FINAL PROJECT REPORT

SECTION 1. ADMINISTRATIVE INFORMATION:

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- University of Arizona

- Uniting Western Restoration Strategies and Traditional Knowledge to Build Community Capacity and Climate Resilience on the Navajo Nation
- G22AC00456
- 2/16/26
- 11/01/22 – 10/31/25
- 223,694.98

SECTION 2. *PUBLIC* SUMMARY:

On the Navajo Nation, chronic drought has demonstrated detrimental effects on ecosystem function and economic well-being. Revegetating degraded areas with locally-sourced, native species, often in conjunction with low-tech approaches following a disturbance, is an increasingly useful tool for land managers. However, understanding of how best to identify effective restoration species and pair them with easy to apply management approaches is missing. We conducted a variety of studies to explore the utility of independent and interactive effects of media rock lunas, seeding and trait-based approaches to enhance dryland restoration outcomes on the Navajo Nation.

Media lunas are half-moon shaped rock structures that passively enhance plant cover and restrict topsoil loss. Although they have been used for thousands of years to get water and seeds into specific areas across a landscape, there is very little formal research associated with their design and deployment. We tested two different spatial distributions of lunas and found that lunas enhance native plant cover and reduce invasive plant cover through time, particularly when paired with seeding. However, we found no effect of spatial distribution on luna outcomes.

We also explored the value of low vs high seeding densities crossed with grazing for dry rangeland recovery. We unexpectedly found that seed density was unimportant for restoration success, but restricting the access of livestock was helpful for plant and soil recovery.

Finally, we completed a greenhouse experiment to identify traits associated with plant performance under two drought conditions in order to determine which species are good candidates for restoration in dry systems. We found that species with high root density and short root lengths performed best under both moderate and severe drought conditions, and thus may be particularly good candidates for restoration in increasingly arid ecosystems.

SECTION 3. PROJECT SUMMARY:

Increasing incidence of drought in the Southwest is resulting in a widescale loss of vegetation cover and soil erosion. On the Navajo Nation, where the Navajo government has declared a state of emergency multiple times in the past ten years, dryland systems are most deeply impacted by drought. And the loss of native plants due to these changes is expected to continue at a rapid rate. Restoration has been identified as a critical element to drought adaptation and erosion control for the Navajo Nation. However, barriers to restoration exist. For example, many Indigenous land management strategies that are successfully employed to maintain heathy conditions might not accommodate increasing incidence of chronic drought.

The overall goal of this project was to explore links among native Navajo plant species of interest, financially feasible dryland restoration technologies, and drought on the Navajo Nation. To achieve this goal, this project addressed two objectives: (*Obj 1*) Identify restoration capacity of Navajo Nation native plant species of interest alone and coupled with restoration techniques; and (*Obj 2*) Identify drought resilience capacity of Navajo Nation native plant species of interest through trait-based analysis.

To address objective 1, we conducted two large field experiments – one at Santa Rita Experimental Range and one on a private ranch on the Navajo Nation. At Santa Rita, we explored how design decisions related to media luna deployment – including shape of clumped lunas and the presence of seeding – affected plant cover. Overall, we found that the way in which lunas are distributed on the landscape is unimportant for native plant density and cover outcomes. Seeding lunas is more effective for desired species cover than not seeding lunas. On the Navajo Nation, we explored how seed density, seeding type and grazing type affected plant cover. Overall we found that deploying seedballs in the absence of grazing resulted in greatest plant cover through time.

To address objective 2, we completed a greenhouse experiment using five grass and three forb species to assess how individual traits and multivariate and bivariate trait relationships respond to moderate and severe drought in order to ultimately determine which species are good candidates for restoration in drought settings. Plants reduced root diameter and increased root tissue density and dry matter content in response to drought. Despite these phenotypic adjustments, plasticity was not an important predictor of plant performance under drought exposure. Rather, we found that species with high root tissue density and low specific root length (i.e., the length of roots per unit mass) performed best under both moderate and severe drought conditions. We also observed an unexpected decoupling of aboveground and belowground traits; conservative root traits (i.e., high root dry matter content) were coupled with acquisitive leaf traits (i.e., high specific leaf area). Our results suggest that dryland species may exhibit unique aboveground–belowground trait relationships and that species with dense roots and low specific root length may be particularly good candidates for restoration in increasingly arid ecosystems.

SECTION 4. REPORT:

Purpose and Objectives: The overall goal of this project was to explore links among native Navajo plant species of interest, financially feasible dryland restoration technologies, and climate resiliency on the Navajo Nation. Outcomes of this work will serve the Navajo community specifically as well as dryland restoration managers generally. To achieve this goal, this project proposed to address two objectives: (*Obj 1*) Identify restoration capacity of Navajo Nation native plant species of interest alone and coupled with restoration techniques; and (*Obj 2*) Identify drought resilience capacity of Navajo Nation native plant species of interest through trait-based analysis. The project also proposed to deliver information related to project outcomes to Navajo community members through a variety of mechanisms. Original experimental goals were met, but design specifics (e.g. location of studies) changed slightly to accommodate end user interests. Initially, this project was described as being deployed on an existing restoration study in partnership with the Diné Native Plants Program. This program closed soon after receiving funds and thus, we were unable to deploy the study in the initially described site. We were able to deploy part of the study on the Navajo Nation. Moreover, in general, most outreach goals were met but not all outreach was delivered in the methods originally described in the proposal. This was largely due to an inability of the project team to find and secure a Navajo translator who was willing to attend an outreach event. We pivoted and instead provided workshops in English and Spanish.

Organization and Approach: We deployed three separate studies.

Seeding and grazing

First, the seeding x grazing experiment was deployed in a working rangeland located northwest of Tsaile, AZ on the Navajo reservation. In July 2023, we randomly assembled 29 sets (each set contained three plots) in two types of areas (open to grazing and fenced to exclude grazing). Each open and fenced area was 30 m long and 30 m wide and sets were about 20 m apart across the site. Each individual plot was 1 m^2 x 2 m^2. A Chapter resolution from the Tsaile/Wheatfields/Blackrock Chapter was approved for this project.

In August 2023, we applied a native plant seed mix using either naked seeds or seedballs to some plots. Seedballs are structures (0.5-1 inch diameter) made of clay, seed, water and organic material (here, cattle manure from a nearby corral). These are used to enhance germination by reducing seed redistribution from wind, and seeds are protected in the structure until adequate rainfall saturates the surrounding clay and nutrients of the seed ball which fuels the seedlings as they emerge. Seeds and seedballs were applied in one of two ways – either a higher or low seeding rate. The high seeding rate included planting the full seeding rate for all 10 native species. The low seeding rate included planting half the seeding rate for all 10 native species. We seeded 10 native species (single species in a plot) and a native seed mix (multiple species per plot) at different densities. The entire footprint of each plot was seeded. The native seed mix included grasses and forbs commonly used in northern Arizona rangeland restoration projects, including Alkali Sacaton (*Sporabulus airoides*), Indian ricegrass (*Achnatherum hymenoides)*, Penstemon firecracker (*Penstemon eatonii*), Sandberg bluegrass (*Poa secunda*), Winterfat (*Krascheninnikovia lanata*), Blue grama (*Bouteloua gracilis)*, James Galleta (*Pleuraphis jamesii Torr)*, Sand drop seed (*Sporobolus cryptandrus)*, Desert globemallow (*Sphaeralcea amigua*), and Purple threeawn (*Aristida purpurea*).

Altogether, the experiment included: (1) control; (2) naked seed, no till, single species; (3) seedball, no till, single species; (4) naked seed, mix 1, spiral till; (5) naked seed, mix 1, no till; (6) naked seed, mix 2, till; (7) naked seed, mix 2, no till, (8) seedball, mix 1, spiral till; (9) seedball, mix 1, no till; (10) seedball, mix 2, spiral till; (11) seedball, mix 2, no till. There are three replicates for each plot. There are a total of 174 1m^2 plots.,87 plots assembled in both fenced and open areas. For three years following installation of the experiment each fall, we collected plant cover and density data across all plots.

Lunas and seeding

The second study was deployed on a working ranch in the Santa Rita Experimental Range (SRER) to assess how media lunas (half moon shaped rock structures) might be useful in reducing weeds in a grazed area. Media rock lunas are generally clumped in groups of threes across a landscape to passively arrest soil moisture and enhance localized plant growth. Nothing is known about best spatial deployment strategies to enhance both local and regional effects of lunas. To understand vegetation responses to media luna design decisions, we investigated herbaceous cover and plant density response to media lunas deployed in different spatial arrangements, with and without seeds added in a semi-arid rangeland. The objectives of this study were to determine if (1) luna shape matters for plant cover and diversity over time; and (2) seedballs and seed spread increase native seedling germination.

In June 2023, media lunas were deployed in a grazed area at SRER. The site has an average annual precipitation of 279 mm with an annual maximum temperature of 40°C and annual minimum temperature of 11°C. The area is defined as a loamy upland ecological site (NRCS 41-3) which is characterized by loamy soils (White House cobbly sandy loam) and is dominated by the non-native grass Lehmann's lovegrass (*Eragrostis lehmanniana*). Native perennial grass basal cover is less than 5%, lovegrass basal cover is more than 1%, litter is 60%, and bare ground with rock and gravel is 15-20%.

We assembled 12 sets of lunas (each set contains three lunas) in two types of triangle shapes (Equilateral and Isosceles) on the contour lines of the landscape where sheet flow is expected. Each individual luna was approximately 10 m long and 1 m wide at its center and sets were about 20 m apart across the landscape. Equilateral luna (60°, 60°, 60°) were 5-8.6 m apart within each set and Isoceles lunas (36°, 72°, 72°) were approximately 5-15 m apart within each set. To construct the lunas, we used a mix of small and large rocks (7-91+ cm diameter) that were transported from Arizona Trucking and Materials in Tucson, AZ. Differences in angles among lunas were expected to cause significant differences in how soil accumulated in and around individual lunas. Lunas were installed by the University of Arizona and Ancestral Lands Group.

In mid-July 2023, we applied a native plant seed mix using either naked seed or seedballs to some lunas. For both the seedball and naked seed treatments, we applied 12 grams of seed per luna. The entire footprint of each luna was seeded, including a 1 m band around the entire footprint. The native seed mix included grasses and forbs commonly used in southeastern Arizona rangeland restoration projects, including Arizona cottontop (*Digitaria californica*), Blue flax seed (*Linum lewisii*), Blue grama (*Bouteloua gracilis*), California poppy (*Eschscholzia californica*), Cane bluestem (*Bothriochloa barbinodis*), Desert globemallow (*Sphaeralcea ambigua*), Desert Indianwheat (*Plantago ovata*), Green spangletop (*Leptochloa dubia*), Palmer's penstemon (*Penstemon palmeri*), Plains bristle grass (*Setaria leucopila*), Rothrock's grama (*Bouteloua rothrockii*), Sideoats grama (*Bouteloua curtipendula*), and Small fescue (*Vulpia microstachys*). In total, the experiment included: isosceles lunas that were seeded with seedballs (seedball-rock-isosceles); equilateral lunas that were seeded with seedballs (seedball-rock-equilateral); equilateral lunas that were seeded with naked seed (naked seed-rock-equilateral); equilateral lunas that were not seeded at all (no seed-rock-equilateral), seedball application in the shape of isosceles lunas (seedball-no rock-isosceles); seedball application in the shape of equilateral lunas (seedball-no rock-equilateral); and no lunas and no seed (complete control). Each fall after deploying the experiment, we collected plant cover data in transects that crossed the lunas for three years.

<u>Plant traits</u>

Finally, in a greenhouse study, we are using a trait-based approach to understand how plants native to the Navajo region respond to drought. We are primarily focusing on below ground traits. We worked with five grass (*Aristida purpurea, Digitaria califor-nica, Koeleria macrantha, Poa secunda, Pseudoroegneria spicata*) and three forb (*Achillia millefolium, Linum lewisi, Ratibida columnifera*) species commonly used in dryland restoration throughout the southwestern United States to address our research questions. Seeds were germinated under ambient conditions between 25 May 2023 and 10 June 2023. Once germinated, seedlings were transplanted into pots filled with a 1:1:1 mixture of porous ceramic media, vermiculite, and field soil collected from a post-agricultural site in Tucson, AZ, composed of Glendale silt loam. Once transplanted, plants were moved into the University of Arizona greenhouse. Plants were watered every other day until they were weeks old, at which point they were randomly assigned to one of three watering treatments (control: watered every other day; moderate drought; watered every fifth day; and severe drought; water secession). The moderate drought treatment aimed to reduce water in pots to a volumetric water content of about 12% or nearly the wilting point of our soil medium prior to being rewatered, whereas the severe drought treatment removed water completely. Plants were grown under treatment conditions for 3 weeks, at which point traits and above and belowground biomass were measured. On average, six replicates of each species by treatment combination were assessed for trait and performance responses to drought treatments(8 species x 3 treatments x 6 replicates = 144 plants total).

We assessed responses of the following traits to moderate and severe drought: leaf dry matter content, specific leaf area, specific root length, root dry matter content, root tissue density, average root diameter, and root mass fraction. All traits were measured according to standardized protocols for leaf and root trait measurements.

Project Results, Analysis and Findings:

Begay is still in the process of analyzing data. However, preliminary data for the first two field experiments is noted here.

Seeding and grazing

In total, 17 plant species were found on site. Of the 10 species included in the seed mixes, six were found in our plots: *Sporabulus airoides*, *Bouteloua gracilis*, *Pleuraphis jamesii Torr*, *Sporobolus cryptandrus*, *Sphaeralcea amigua*, and *Aristida purpurea*. Both vegetation density and cover were higher in fenced locations in comparison to open locations (Fig. 1). Both vegetation density and cover were higher in plots with seeding treatments (Fig. 2). Tilling did not significantly affect plant cover and density, however, no till plots had higher cover and density than spiral till plots. Mean litter cover was higher in fenced locations than open areas.

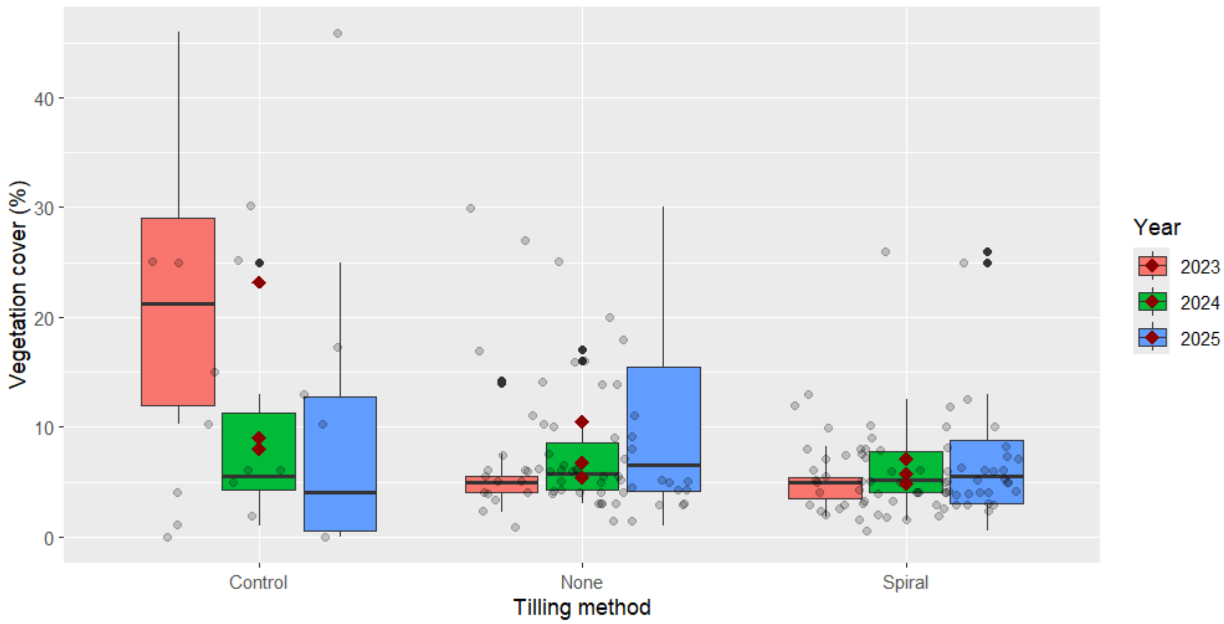

Figure 1: Percentage total vegetation cover measured in spiral till and no till plots from 2023-2025. Boxplots represent the lower and upper quartiles and median. Raw data represented by grey circles.

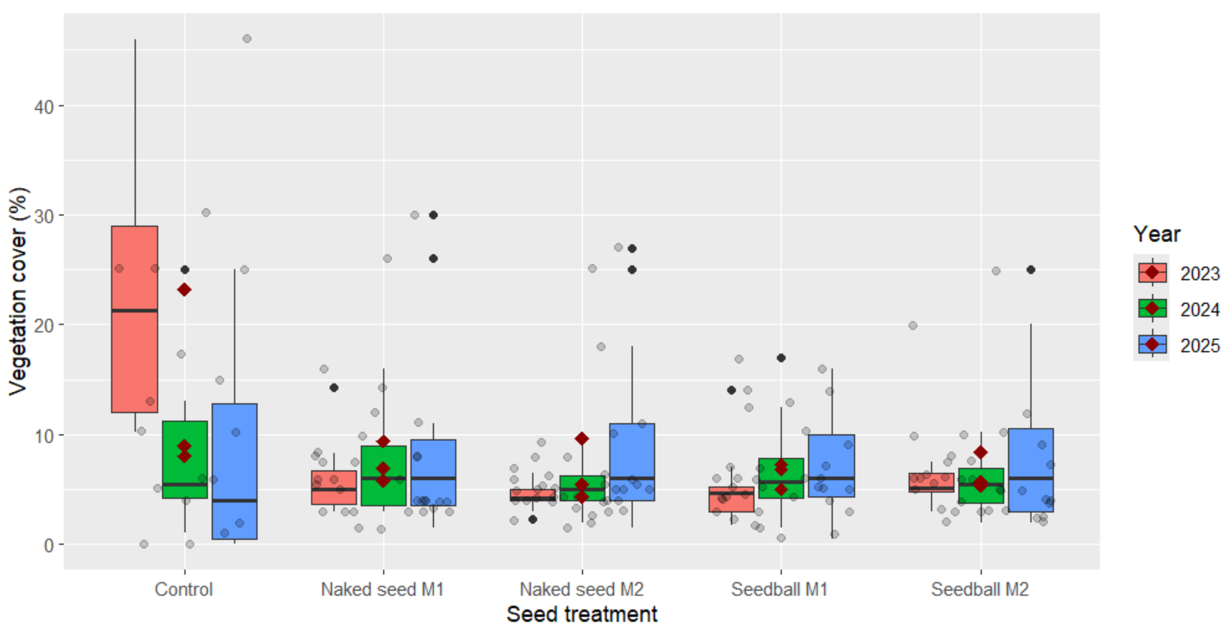

Figure 2: Percentage total vegetation cover measured in plots with different seeding treatments from 2023-2025. Boxplots represent the lower and upper quartiles and median. Raw data represented by grey circles.

Lunas and seeding

Arranging media lunas in the shape of isosceles triangles might lead to slightly higher native species cover (Fig. 3). Invasive species declined through time in the presence of lunas, irrespective of luna shape (Fig. 4).

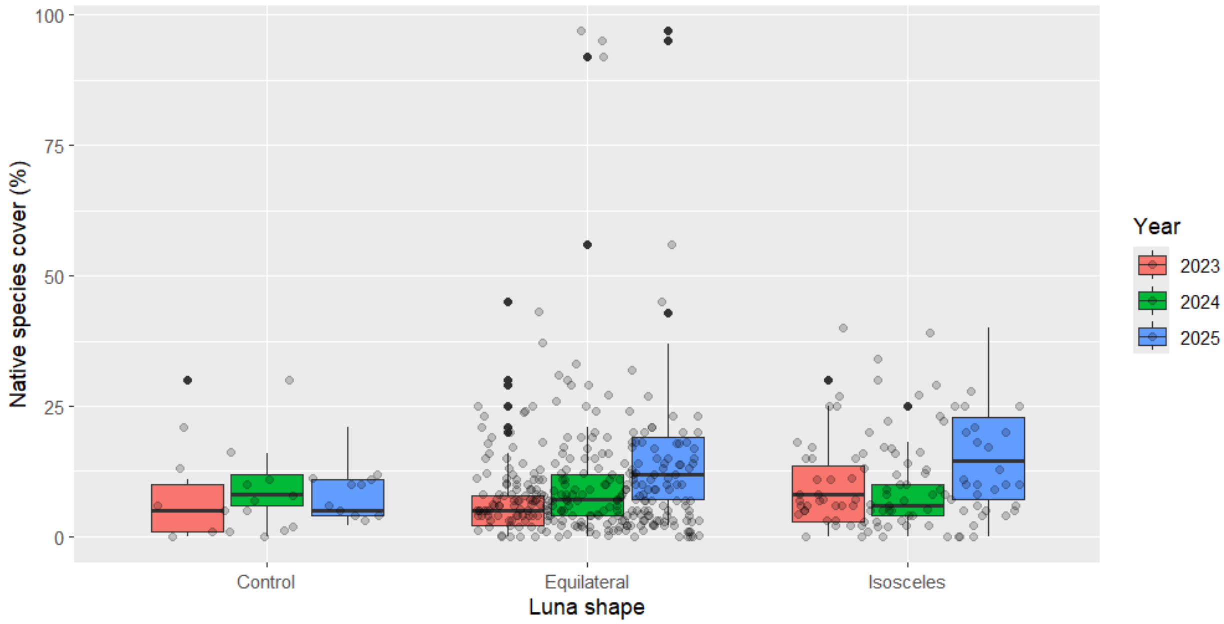

Figure 3: Percentage native species cover across lunas of different shapes from 2023 – 2025. Boxplots represent the lower and upper quartiles and median. Raw data is represented by grey circles.

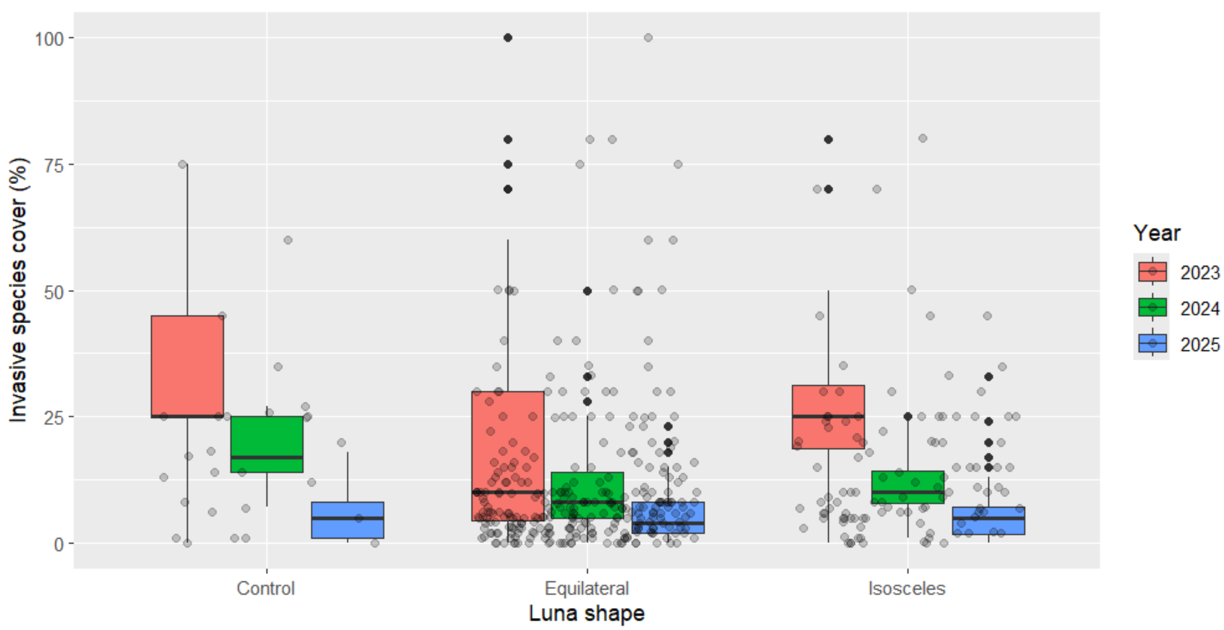

Figure 4: Percentage invasive species cover across lunas of different shapes from 2023 – 2025. Boxplots represent the lower and upper quartiles and median. Raw data is represented by grey circles.

Plant traits

We found that overall root diameter decreases with drought but root tissue density and root dry matter increase (Fig. 5). Basically, roots are getting thinner and denser, suggesting that the plants may be trying to maximize acquisition via thin roots and increase tolerance at the same time. This is a neat strategy that has been identified in some other systems.

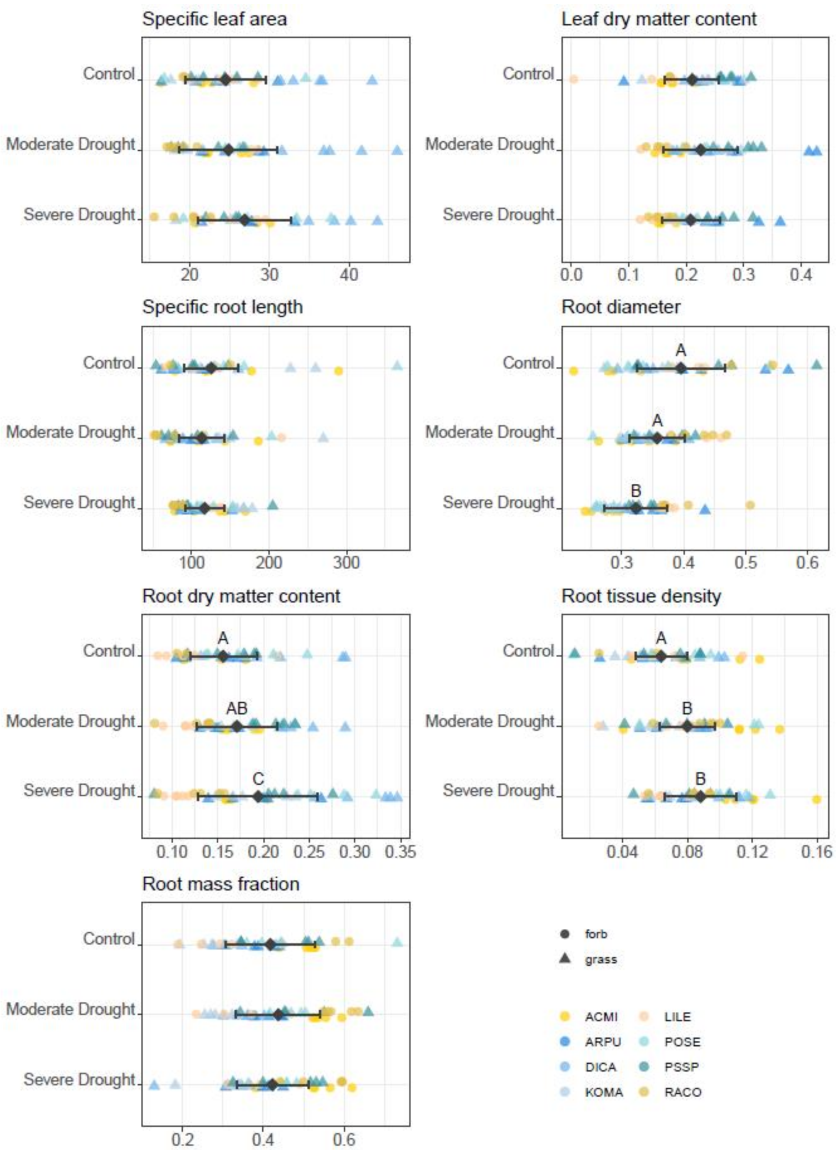

Figure 5: Root traits in response to experimental drought as measured in a greenhouse. Species codes as follows: *Achillia millefolium* (ACMI), *Aristida purpurea* (ARPU), *Digitaria californica* (DICA), *Koeleria macrantha* (KOMA), *Linum lewisii* (LILE), *Plantago insularis* (PLIN), *Poa secunda* (POSE), *Pseudoroegneria spicata* (PSSP), and *Ratibida columnifera* (RACO).

Species are most often not both drought resistant (i.e., maintain biomass under moderate moisture deficit) and drought tolerant (i.e., survive under severe drought). However, *Pseudoroegneria spicata* and *Digitaria californica* are "good bets" under both conditions (Fig. 6).

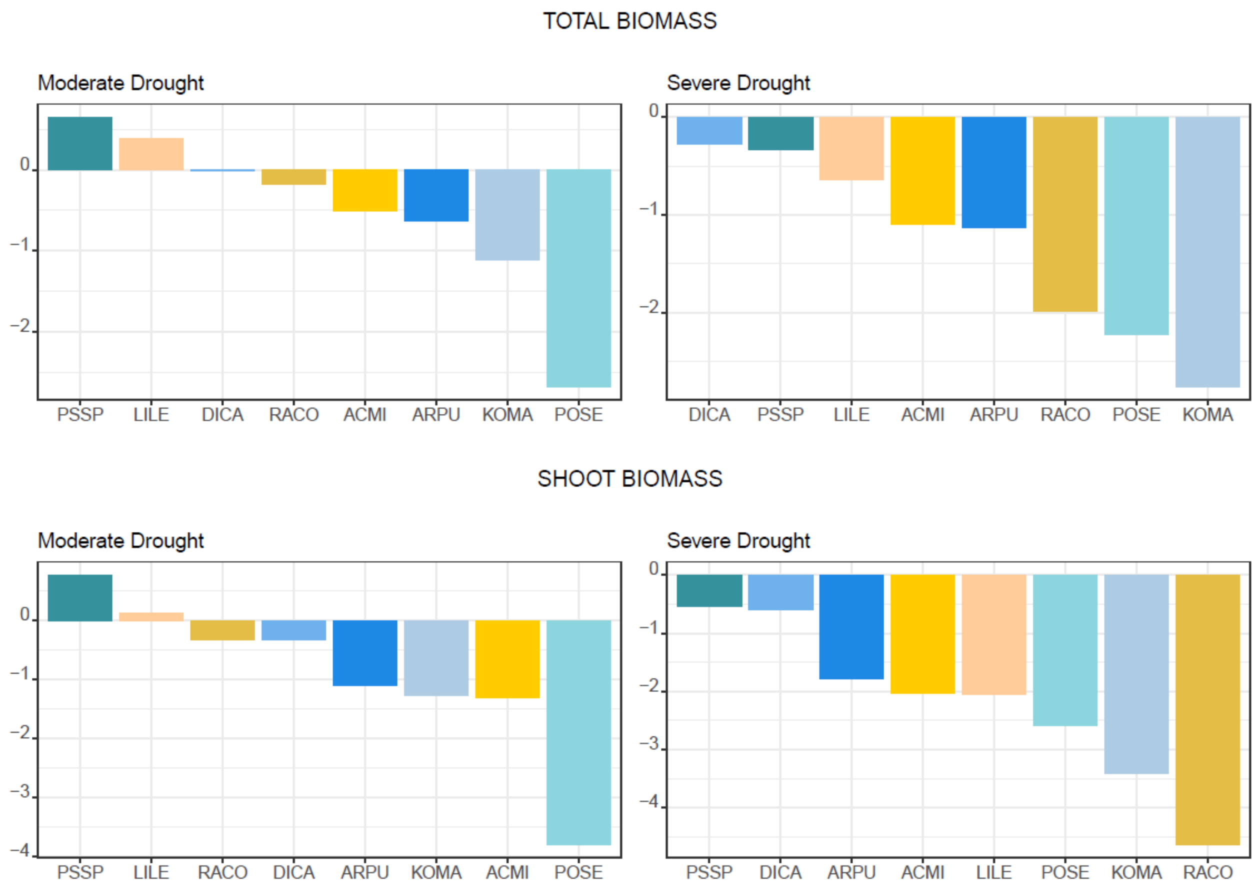

Figure 6: Standardized biomass responses for total (top panels) and shoot (bottom panels) biomass. Species codes as follows: *Achillia millefolium* (ACMI), *Aristida purpurea* (ARPU), *Digitaria californica* (DICA), *Koeleria macrantha* (KOMA), *Linum lewisii* (LILE), *Plantago insularis* (PLIN), *Poa secunda* (POSE), *Pseudoroegneria spicata* (PSSP), and *Ratibida columnifera* (RACO).

Finally, some trait relationships are consistent across watering treatments (e.g., SRL and root diameter), whereas others are not (Fig. 7). This suggests that there is belowground coordination to cope with drought, but likely decoupling of leaf and root traits as plants get stressed.

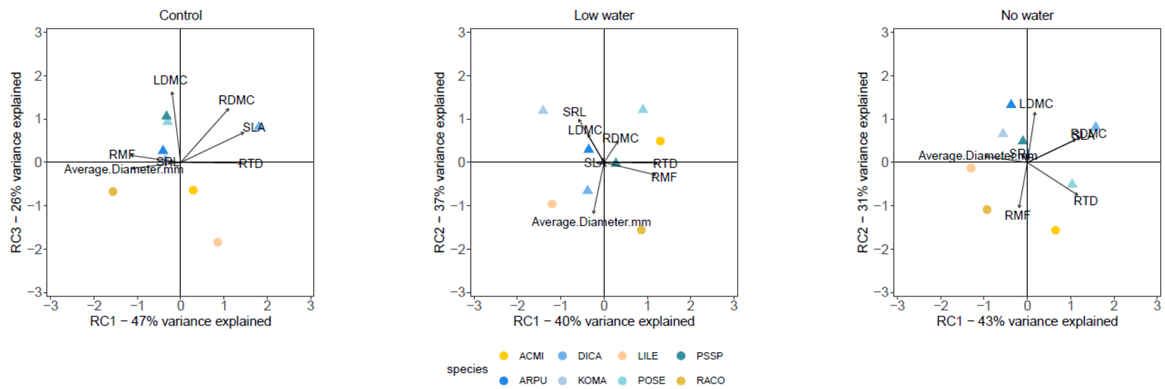

Figure 7: Community ordination plots (PCA). Species codes as follows: *Achillia millefolium* (ACMI), *Aristida purpurea* (ARPU), *Digitaria californica* (DICA), *Koeleria macrantha* (KOMA), *Linum lewisii* (LILE), *Plantago insularis* (PLIN), *Poa secunda* (POSE), *Pseudoroegneria spicata* (PSSP), and *Ratibida columnifera* (RACO).

Conclusions and Recommendations:

Seeding and grazing

The advantages of seed selection, till methods, and physical barriers particularly in disturbed rangeland areas, are substantial and should be included in revegetation efforts. Vegetation cover is a critical resource in desert rangelands as it provides soil stability and resilience against desertification. Understanding how to maximize ground cover and plant populations may facilitate more successful restoration efforts. Although seed establishment after reseeding application takes multiple years to establish, changes in vegetation cover can be seen in short term using fencing and seeding methods. In particular, future efforts should include seeding warm season grasses due to their ability to withstand unpredictable and harsh conditions, no till methods due to less soil erosion impact, and fencing to protect plants from grazing.

Lunas and seeding

Supporting previous fundings from our lab, media lunas appear to be effective for passive restoration of degraded rangelands. Unexpectedly, we did not find any effects of spatial distribution of lunas on desired outcomes. This suggests that, generally, lunas can be deployed where and when they are needed to resist top soil loss and enhance desired plant cover. Although spatial effects in terms of luna clumped shapes (triangles) were not important for driving differences in desired plant outcomes, this work demonstrated that other spatial effects might be important but cannot be critically evaluated at field scale. As a result, we have used this work to support another study looking at spatial distribution of individual lunas using a wind tunnel. This scaled down study will highlight treatment types that could then be explored at larger scales.

Plant traits

We found that species with low specific root length and dense roots were best able to cope with drought. Specifically, we observed the smallest reductions in biomass in response to drought in three species with low specific root length and high root tissue density: *Digitaria californica*, *Linum lewisii*, and *Pseudoroegneria spicata*. Our findings provide additional evidence for high root tissue density being a key trait associated with plant performance under drought. However, it is important to note that the relationship between root tissue density and performance was only observed under severe drought, whereas relationships between performance and specific root length were observed in both moderate and severe drought conditions. This suggests that dense roots alone do not support drought tolerance, but rather dense roots of the right diameter are needed. In our case, species with dense roots of average diameter (0.32 mm–0.39 mm) that resulted in low specific root length performed best under drought. Because we assessed whole root systems, this may reflect the need for plants to have both fine dense roots for soil exploration and thicker dense conductive roots for water transport. Additional research that assesses traits of fine and conductive roots independently would provide further insight about which root traits of which root orders are most important for plant performance under drought.

Outreach and Products:

Student training

The study was largely conducted by Navajo PhD student Marquel Begay, who was assisted in the field by early career researcher Albert Kline (Field Technician). A Postdoctoral Scholar was brought on to assist in generating data (Magda Garbowski), and she was assisted by Navajo undergraduate student Aneeya Lowe.

Website

Project updates, talks and papers were extended to the community through posting on the EcoRestore website as well as being blasted out in an email listserve monthly to over 2400 dryland management enthusiasts.

Presentations

Marquel has presented preliminary findings to five Chapter Houses across the Navajo Nation.

Gornish ES. Let's not reinvent the wheel: Using VERY old school strategies for cheap and easy restoration success! Forest Service. Zoom. Invited oral presentation. 11/24

Gornish ES. Managing invasive plants in the southwest. Native Plants in the Managed Landscape Seminar. Zoom. Invited oral presentation. 09/23

Lowe A, Garbowski M, **Gornish ES**. Seed variation and the effect on germination mean. UROC final presentation. Tucson, AZ. Invited oral presentation. 08/23

Gornish ES. Let's not reinvent the wheel: Using VERY old school strategies for cheap and easy restoration success! Reshaping the Earth Summit. Zoom. Invited oral presentation. 08/23

Gornish ES. Let's not reinvent the wheel: Using VERY old school strategies for cheap and easy restoration success! Arizona Master Naturalists. Zoom. Invited oral presentation. 04/23

Gornish ES. Seedballs to confront restoration challenges on aridlands. Great Basin Fire Science Exchange. Invited oral presentation. 3/23

Begay M, **Gornish ES**, Munson S, Nauman T. Wind erosion risk on Navajo Lands of the Colorado Plateau. Intertribal Agricultural Council Conference. Las Vegas, NV, poster presentation. 12/22

Gornish ES. Can rocks solve all of our problems? Collaborative Conservation Strategy and Adaptation Strategy Toolbox. Zoom, invited oral presentation. 12/22

Gornish ES. Can rocks solve all of our problems? Collaborative Conservation and Adaptation Strategy Toolbox webinar. Zoom, invited oral presentation. 11/22

Gornish ES. Let's not reinvent the wheel: Using VERY old school strategies for cheap and easy restoration success! Natural History Institute, Prescott AZ. Invited oral presentation.

10/22

Gornish ES. Restoration challenges and successes in the southwestern US. Environmental Science class at the University of Virginia. Invited oral presentation. 10/22

Gornish ES. Seedballs to confront restoration challenges on aridlands. Bisbee Science Fridays. Invited oral presentation. 10/22

Gornish ES. Let's not reinvent the wheel: Using VERY old school strategies for cheap and easy restoration success! Herbarium Lunch Series, University of Arizona. Invited oral presentation. 10/2022

Gornish ES. Seedballs to confront restoration challenges on aridlands. North Washington Native Plant Society. Zoom, invited oral presentation. 10/22

Gornish ES. Seedballs to confront restoration challenges on aridlands. Forest Service monthly meeting virtual conference. Zoom, invited oral presentation. 05/22

<u>Guides for managers</u>

Gornish ES, Shriver L, Corwin R, Havrilla C, Costanzo S, Ghering C (2024) Germination information for common Arizona restoration species. *University of Arizona Cooperative Extension* az2076

Gornish ES, Shriver L, Corwin R, Havrilla C, Costanzo S, Ghering C (2024) Informacion de germinacion para especies communes de restauracion de Arizona. *University of Arizona Cooperative Extension* az2076

Lowe AA, Garbowski M, **Gornish ES**. Species identity and the effect on germination. *University of Arizona Cooperative Extension* az2092

<u>Field days</u>

Tsalie – Fall 2024. Included six students from Diné Community college on a field tour.

Santa Rita Experimental Range – Fall 2025. Included 36 attendees from the Society for Ecological Restoration, Southwest Chapter.

<u>Workshops</u>

Southwest Indian Agricultural Association, Inc. – Spring 2023. Plant restoration workshop. 27 attendees

Coconino Master Gardeners – Spring 2023. Seedball workshop. 32 attendees

Malpai Borderlands Group – Fall 2023. Soil health on rangelands workshop. 75 attendees

Maricopa County Parks and Rec – Fall 2024. Seedball workshop. 20 attendees

University of Arizona, Cooperative Extension (zoom) – Fall 2025. 83 attendees

Papers

PhD student Marquel Begay has one paper in review and two papers in preparation for submission. We are (two years on) still waiting on Navajo IRB for permission to publish survey data from Chapter House presentations.

Garbowski M, Avi A, Kline A, **Gornish ES** (2025) Dense roots with low specific root length underpin performance of dryland restoration species under two types of drought. *Restoration Ecology* e70021

Gornish ES, Shriver L, Corwin R, Havrilla C, Costanzo S, Gehring C (2024) Información de germinatión para especies communes de restauración de Arizona. *University of Arizona Cooperative Extension* AZ2076

Gornish ES, Shriver L, Corwin R, Havrilla C, Costanzo S, Gehring C (2024) Germination information for common Arizona restoration species. *University of Arizona Cooperative Extension* AZ2076

Gornish ES, Lauman S, Begay M, Martyn T, Johnstone P, Ossanna L (2023) Restoration Ecology Activity Book. *University of Arizona Cooperative Extension* AZ2049