusts—multiple factors should be considered.

If inoculating with dry material—using the ground-up harvested crust to cultivate more crusts in controlled conditions before transferring the cultivated crusts to the application site—the chosen substrate soil will affect the resulting crust (Ayuso et al., 2020). Typically, a common sandy substrate is chosen, as the larger pore size provides better gas exchange as the cyanobacteria bring in CO₂ and release O₂, a dynamic thought to decrease the intensity of the microenvironment as the cyanobacteria establish, leading to better crust yield (Garcia-Pichel & Belnap, 2003). Alternatively, dry inoculations can be added to a substrate of soil from the application site or of their native soil (Ayuso et al., 2020). Here the soil texture matters—substrate textures different from the harvest site can cause a subtle shift in species selection as cultured crusts develop (though typical cyanobacteria species found in biocrusts usually remain dominant) (Ayuso et al., 2020). These species shifts can slow growth and thus lower final crust yield but may be more effective in field establishment (Ayuso et al., 2020).

Cultivation conditions have many variables that affect community composition and field survival rates. Picking the ideal harvest source, irrigations regimes, which nutrients are supplied and in what quantities, and light intensity all affect the final product (Bowker, 2007; Velasco Ayuso et al., 2017; Faist et al., 2020). Likewise, various application considerations should be made to increase survivability. If the target soils for application are easily mobile with wind or precipitation, odds of biocrust survival decrease (Faist et al., 2020). Even if biocrusts do survive, several years of establishment will be needed before they have much resistance to intense wind or rain events (Belnap & Büdel, 2016; Chamizo et al., 2017). To mitigate the effects of strong wind or rain, some studies choose to provide protective barriers such as layers of straw to help protect field sites from erosion (Xhao et al., 2016; Faist et al., 2020). Available moisture

and/or shade are also important conditions for cyanobacterial biocrust establishment and growth-- conditions not often available in the interplant spaces in arid landscapes. (Bowker et al., 2010; Kidron et al., 2010; Bu et al., 2014; Velasco Ayuso et al., 2017).

Bearing all these challenges in mind, as well as the starting conditions of the site being restored, Faist et al. (2020) write that current restoration methods may not be any more effective than natural recovery in some cases. Biocrusts on soils with a finer texture seem to recover faster, likely because the colonization of smaller soil pores requires less energy (Zheng et al., 2011; Rosenstein et al., 2014).

Cyanobacterial biocrusts clearly make important ecological contributions in their environments, and could be key in arid land soil restoration, but effective cultivation and application methods remain a primary obstacle, with soil texture likely the dominant factor to consider (Faist et al., 2020).

4. Conclusions

This review focused on two land treatment options that increase above- and/or belowground biodiversity to improve soil health in arid environments. Rotational grazing, in many cases, has been demonstrated to increase plant cover, increase organic carbon, and increase soil water content, though studies are mixed on when and how to effectively implement ARG. Compared to soils in wetter climates, arid soils are particularly well positioned to benefit from rotational grazing because the aforementioned metrics are particularly deficient in arid soils. Well-draining soils and soils containing C3 grasses and drought-tolerant tree species seem best suited to benefit from ARG treatments.

Adding cyanobacterial inoculants to arid soils also has the potential to increase soil stability through crust formation. Biocrusts can improve organic and nutrient matter and have potential to be more effective and widely applicable than ARG. However, successful inoculation methods are not yet certain. With the current limitations on liquid cyanobacterial treatments effectively establishing in the soil, this is clearly an area for further research, particularly regarding source vs. target soil texture differences, availability of water and shade, and erosion protection.

Additionally, I suggest that there is great potential to use a combination of these two treatments by first implementing grazing to provide slight disturbance to an area followed by cyanobacterial inoculation. There is also a need to identify particular cyanobacteria species that work in tandem with animal disturbance to supplement the particular deficiencies of grazing treatments.

Increasing Water Retention in Arid Soils through Biological Amendments: adaptive rotational grazing, cyanobacteria inoculation, and compost extract

1. INTRODUCTION

Soil degradation is a pressing environmental issue, negatively impacting 3.2 billion people, with arid regions being especially vulnerable to desertification (Zarch et al., 2017; IPBES, 2018; Berdugo et al., 2020). An estimated 50-700 million people of the >2 billion people that currently live in arid lands are likely to migrate due to land degradation and climate change by 2050 (IPBES, 2018; Berdugo et al., 2020). In 2019, the United Nations added dryland restoration to its list of sustainable development goals (United Nations Sustainable Development Goals, 2019). Drylands, covering ~45% of Earth's land mass, are increasing and expected to continue to increase in land area over the remainder of this century because of climate change and land degradation (Berdugo et al., 2020). Each year, roughly 12 million hectares of land are newly classified as degraded (IPBES, 2018). These ecosystems are being degraded through human activity, with the “unsustainable management of croplands and grazing lands...currently the most extensive direct driver of land degradation,” and shifting precipitation patterns caused by global climate change exacerbating land degradation impacts while complicating current solutions (Kemp & Michalk, 2007; Cayan et al, 2010; IPBES, 2018, p. 3; Antoninka et. al., 2020, Berdugo et. al., 2020). In arid regions, ecosystem health depends on adequate water stores for organisms to survive the dry periods, but as droughts lengthen and rain events become less frequent overall, sufficient soil water storage is often a limiting factor in arid soil health (Cayan et al, 2010). Without enough water, soils degrade and disrupt natural ecosystem services in the soil, including nutrient cycling, plant productivity, and microbial community functions (Berdugo et al., 2020). These disruptions can create positive feedback loops leading to worsening soil degradation over time.

Soil degradation has many components, and a degrading soil can experience one or many of these symptoms over the course of degradation. Some degradation includes loss of key soil components: loss of soil through erosion at a rate faster than it is formed, nutrient removal in harvest greater than it is replaced, and depletion of soil organic matter. Some degradation includes the build-up of soil components to a level that becomes degrading: increasing metal or organic toxicity to the point where it cannot support former uses, increasing salinity, and increasing acidity. Other forms of degradation are changes to the physical nature of the soil: surface sealing, surface compaction, and the persistent loss of vegetation productivity or cover (IPBES, 2018). Many of these degradation symptoms can happen naturally as ecosystems evolve, but more commonly they are the result of human impact, especially agricultural impact with an emphasis on the impact of grazing livestock (Berdugo et. al., 2020). This research will focus on two land management practices intended to reverse land degradation.

1.1. Livestock management

In livestock husbandry, production success is often evaluated by the total animal product per acre to maximize animal size and/or number (Kemp & Michalk, 2007). A “total-animal-output” production focus, in most cases, leads to overgrazing of pastures and thus land degradation (Kemp & Michalk, 2007). Overgrazing happens when plant consumption by livestock exceeds plant growth and recovery rates of desirable plant species, in turn leading to impaired ecosystem functioning, and eventually pasture and animal productivity declines (Kemp & Michalk, 2007). When rainfall is high, plant growth and recovery rates are sufficient, so overgrazing is less likely. However, in hot arid climates, the risk of overgrazing is

much higher (Kemp & Michalk, 2007). As grazing pressure increases, disturbance and soil compaction also increase, leading to a decline in perennial vegetation and increases in annual species that cause higher numbers of less palatable weed species (Kemp & Michalk, 2007). These changes in pasture vegetation can cause changes in the soil microbial community composition, soil pH and salinity, and an increased likelihood of soil erosion including nutrient and water infiltration losses through surface runoff (Kemp & Michalk, 2007; Berdugo et al., 2020).

For truly sustainable grazing production, soil ecosystem processes must be maintained, otherwise land degradation will worsen (Kemp & Michalk, 2007; IPBES, 2018). Abundant research points toward greater biodiversity as a requirement for stable ecosystems (Hector & Bagchi, 2007; Maestre et al., 2012; Zavaleta et al., 2010; Bowker et al., 2013). Hot arid landscapes are a punishing environment for soil, plant, and animal species not well-adapted to the extremes of temperature and water availability often present. Therefore, encouraging greater biodiversity is often a major challenge. Increasing the amount of water held in the landscape would help mitigate some of these challenges. Soil health is a keystone metric for arid lands and healthy soils hold more water, which creates a more suitable environment for plants to thrive. Greater biodiversity can create functional redundancies, making the maintenance of ecosystem services more likely, even as climatic and environmental conditions change (Yachi & Loreau (1999); Bender et al., 2016).

Grazing management influences the composition of the soil microbiome, where intensive grazing practices generally lead to microbial communities composed of fewer species, deeper practical understanding is needed to protect against the decline of microbial species diversity within these communities, either through better grazing practices or supplementing microbial species diversity through inoculations (Chaparro et al., 2012; Bender et al., 2016).

Combating soil degradation and increasing arid soil water storage will only become more difficult and expensive over time (IPBES, 2018). Reliable methods to increase desert soil water retention are urgently needed: methods that will allow more rainwater to infiltrate into soil, supply the water needs of plants, and recharge dwindling groundwater supplies (Conway, 2015). This research investigates the viability of three biological approaches to mitigating arid soil degradation while increasing soil water storage: macrofauna - adaptive rotational grazing of livestock, and microfauna - compost extract inoculations, and cyanobacterial inoculations.

1.2. Adaptive rotational grazing

Adaptive rotational grazing (ARG), otherwise known as high-intensity multi-paddock grazing, is a method of grazing livestock, especially cows, goats, and sheep. Scientists and practitioners of ARG hypothesize that by keeping the animals densely stocked in small paddocks and moving the animals regularly to new paddocks of fresh pasture, land managers can protect the health of their animals, vegetation, and soils. The animals experience less parasite pressure from being around their own waste, and the soils and grasses have time to recover from the animal impact before being grazed again (Prasad et al., 2019). As many drylands are already in use as rangeland, and unsuitable for many other purposes, ARG could be a relatively inexpensive option for land managers who would like to improve the health of their soils while also keeping the land in production.

1.3. Soil microbial inoculation

As arid soils degrade either physically (i.e. compaction, erosion, reduced infiltration) or chemically (i.e. salinization, acidification), the microbial composition of the soil is likely to shift (Berdugo et al., 2020). These changes in microbial species and population densities can lead to further soil degradation. For example, microbial population changes can lead to plant-microbial interaction changes, changes in nutrient cycling, and changes in plant species within the ecosystem (Berdugo et al., 2020). Microorganisms perform many functions in soil, including the formation of soil aggregates (and soil structure), and the cycling of nutrients including nitrogen and carbon—each species of microorganism may perform one or a few of these functions, so the microbial community working together performs the necessary functions of the ecosystem (van Veen et al, 1997).

There is an increasing interest in attempts to augment the microbial community—that is, to inoculate degraded soils with microbial strains that may have been lost through degradation in hopes of staving off further degradation and potentially restoring ecosystem functions (Berg, 2009). Chaparro et al. (2012) provide several examples of benefits to adding microorganisms to the soil, including: “maximize plant nutrient uptake (Kirankumar et al., 2008), increase plant growth (Cummings, 2009; Guiñazú et al., 2009), confer resistance to abiotic stress (Selvakumar et al., 2012), and suppress disease (De Vleeschauwer and Höfte 2009).” A frequent limitation of microbiological soil inoculations is low survival rates of field applied organisms (Bender et al., 2016). However, in soils lower in microbial biomass (typical of arid soils), inoculation survival rates are shown to be higher (relative to survival rates in higher biomass soils) due in part to less microbial competition for resources and are thus more likely to provide outcomes that improve ecosystem functions (Fliessbach et al., 2009; Chaparro et al., 2012; Bender et al., 2016).

1.3.1. Compost extract

Composting manure and other organic waste can provide valuable organic matter and nutrients when applied to the soil, potentially improving the soil physically, chemically, and biologically (Oyewusi et al., 2023). Extracting the nutrients and microbial community from the solid compost and preparing them in a liquid culture can serve as a cost effective and efficient way to spread these microbes and water-soluble organic matter on landscapes, being less labor intensive than spreading solid compost (Oyewusi et al., 2023). On the other hand, extracts do not spread organic carbon and other non-soluble parts of the solid compost, so solid composts are more suited to those purposes (Sodhi et al., 2009). Compost extracts have been shown to increase plant productivity and provide microorganisms to support key soil functions such as nutrient cycling (Kannangara et al., 2006; Oyewusi et al., 2021; Oyewusi et al., 2023).

1.3.2. Cyanobacteria

Cyanobacteria are photosynthesizing microbes that are common in arid soils. To inoculate soils, cyanobacteria communities are harvested from healthy biological soil crusts, and in many cases, lab grown in liquid solutions to be applied to degraded areas. Cyanobacteria are a genus of pioneer species within desert soil ecosystems, performing several functions including facilitation of soil aggregation, enhancement of soil fertility including carbon and nitrogen cycling, and improvement of landscape hydrology (Antoninka et al., 2020; Belnap et al., 2016). These services make cyanobacteria a potential tool to improve degraded arid soils.

1.4. Research objectives

Therefore, given that many arid and semi-arid ecosystems are becoming drier, this study investigates two methodologies to answer one main question: are macro-biological or micro-biological treatments more effective at increasing soil water storage in arid lands? The methodologies were micro (Cyanobacteria inoculations and compost extract inoculations) and macro (Adaptive Rotational Grazing) in nature. My first objective was to learn if ARG, Cyanobacteria inoculants, or compost extracts increase organic carbon in soil. Organic carbon was measured, because it can absorb water, increasing water retention. My second objective was to learn if these treatments increase water infiltration. An increase of water quantities entering the soil can correlate positively with increases in soil water storage, thus soil bulk density and hydraulic conductivity were measured. Decreases in soil bulk density would allow more soil pore space for water. Hydraulic conductivity can be used to measure soil infiltration (Inforsato et al., 2023). Because the experimental site had a history of ARG treatments, a third objective was to compare a single season of ARG (short-term) to three seasons of ARG (longer-term). As some of these fields differed in dominant vegetation, we had the opportunity to evaluate dominant vegetation effects on ARG treatment success. Because the current biocrust literature is very promising, I hypothesized that the cyanobacteria treatments would have the greatest positive effect on the measured soil metrics, followed by ARG. I hypothesized that the compost extract treatment would not have an effect on these metrics.

2. METHODS

2.1. Site description

This study occurred on agricultural grazing lands near Picacho Peak in Red Rock, Pinal County, Arizona, U.S.A. (32.5787 N, 111.3351 W). Mean annual precipitation (MAP) at the site is 239 mm and mean annual temperature (MAT) is 21.5 °C (Prism Climate Group). Soils at the site have a sandy loam texture and are classified as fine, mixed, superactive, hyperthermic Typic Calciargids in the Contine-Mohall soil complex (Soilweb). The ecosystem type at the site is a dry mesquite grassland with dominant plant species being six-weeks fescue (*Vulpia octoflora*), London rocket (*Sisymbrium irio*), alfilaria (*Erodium cicutarium*), velvet mesquite (*Prosopis velutina*), and honey mesquite (*Prosopis glandulosa*). The site is operated by the Drylands Alliance for Addressing Water Needs (DAAWN)—a working farm, ranch, and land management research center (dev.drylandsalliance.org). Land subsidence and earth fissuring due to groundwater overuse have been particularly severe in this region of Arizona (Conway, 2015).

2.2. Experimental design

The study site was selected with assistance from the land manager to focus on a highly degraded area with a long history of cattle grazing. One subarea was a fallow field that had been abandoned more than 25 years ago and two subareas were fields where farm management has used ARG with sheep and goats for 2 years of grazing in attempts to restore soil health. The fallow field was used to test the short-term effects of each biological treatment from a single season of application. We established four treatment rows running east to west, each ~60 meters long by ~3 meters wide, with 10-15 meters between each treatment plot. Rows were parallel and each was at least 10 meters distance from the others. Each of four treatments (compost, cyanobacteria, control, and tilled-and-watered control [TWC]) was randomly assigned within each replicated row, while the fifth treatment (adaptive rotational grazing [ARG]) was placed at the western end of each row to minimize fencing needs and costs for animal management. The previously

existing ARG fields were also divided into plots and randomly assigned ARG or control (i.e., we used a random number generator at each plot. Even numbers received ARG treatment, odd numbers were untreated controls. Once four plots of one treatment had been established in a field, all other plots in that field were labelled with the other treatment). This was to test the longer-term effects of ARG, comparing soil metrics before and after year three of treatment to the ARG and control plots from the short-term field. In the long-term study, the two fields differed in dominant vegetation: one was primarily dryland grasses and the other was primarily mesquite trees. Because of this, we also tested the effects of treatment in light of the dominant vegetation in each plot. Plots were established at least 10 m apart from each other to minimize treatment cross-contamination, such as compost extract or cyanobacteria inoculations moving with surface water during a rain event into adjacent plots. Each sampling zone was an equilateral triangle with 2 m on each side (size of plot = 2 m²) within the treatment plot (Figure 1b). We measured infiltration three times at each plot, once on each side of the triangle, and averaged the results. An average of three infiltration measurements was used to minimize human error within the measurement process.

We set up 36 plots for treatment on October 7th and 10th, 2022 (Table 4).

2.2.1. Soil inoculations

2.2.1.1. Collecting cyanobacterial biocrust

Biocrusts were collected from known biocrust patches 1.5 km north of the experimental site. This was to ensure that, though the cultured microorganisms would be inoculated and therefore introduced to a new location, cyanobacterial species selected would be local to the studied environment—this gave us confidence that the microorganisms were capable of survival in the local soils and climate.

Three samples were taken from each of three cyanobacteria harvest sites and placed in sealed plastic containers for transport back to the laboratory in Tucson. At the laboratory, samples were observed under a microscope at 100x, looking for the blue to green filamentous strands indicative of some cyanobacteria species—these pieces were placed into petri dishes and watered with deionized water until saturated on Mondays and Fridays. The selected biocrusts were placed under light:dark cycles (16:8 h) : light to drive their photosynthetic processes, and dark to allow time for them to use the stored energy to grow, simulating their natural rhythms. Biocrusts were watered until saturation twice weekly until subsamples were taken for culturing (see section 2.2.1.2.).

After several weeks of consistent watering, photosynthesizing microbes were clearly present, as cyanobacteria within some of the crusts had changed the color of the crust from sandy brown to cyan blue (Figure 1).

2.2.1.2. Culturing Cyanobacteria

When color change indicated that microbial communities were abundant in numbers, crusts were again examined under the microscope at 100x magnification. Where photosynthesizing communities were clearly present, indicated by groups of green microbes (some filamentous) visible with magnification, I removed small samples of the biocrust (0.5g) and placed them into a 2 L flask in 500 ml of BG-11 (Gibco) nutrient solution at room temperature (roughly 26 °C) and exposed to light:dark cycles (16:8 h) (Hydrofarm FLT44 System 4' Fluorescent Grow Light, 20,000 lumens). Loose caps were placed on each

flask to reduce the risk of contamination from potential airborne microorganisms in the lab. Flasks were monitored weekly for 16 weeks to maintain adequate hydration. Equal parts deionized water and BG-11 were added to each flask to maintain at least 500 ml of liquid per flask.

2.2.1.3. Evaluation of chlorophyll-a

Because chlorophyll-a is a good proxy for total biomass in cyanobacteria (Schagerl & Künzl, 2007), we measured chlorophyll-a concentrations in the 12 cultures to find the most cell-dense flasks. We are confident that other photosynthesizing microorganisms (and non-photosynthesizing) were transferred from the biocrusts and cultivated in the flasks. To minimize contamination from non-crust organisms, flasks and other tools used in the transfer of organisms were sanitized before use and flasks were covered during cultivation. Using methods outlined by Schagerl & Künzl (2007) and Castle et. al. (2011), I sonicated a subsample from each culture at 50% power for 20 s and then added a 3 ml subsample to a 15 ml centrifuge tube in triplicate. After adding 9 ml of acetone to each vial, I placed the vials on a shaker table for 5 h. Then the samples were centrifuged at 3000 rpm for 6 min. I then poured the supernatant into cuvettes to read on a spectrophotometer (Thermoscientific Genesys 50) at 652, 665, and 750 nm. Using calculations from Ritchie (2006), the five cultures with the highest chlorophyll-a content were selected for further culturing.

2.2.1.4. Determination of inoculant cell concentration

Before field application, each of the five selected cultures was measured for cell concentration, with an average of 1.1×10^9 cells per L. I observed the cells occupying five randomly selected central squares of a hemocytometer at under a microscope 100x magnification for this measurement. I then mixed 1 L from each of the five cyanobacteria cultures together in preparation for field application.

2.2.2. Compost extract

A compost was prepared at the farm in a layered combination of cow manure and garden waste in equal parts by mass. The pile was composted for 3 months, monitoring moisture levels and internal temperature, turning and watering as needed to maintain an internal temperature of 55-70 °C. I then placed 2.3 kg of compost in a 50 L nylon bag with 400 micron mesh. Then I put the compost-filled bag in a 19 L bucket with 15 L of water. I added 2.5 ml of soluble humic acid (Ferti-Organics brand) to react with any chlorine in the tap water, making it inert. Finally, I mixed the bucket contents using an air-stone for 2 hours.

2.2.3. Field inoculation application

Because microbial inoculations have low survival rates when field-applied (Antoninka et al., 2019), I attempted to ameliorate the habitat within inoculated plots with plowing similar to the roughening technique used by Antoninka et al. (2019). Keyline plowing was planned to provide shade and cover for introduced microbes without substantial soil disturbance. Unfortunately, due to user error on application day, a subsoiler plow blade was used (12 cm depth) instead of a keyline plow blade and significant soil disturbance resulted. The plow broke up the top layers of soil, turning them to each side of the furrow (rather than cutting a furrow in the soil and leaving the soil in place, as intended). Because of this extra disturbance, some existing soil aggregate structures were likely destroyed, meaning the inoculations were applied to looser soils and were more exposed to sun, wind, and rain than intended. This may have affected microbial survival rates and slowed their ability to colonize the plots. All plots with cyanobacteria, compost extract, and TWC were plowed prior to the first inoculation. Inoculations were

applied directly to plowed furrows. To reinforce microbial populations and increase likelihood of microbial soil colonization, applications of cyanobacteria, compost extract, and water (for TWC plots) were added approximately monthly over the course of the study on February 9, 2023; March 17, 2023; and April 21, 2023.

Because the farm managers had previously used the compost extract at 197 Liters per hectare on agricultural fields, seeing anecdotal increases in hobby farm crop yields, the same concentration was used on study plots (0.038 L per 2 m² plot) diluted with tap water to 1 L total per plot. Because the cyanobacteria culture cell count (1.1×10^9 cells liter⁻¹) was within appropriate application concentrations (Wang et al., 2008), the cyanobacteria culture did not require dilution, so 1 L was applied per plot. To keep irrigation consistent across all treatments, 1 L of tap water was applied to each TWC plot.

2.2.4. ARG schedule

Electrical animal fencing was used to surround and protect the six sheep within each experimental plot. Sheep grazed each plot once during the experiment—the first plot was grazed on January 27, 2023, and the final plot on April 21, 2023. Paddocks were sized to approximate 21,700 animal kg per hectare, and timed to approximate 1,000-2,000 kg hectare⁻¹ per h. Where forage in a plot was insufficient for the allotted time, food such as alfalfa and straw were added to keep the animals feeding. This happened in four of the 12 plots.

2.3. Soil water infiltration

Water infiltration, or hydraulic conductivity, was measured in the field using a mini-disk infiltrometer (Decagon Devices, Inc.) based on Zhang (1997). Three measurements were conducted per plot, and results were averaged to alleviate some inherent variability for the mini-disk method.

I measured water infiltration in the same manner as the pre-treatment tests using the mini-disk infiltrometer based on Zhang (1997). This concluded the trial after roughly 3 months of treatments. The field experiment was intended to be 9 months in duration, but was repeatedly delayed by farm management.

2.4. Soil sampling and physicochemical measurements

In order to establish initial soil conditions before treatments were applied, initial measurements were taken at each plot on November 18 and November 30, 2022. The same measurements were taken for the final samples. After the conclusion of treatments, I took final soil samples on May 18, 2023.

In order to quantify total carbon, total nitrogen, and bulk density I sampled soils (0-10 cm) using a 50 cm long metal pipe with an internal diameter of 5.1cm. Samples were taken from one random edge of each sampling zone (within the larger treatment area) by driving the pipe 10 cm into the soil, carefully removing the pipe, and then releasing the pipe's soil contents into a sealed plastic bag. Because the infiltration measurements were taken on each edge of the sampling zone, and in order to minimize effects of soil heterogeneity within a plot, soil samples were taken at one edge of the sampling zone triangle also.

To determine soil carbon and nitrogen concentrations, I sieved (2 mm), oven-dried (105 °C), and ground each soil sample with mortar and pestle. Samples were then weighed (1 g) for analysis on an elemental combustion system (Vario Max Cube, Elementar Americas, Ronkonkoma, NY, U.S.A.). Because soil

samples did not effervesce following addition of hydrochloric acid, I did not remove carbonates before combustion analysis, thus assuming all carbon was organic. I measured soil bulk density with a known volume of sampling pipe. Soils were sandy with very little gravel, so bulk density was calculated using the traditional core method (i.e., whole dry soil mass/whole soil volume).

2.5. Statistical analysis

Statistical analyses were performed using JMP (2018 SAS Institute Inc., JMP 14.2.0 64-bit). To analyze response variables, I used two-way (for short-term: treatment by time) and four-way analysis of variance (ANOVA) tests (for long-term: treatment by time by field history by primary vegetation). I investigated significant interactions and significant single-factor effects using the R statistical computing environment (R Core Team 2023, version 2023.06.0+421).

3. RESULTS

3.1. Short term – (single season, three treatments)

Neither Cyanobacteria ($p = 0.509$) or compost extract ($p = 0.616$) inoculations significantly affected soil nitrogen compared to controls, however ARG yielded significant increases in nitrogen (Figure 2) ($p = 0.033$). Similarly, ARG significantly increased soil carbon ($p = 0.002$) compared to controls, while neither Cyanobacteria ($p = 0.778$) or compost extract ($p = 0.739$) inoculations showed this effect (Figure 3). No treatments yielded significant differences in bulk density or in hydraulic conductivity compared to controls (Figures 4 & 5).

3.1.1. Temporal variation

Bulk density significantly increased over all treatments from initial samples to final samples (Figure 6) ($p = 0.003$). Counterintuitively, this increase in bulk density coincided with an overall increase in hydraulic conductivity over the study period (Figure 7) ($p = 0.003$).

3.1.2. Short term correlations

Carbon and nitrogen were strongly positively correlated, while several other weaker correlations were observed. Carbon and nitrogen were positively correlated ($r = 0.82$) (Figure 8). Nitrogen and bulk density were negatively correlated ($r = 0.37$) (Figure 9) as are carbon and bulk density ($r = 0.4$) (Figure 10). Bulk density and hydraulic conductivity were positively correlated ($r = 0.4$) (Figure 11).

3.2. Long term – one year ARG compared to three years ARG

3.2.1. Nitrogen

Though ARG significantly increased soil nitrogen in the fallow field compared to controls ($p = 0.033$), in plots with three years of ARG, that significant difference in nitrogen over controls was no longer evident ($p = 0.145$) (Figure 12). However, due to plot placement constraints, some plots in the previously grazed fields included mesquite trees as the dominant vegetation. Primary vegetation plays a factor: nitrogen is significantly higher in mesquite-covered areas than it is in fields dominated by grasses ($p = 5.6 \times 10^{-7}$) (Figure 13). When observing soil nitrogen differences isolating by vegetation, grazing in mesquite-

covered areas does not increase soil N levels significantly, but ARG does significantly increase soil nitrogen in grass-dominated dryland plots lacking mesquite (p-value 0.004; $r = 0.46$) (Figure 14).

3.2.2. Carbon

Soil carbon followed the same pattern as nitrogen. While we observed significant increases in soil carbon in the fallow field ($p = 0.002$), long term, grazing provided no significant increase in carbon over controls ($p = 0.151$) (Figure 15). When separating by vegetation type, mesquite-covered areas had significantly more carbon than grass zones ($p = 2.61 \times 10^{-6}$) (Figure 16). When isolating only grass zones, ARG marginally significantly increased soil carbon (p-value 0.057) (Figure 17).

3.2.3. Soil bulk density

In the long-term, ARG made no significant difference in soil bulk density over controls ($p = 0.151$) (Figure 18). Like the short-term results, bulk density significantly increased from initial sampling to final sampling, indicating a temporal variation ($p = 2.86 \times 10^{-5}$) (Figure 19).

3.2.4. Infiltration

Likewise, ARG made no significant long-term difference in soil hydraulic conductivity ($p = 0.151$) (Figure 20). Infiltration significantly increased across all plots from initial samples to final samples ($p = 0.001$) (Figure 21).

4. DISCUSSION

This study investigated two methodologies to answer one main question: Are macro-biological or micro-biological treatments more effective at increasing soil water storage in arid lands? The first objective was to learn if ARG, cyanobacteria inoculants, or compost extracts increase organic carbon in soil. The second objective was to learn if these treatments increase water infiltration. I hypothesized that the cyanobacteria treatments would have the greatest positive effect on these metrics as the biological soil crusts involved have evolved to directly impact these systems. Secondly, I hypothesized that ARG would also improve these metrics but to a lesser extent. I hypothesized that the compost extract treatment would not have an effect on these desired outcomes given the short experimental period.

4.1. Short-term effects of treatments

The cyanobacteria inoculation did not affect soil organic carbon, soil bulk density, or soil water infiltration after 3 months. The buildup of soil organic carbon due to cyanobacteria requires years. The soil crusts likely needed much more time because of low rates of photosynthesis compared with plants. At the final sampling, there was no visible evidence of living cyanobacteria populations in the plots. Without significant organic carbon inputs and with no evidence of inoculated cyanobacteria survival, these inoculations were unlikely to affect soil bulk density or water infiltration. If populations survived, I think with more time, the cyanobacteria could develop crust structures but would likely only have effects near the soil surface. A study with a timeframe of 12-24 months would be more appropriate to observe cyanobacteria crust establishment and subsequent soil changes (Antoninka et al. 2017). In addition, providing shade or supplemental water in future experiments would likely increase survivability (Antoninka et al., 2020).

Likewise, the compost extract amendment caused no changes to soil carbon or water infiltration. To cause changes in soil carbon, bulk density, and water infiltration, applications of solid compost would likely have been more effective (Sodhi et al., 2009). A compost extract can be effective as a nutritional supplement by increasing plant-available nitrogen, but it is less effective in severely nitrogen-depleted soils (Mahmoud et al., 2014; Mohd Din et al., 2017). This aspect of the study was included at the request of the farm manager because compost extract had been used on the farm as a fertilizer. Future studies should evaluate ecosystems with soils nearing total soil surface plant coverage to measure increases in plant production.

Short-term ARG treatments increased soil organic carbon and marginally decreased soil bulk density, but this did not translate into increased water infiltration. Other studies have found organic carbon gains during ARG treatments in arid rangelands (Xu et al., 2018; Hawkins et al., 2021). Cattle and Southorn (2010) also found that ARG decreased soil bulk density. I expected infiltration to increase as bulk density decreases, but the data show infiltration increasing with higher bulk densities, though the effect was small. Perhaps these mechanisms develop sequentially—that is, perhaps organic carbon increases to a point that causes bulk density to decrease, and only then does infiltration increase. Because there may be more dynamism in the sorptivity data compared to infiltration, in a future step we will review the infiltration data, evaluating sorptivity.

Soil bulk density on average was higher in May than in November. Denser soils generally have less organic matter that provides better pore-size distribution for promoting infiltration and plant-available water (Zaffar & Lu, 2015). And yet, the infiltration rate also increased significantly from initial samples to final samples. These results combined are counterintuitive. A look at the expected vs. actual precipitation provides one explanation for these findings. Initial samples were taken in November, a month that typically gets about 1 cm of rain in the study area, and November 2022 only received trace amounts (Prism Climate Group)—initial sample conditions were drier than normal, which may have skewed infiltration tests toward greater infiltration. Though drier soils are also known to be hydrophobic due to a buildup of organic matter residue, these soils contained very little organic matter, so we do not believe that mechanism factored in these soils. Conversely, average precipitation for May is about 0.51 cm, but May 2023 received 1.35 cm of rain — final samples were wetter than normal, potentially skewing infiltration tests toward less than expected infiltration. In future studies, a timeframe of 2-3 years, with more sampling times and annual sampling times, would likely even out this variation. Similarly, future studies would find value in tracking and controlling for precipitation in the data. Single season ARG did increase soil organic carbon, which I would expect to increase soil water infiltration over time. Based on these results, ARG is a more beneficial treatment for increasing soil carbon compared to microbial treatments in these arid systems.

4.2. Longer-term effects of ARG

The short-term positive effect of ARG on soil nitrogen and carbon aligns with initial expectations, but longer-term effects do not. The grazing ruminants are depositing nitrogen and carbon regularly through their feces and urine. These additions are then trampled into the soil profile due to the limited grazing areas given to the animals at any one time. It is less clear why this effect seemed to diminish over subsequent grazing seasons, as observed in the previously grazed fields. Though this result is reinforced by a similar study in which a single season of rotational grazing increased soil carbon accumulation, but

the following seven seasons showed less soil carbon accumulation (Abagandura et al., 2024). One possible explanation is that the initial ‘severely depleted’ state of the soil allows for quick uptake of carbon and nitrogen, but soils may reach a plateau state (potentially a state of carbon saturation) where enough of the required nutrients are available so that other nutrient cycling microbial systems can begin (Frouz, 2016). This nutrient cycling may dull the effect of subsequent grazing season inputs, while the short-term effects on a fallow field are more significant.

4.3. Conclusions

Future studies should focus on ARG in grasses specifically and if increases in soil carbon with ARG can be correlated to increases in soil moisture. Additionally, this study was done with sheep as the grazing ruminant animal—a comparison of the effects of other ruminants may also be useful as animal size and diet will alter trampling rates and nutrient inputs. So that ARG treatments can maximize soil carbon increases and minimize deleterious effects of grazing, tests should also be done to find ideal stocking densities. In order to test ways of increasing soil water infiltration rates, testing the combination of grazers and compost or mulch may provide a mechanism for slowing surface water flow. As global climate change continues to speed the evolution of ecosystems, ARG is shown to increase soil carbon in arid environments--further tests, building on this data, may show ARG to be a valuable tool to increase soil water storage in arid landscapes.

TABLES AND FIGURES

Table 1. Benefits to increased soil water retention based on Teague et al, 2011; Hawkins et al, 2021.

| Benefit | Result |
|----------------------------------|---|
| Enhanced soil microbial activity | Improved plant growth conditions |
| Soil aggregate stability | Less erosion and evaporation |
| Improved plant growth conditions | Increased soil organic matter; increased nutrient retention |

Table 2. Benefits to increases in soil organic carbon based on Charman & Murphy, 2000; Lal, 2008; Neely et al. 2009; Teague et al., 2011; Rowntree et al. 2016; Teague et al. 2016; Gosnell et al, 2020

| Chemical benefit | Physical Benefit | Biological benefit |
|---|---|---|
| Increases soil water holding capacity | Contributes to soil structure stability | Increases organic acids that make nutrients available to plants |
| Increased nutrient adsorption, including cations and trace elements | Improved water catchment | Increased plant production |
| Prevents nutrient leaching | | |
| Atmospheric carbon sink, critical to global climate change | | |
| Increased cation exchange capacity | | |

Table 3. Cyanobacteria biocrust ecosystem services performed

| Service | Benefit | Reference |
|------------------------------|--|--|
| Stabilizing soil surfaces | Preventing erosion; trapping dust; | Reynolds et al., 2001; Bowker et al., 2018; Antoninka et al., 2020 |
| Photosynthesis | Sequestering carbon in the soil; balancing thermal energy | Rutherford et al., 2017; Bowker et al., 2018; Antoninka et al., 2020 |
| Fixing nitrogen | Building soil nutrient stocks | Elbert et al., 2012; Bowker et al., 2018; Antoninka et al., 2020 |
| Mediating hydrological cycle | Balancing moisture levels; minimizing evaporation | Chamizo et al., 2016; Bowker et al., 2018; Antoninka et al., 2020 |

Table 4. Experimental plots

| Duration of treatment | Treatment type | Abbreviation | Dominant vegetation | Number of replicates |
|-----------------------|-----------------------------|--------------|---------------------|----------------------|
| Short-term | Control | C | Desert grassland | 4 |
| Short-term | Compost Extract | Comp | Desert grassland | 4 |
| Short-term | Cyanobacteria | Cyan | Desert grassland | 4 |
| Short-term | Tilled and watered control | TWC | Desert grassland | 4 |
| Short-term | Adaptive rotational grazing | ARG | Desert grassland | 4 |
| Longer-term | Control | C | Desert grassland | 4 |
| Longer-term | Adaptive rotational grazing | ARG | Desert grassland | 4 |
| Longer-term | Control | C | Mesquite trees | 4 |
| Longer-term | Adaptive rotational grazing | ARG | Mesquite trees | 4 |

Table 4. The short-term study was done in a degraded fallow field that had been unused for over 20 years. This study duration tested the effects of each treatment over a single season. The longer-term study plots were prepared in fields that had two previous years of ARG treatment. This study tested the effects of three seasons of ARG vs. one season of ARG, in fields dominant in desert grasses and in fields dominant in mesquite trees.

Figure 1. Biocrust color change



Figure 1. Crusts harvested June 2nd, 2022, initially appeared sandy brown in color. By September 30th, 2022, cyanobacteria within some of the crusts had changed the color of the crust to the cyan blue seen here.

Figure 1b. Treatment plot and sampling zone

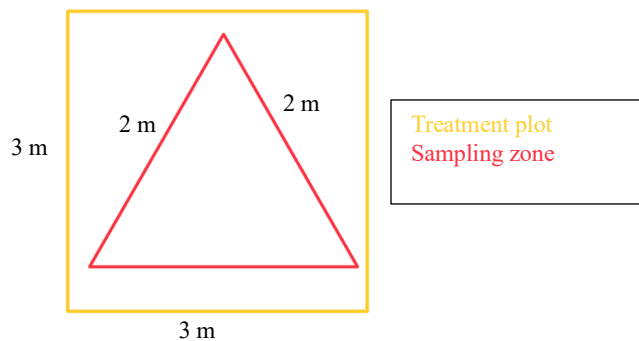


Figure 1b. The treatment plot (yellow) is roughly three meters square, dictated by the plow used. The sampling zone (red) is an equilateral triangle (2 m on each side) within the treatment plot. Sampling from the sampling zone aims to remove “edge effect” in sampling.

Figure 2. Percent Nitrogen by Treatment (Short term)

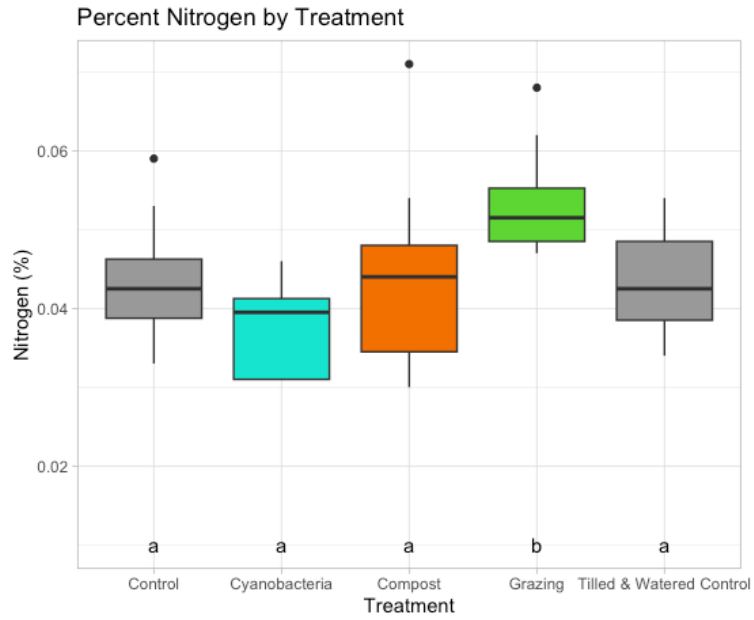


Figure 3. Percent Carbon by Treatment (Short term)

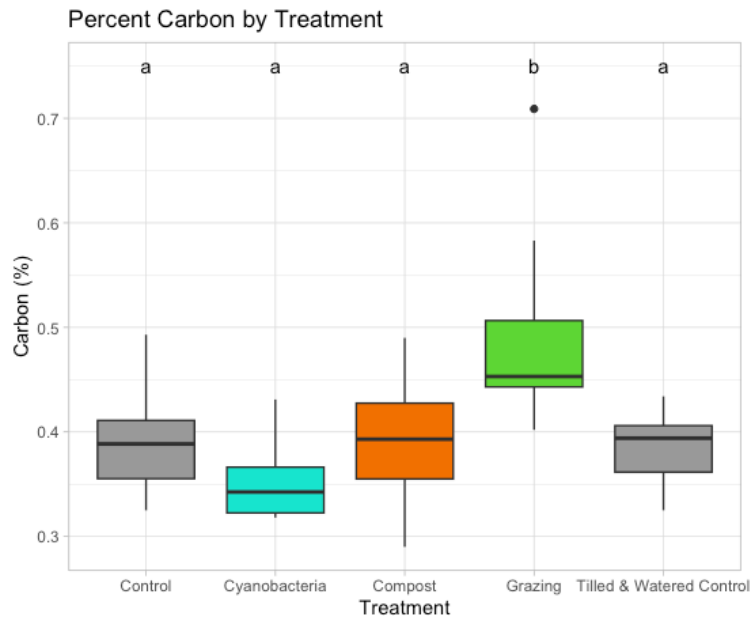


Figure 4. Bulk Density by Treatment (Short term)

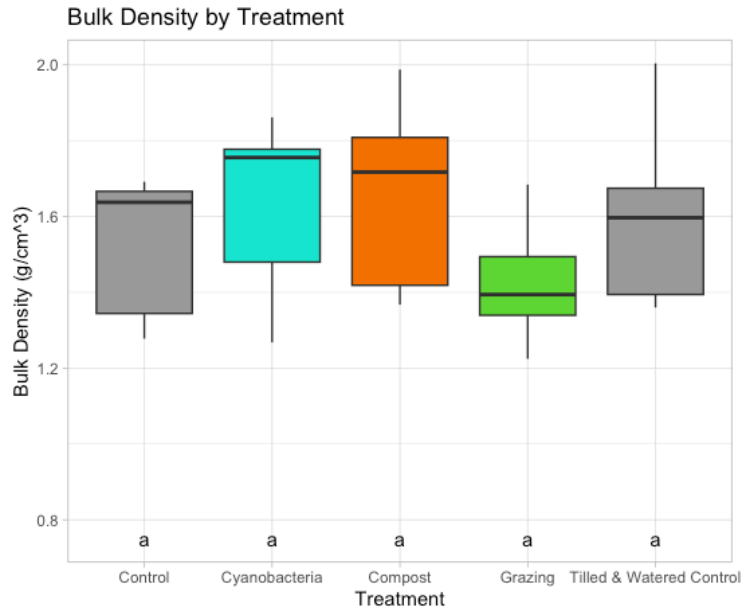


Figure 5. Hydraulic Conductivity by Treatment (Short term)

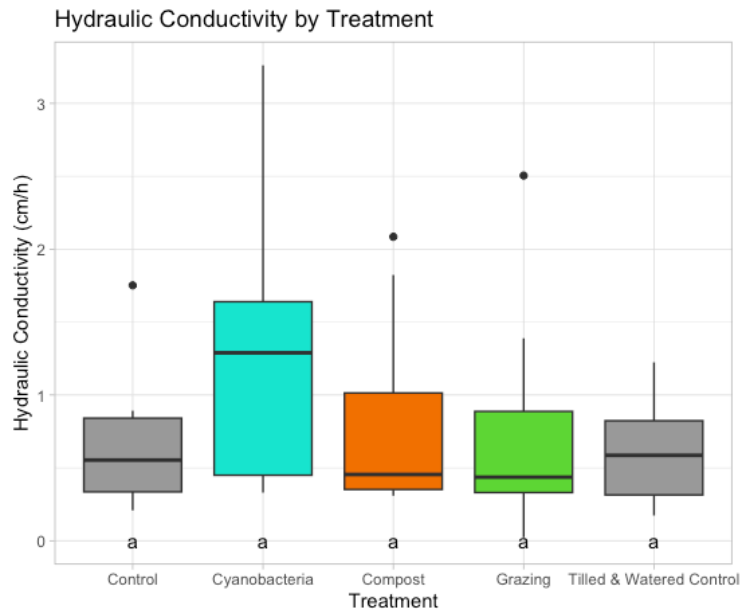


Figure 6. Bulk Density by Sample Day (Short Term)

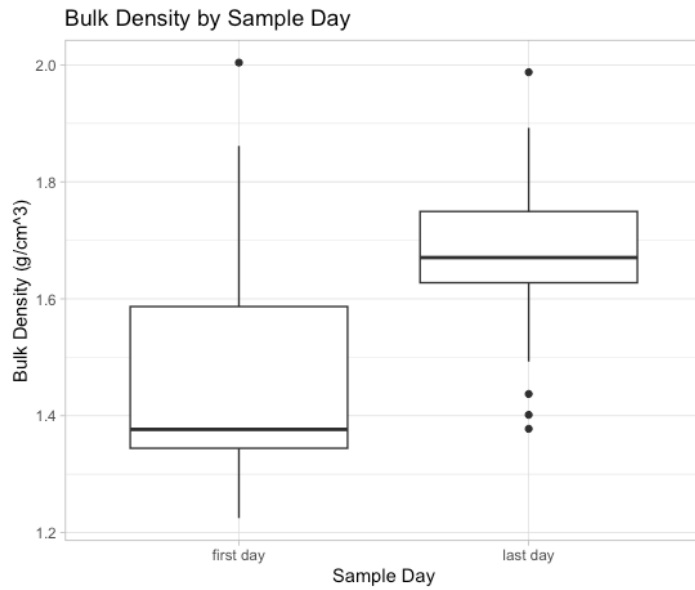


Figure 7. Hydraulic Conductivity by Sample Day (Short Term)

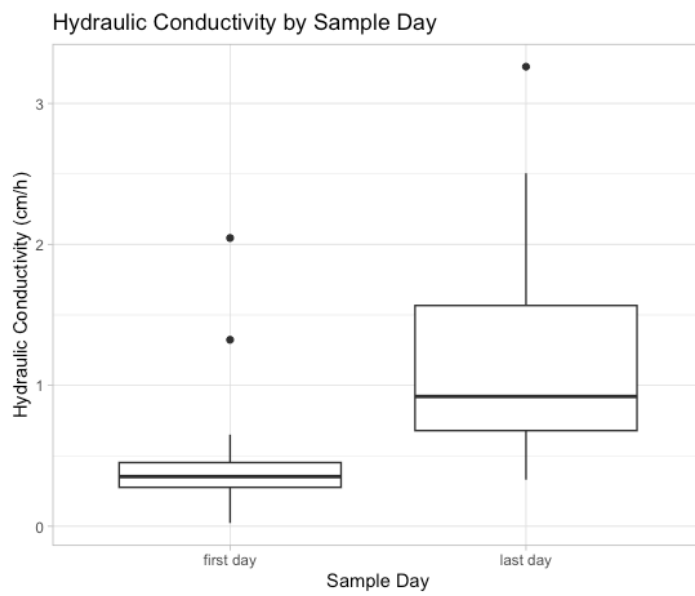


Figure 8. Bivariate fit of N by C (Short Term)

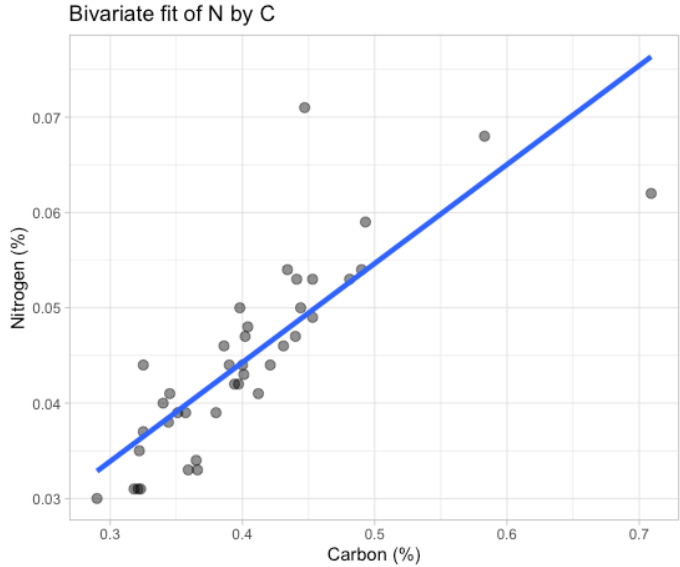


Figure 9. Bivariate fit of N by Bulk Density (Short Term)

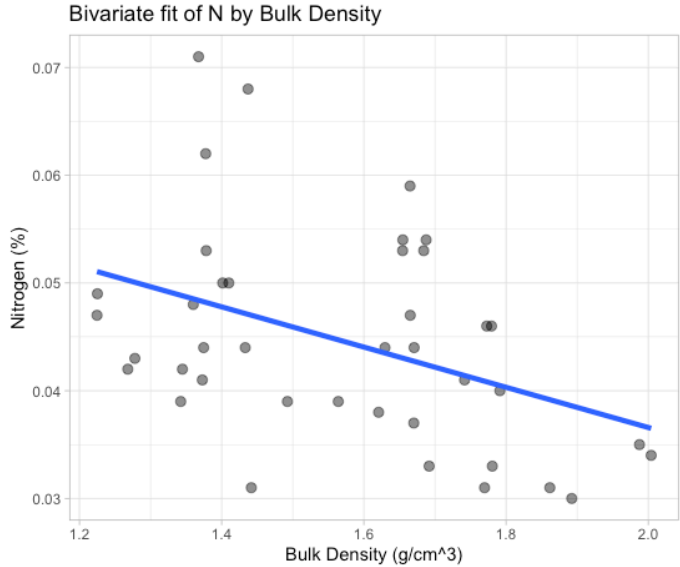


Figure 10. Bivariate fit of C by Bulk Density (Short Term)

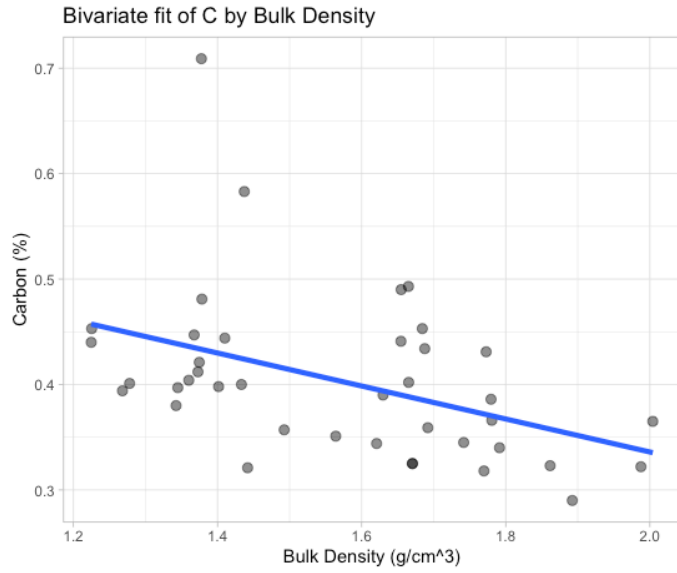


Figure 11. Bivariate fit of Hydraulic Conductivity by Bulk Density (Short Term)

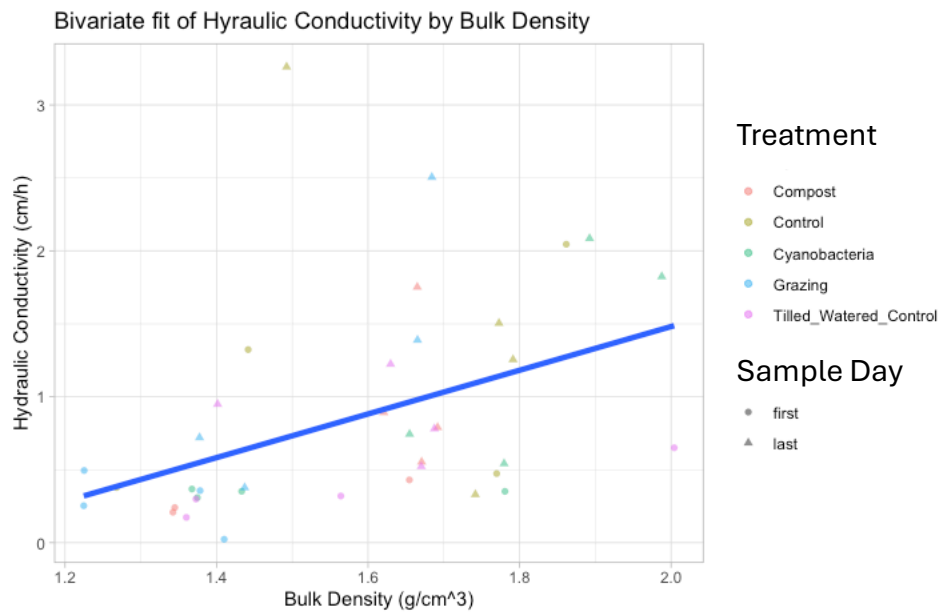


Figure 12. Percent Nitrogen by Treatment within Field History.

Fallow = one season ARG, Grazed = three seasons ARG.

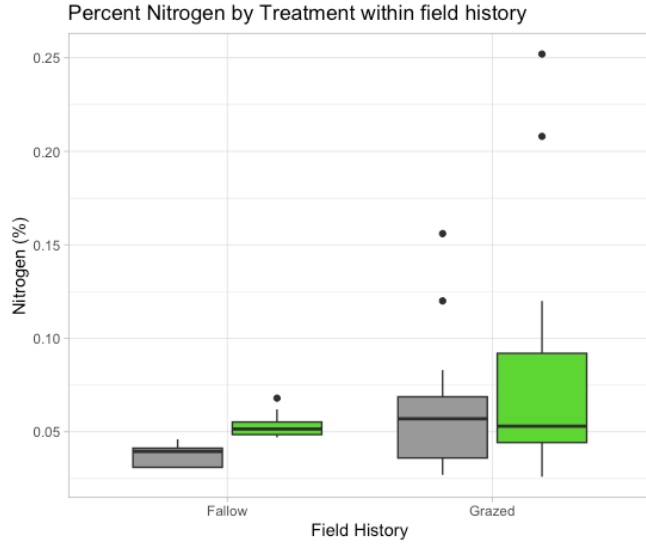


Figure 13. Percent Nitrogen by Treatment Considering Vegetation

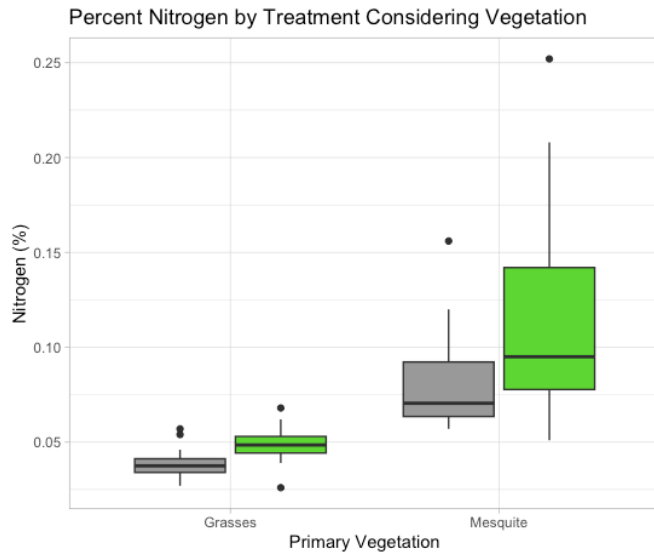


Figure 14. Percent Nitrogen by Treatment in Grasslands

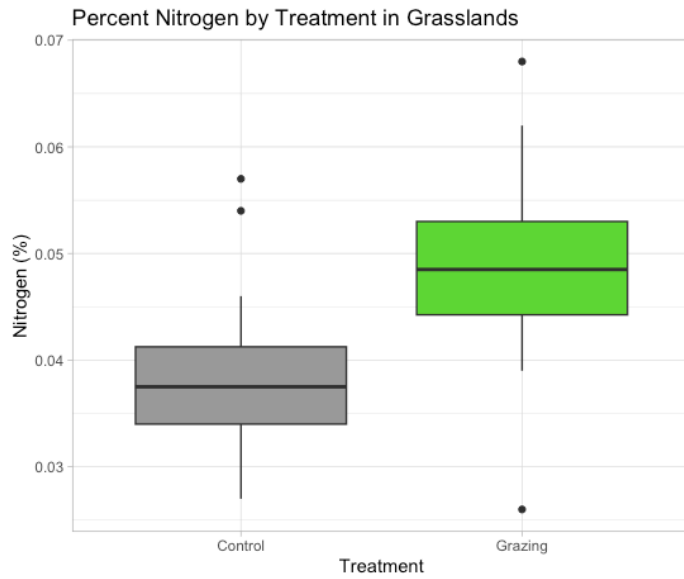


Figure 15. Percent Carbon by Treatment within Field History.

Fallow = one season ARG, Grazed = three seasons ARG.

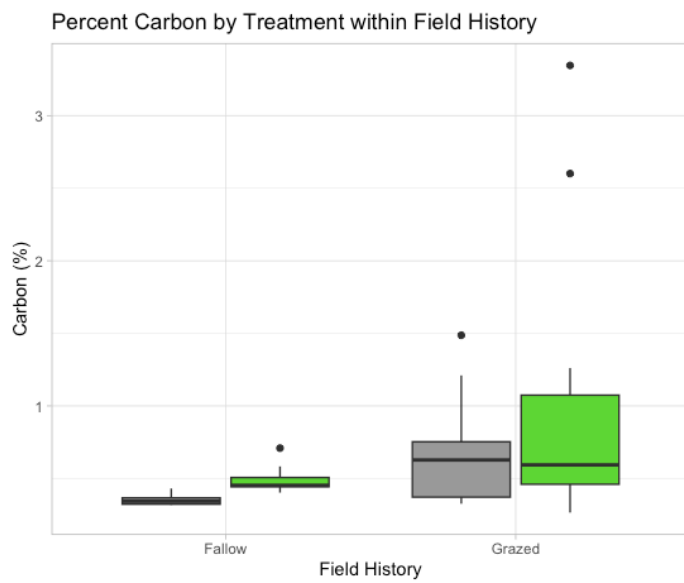


Figure 16. Percent Carbon by Treatment Considering Vegetation

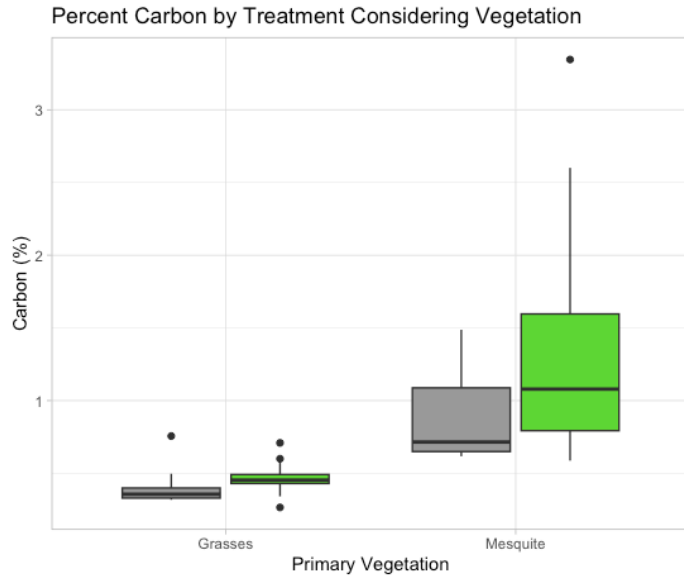


Figure 17. Percent Carbon by Treatment in Grasslands

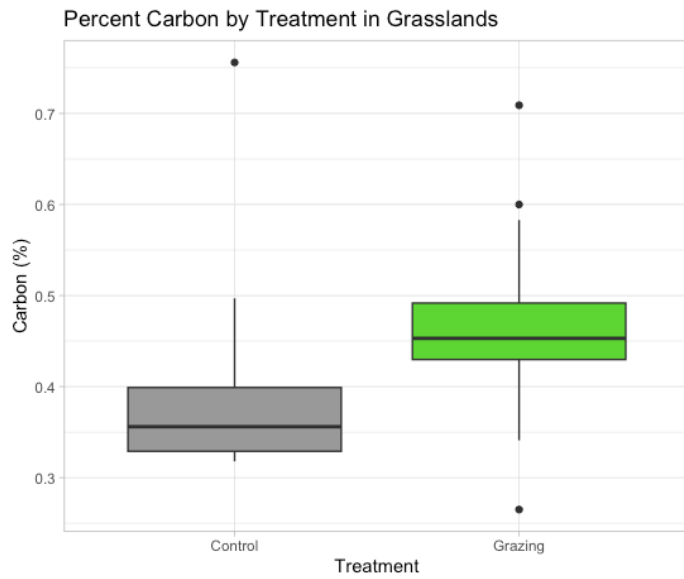


Figure 18. Bulk Density by Treatment (Longer Term)

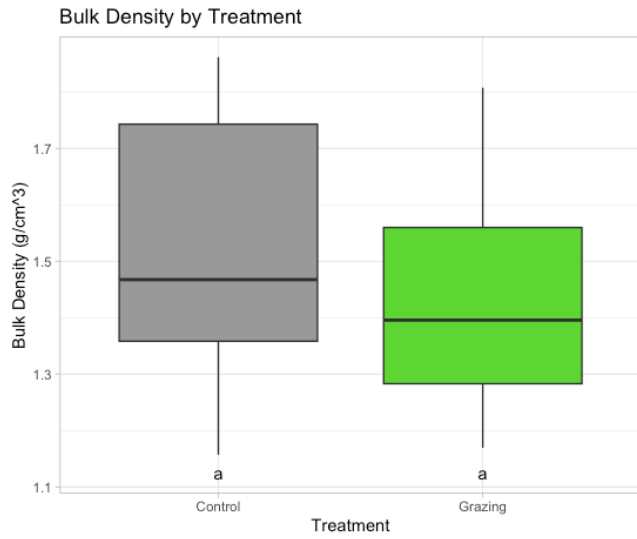


Figure 19. Bulk Density by Sample Day (Longer term)

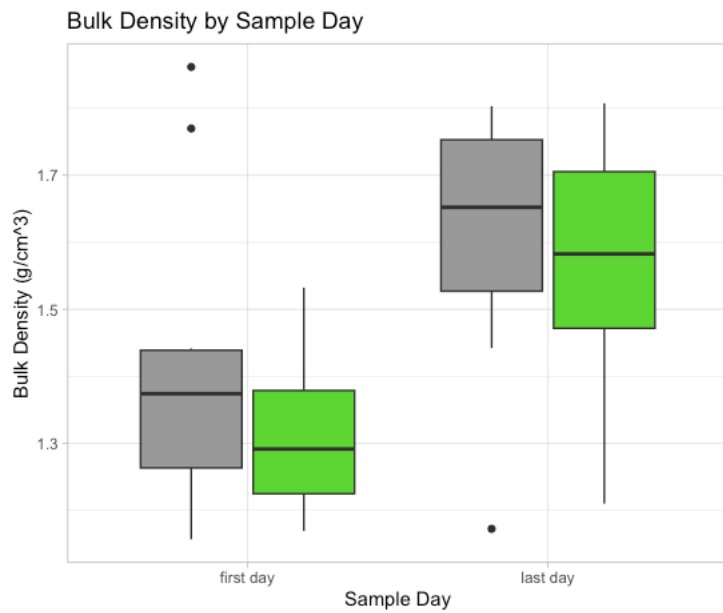


Figure 20. Infiltration by Treatment

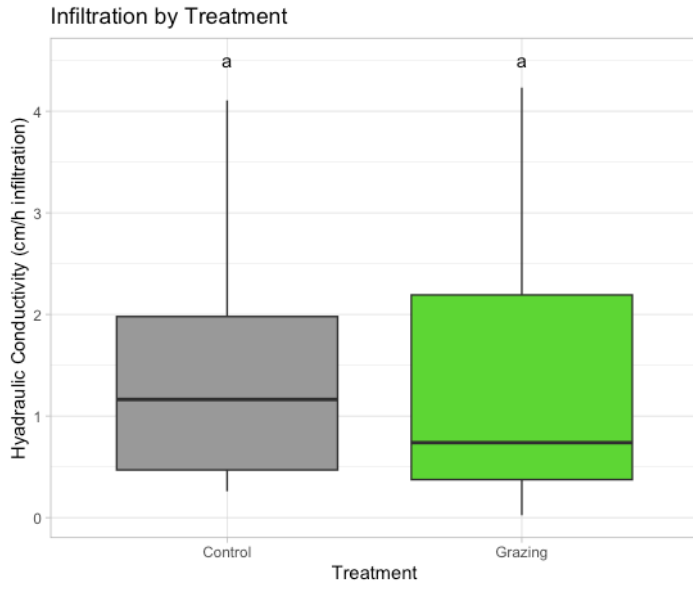
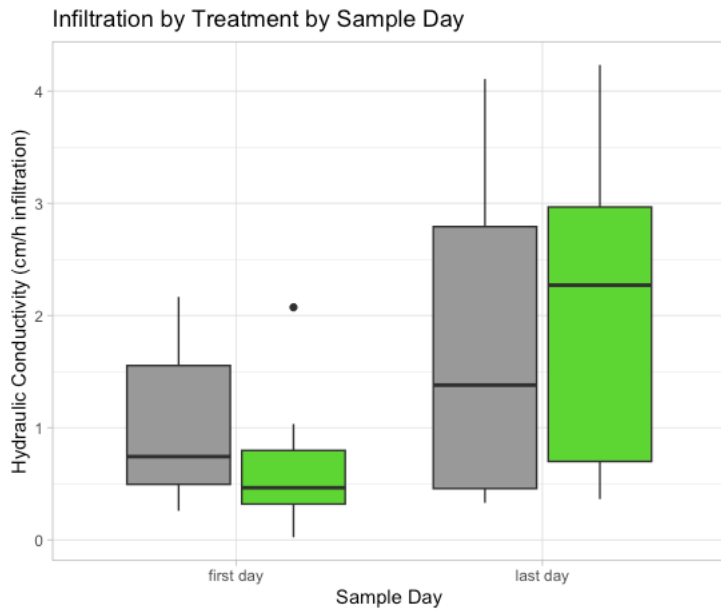


Figure 21. Infiltration by Treatment by Sample Day



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