DISSERTATION

ON GROWING AND BEING: SITUATED APPROACHES TO RESTORATION ECOLOGY IN THE DRYLANDS OF THE WESTERN UNITED STATES

Submitted By

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ABSTRACT

ON GROWING AND BEING: SITUATED APPROACHES TO RESTORATION ECOLOGY IN THE DRYLANDS OF THE WESTERN UNITED STATES

Global land degradation is a result of systems of coloniality and extraction. Therefore, supporting the healing of ecosystems must work to dismantle systems of oppression while fostering ecological flourishing. My dissertation aims to support contextualized ecological healing in dryland ecosystems in the desert southwest of the United States. I approached this work with the ecofeminist understanding that systems of harm like colonialism and its subsequent structures of white supremacy culture, cis-heteropatriarchy, and extraction economies fracture people and land from each other, and that therefore, the restoration of ecological and social health are intertwined. In this work I asked 1) what restoration strategies may result in ecological healing through encouraging plant establishment in drylands, 2) what are the social and ecological nuances embedded within these dryland restoration practices, and 3) how can restoration practice be rooted in embodiment and liberation? All chapters within my dissertation focus on different aspects of these questions. The first two chapters emphasize how human action can support ecological health and analyze data about how ecological beings interact with each other. (1) Chapter 1 frames the dissertation through outlining intersections between land degradation and colonialism, as well as practices which support the healing of drylands through seed-based and precision restoration being entwined with centering communities. (2) Chapter 2 asks how indaziflam, an herbicide developed to manage cheatgrass (*Bromus tectorum*), impacts native plant

communities and the soil microbiome. I found that application of indaziflam reduces cheatgrass cover and increases native plant establishment but also shifts the microbiome towards chemical decomposers. (3) Chapter 3 focuses on precipitation dynamics of seeding native desert southwest plants with seed-based restoration treatments (seed pellets). In this study, I report that mechanically-made seed pellets significantly increased native plant establishment. (4) Chapter 4 addresses various levels of relational healing through analysis of a regional, community-based, and networked ecological restoration experiment called RestoreNet. I found that compost, mulch, and soil pitting resulted in higher seeded plant density and cover than seeding alone. Finally, (5) Chapter 5 is a synthesis paper that proposes principles of practicing an embodied approach to ecological restoration ("Embodied Ecology") which draws from articulations of Cuerpo Territorio, ecofeminism, and environmental justice. In this work I learn from the conceptualization of Cuerpo Territorio by Indigenous feminists from Abya Yala, and trace how histories of violence against the land and violence against women, queer people, and children have been interconnected, to propose a framework for ecological restoration that embodies liberatory practice. By grasping at these intricate questions in each of these chapters, I work towards an ecological restoration practice that embraces and intertwines itself with fields of environmental justice and ecofeminism. By inviting these fields into my positionality,

writing, and context, I move to advance the field of restoration ecology towards a more holistic ecological healing practice.

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This work has been a practice in, as the scholar Shireen Roshanravan beautifully puts it, "cultivating a depth of sorrow, animated by a great anger, and directed by love". I believe in a world where the colonial machine is ground to a halt. I believe in a free Palestine. I believe in queer liberation. I believe in a flourishing desert. I believe in a world free of sexual and domestic violence and all violence. In the last four years, I have sobbed with the understanding of how deep and wide the suffering held in this land and our bodies is. I have chanted, fought, loved, kissed, laughed, and dreamed a different world into being. I am tired, but I will keep going as long as I live, and I will live beautifully.

POSITIONALITY STATEMENT

Where I call home is a large valley that the Northwestern Band of the Shoshone know as Sihiviogoi, meaning willow river. Long before I was born, the valley bottom was thickly riparian with braided stream channels, covered in willows and cottonwoods, and dotted with beaver dams. But in the 1820's, white fur trappers from the east came to the valley and began to kill the beavers for hats. In the 1850's, Mormon colonists and Westward Expansion settlers moved into the valley, violently displacing the Indigenous peoples who lived there and taking more from the ecosystem (Watkins, 2023). As the willows receded, and the beavers disappeared, the Bear River began to straighten. Water was pumped for intensive industrial agriculture, cattle and sheep grazing, and lumber production, and the great Bear River shrunk into the low cracks in the valley floor. Now, developers fight over water rights for their new subdivisions that they scour mountain faces for, and the river runs dry. Because of the industrial pollution and the valley's shape, we have chronic inversions in the winter, where a thick layer of smog settles on our lives. From almost every point in town, you can see the towering Mormon temple, and dotted along the street are churches and tabernacles. Police lives matter flags cover the back windows of lifted trucks. There are still wild places, wide, scarred, beautiful mountains where I trace river birch bark with my fingers and follow deer trails up the ridgelines, but when I stand there, at the top of the ridge overlooking the valley, I see that the land I am from tells the story of how systems of harm like colonization, white supremacy, and cis-heteropatriarchy fracture us.

Tema Okun's definition of white supremacy culture demonstrates how these systems of harm in which the United States is enmeshed, is the basis of these fractures:

> "The term white supremacy culture refers to the ways in which the ruling class elite or the power elite in the colonies of what was to become the United States used the pseudo-scientific concept of race to create whiteness and a hierarchy of racialized value in order to:
>
> - disconnect and divide white people from Black, Indigenous, and People of Color (BIPOC);
> - disconnect and divide Black, Indigenous, and People of Color from each other;
> - disconnect and divide white people from other white people;
> - disconnect and divide each and all of us from the earth, the sun, the wind, the water, the stars, the animals that roam(ed) the earth;
> - disconnect and divide each of us from ourselves and from source...
>
> The power elite constructed white supremacy (and construct it still) to define who is fully human and who is not." – Tema Okun, *White Supremacy Culture: Still Here*

I like Tema Okun's definition because it outlines how these systems of harm, violence, and fracture, are all based on reducing relationships for capital production and maintaining a power elite system (Okun & Jones, 2001). Therefore, it is the restoring of relationships that can move the land and people that are now referred to as the United States as a whole, and in the little corner of the desert

southwest that I work in, towards a different way of being. In understanding that white supremacy culture, since its establishment in what is now called the U.S. by colonial forces, is the way of being that creates disconnection and division from each other and the land, I have come to understand that the healing of relationships people have with the land and each other is the way towards healing as a whole society, and for me personally, healing as a white-bodied person.

In a few years, my parents are moving away from Willow Valley to Sula, Montana, where my grandparents, 5 horses, and 3 cats live on 10 acres of land near the Bitterroot River. In the summers, I go to stay with them often. At the edge of the land, there is a slope down to the river, and a patch of forest in the floodplain. My grandparents don't go down the hill, so the whole river corridor has grown in and become a pathway for the animals of the canyon. In June one year, my father and I walked down into the tall Timothy grass towards the river, and accidentally scared a baby fawn out of the place her mother hid her. I felt so sorry for frightening her, and so grateful to have seen her. The river corridor is the place that I feel most peaceful now. It's there, with the sounds of horses in the pastures, the river running over stones, and the pileated woodpeckers that live in the big dead aspen trilling, that I feel most myself.

When I sit with the river there, and watch the water move downstream, I think about how this gift of closeness and love with the land is a responsibility and an honor. I think about willow valley, and the way that people who looked like me, with white skin and blue-green eyes, with crucifixes like my

grandmother's hanging around their necks, and with fur caps like the one my great-great grandmother wore on their heads, inflicted cruel and deeply harmful violence on the land and on people. Those are wounds that I am still healing from, and that the land is still healing from. Because to kill kills you, and to heal heals you. Which is why I know that taking care of the land is one of the most important things that I will ever do.

I see this dedication to repair of relationships on many different levels, in all different ways, as the most critical to dismantling white supremacy culture and all the systems of harm that fracture us. In being with my family on the land they steward, and being a restoration ecologist, I try to maintain my ecological relationships. But to be connected to healing relationships between people, and to practice healing relationally myself, I also work as a survivor advocate and birth and loss companion/doula. I work now at Crossroads Safehouse in Fort Collins, but I have worked at five different non-profit organizations that support survivors of domestic and gender-based violence over the past seven years. It's through being in these spaces that I see how these systems of harm disconnect people from one another. Each day I work at the shelter, I get at least five calls from people experiencing domestic violence. Shelters around the state are consistently full of people fleeing dangerous, lethal, relationships that are supposed to be based in love and care. And as a doula, I've seen partners unsure of how to hold their spouses when they're in pain, and doctors inflict harm onto birthing people's bodies. In seeing these things, it feels impossible to me that the issue is not systematic, that it is not something about the

way in which these systems teach that to love is to possess, or that some people are entitled to extract from other people's bodies and the body of the land.

I feel clear that the roots of violence on the land and the roots of violence in relationships in the U.S. West are white supremacy culture, colonialism, cis-heteropatriarchy, ableism, classism, and all of other structures of bias that uphold a capitalist structure of extraction in the name of supporting an arbitrary and violent elite class. And as Resmaa Menakem says, the trauma and daily manifestations of these systems of harm reside in bodies, "white supremacy — and all the claims, accusations, excuses, and dodges that surround it — are a trauma response. This response lives not inside psyches, but deep within bodies" (Menakem, 2017). As these systems of harm, which inflict racialized, gendered, and classed forms of traumatic experiences and reactions within our bodies, also inflict harm onto the bodies of ecological beings. I see this in my home, in my life and relationships, and in all of the spaces that I work within, and I therefore look for healing that is embodied practice.

It is my hope that my dissertation work can be a part of supporting embodied healing in the U.S. Western context. This is so critical to me because I see how much joy is possible in loving each other well, I feel how my body uncoils when I sit next to the river or when I sit listening to my horse's breath on the granite ridge. I feel how sweet it is to grieve and be held by my community, how beautiful it is to feel safe, and I know that trauma from violence, exploitation, and logics of domination, sever people from each other, and sever people from the land. As much as I feel the hope, I also feel the harm.

I bring all these stories of hope, harm, and healing to my dissertation research. For the conceptual framing of my dissertation work, I am looking to literature that is ecofeminist, centers principles of

healing and/or restorative justice, and considers relationships between ecological and human beings. All chapters of my dissertation work will be rooted in questions around relationships with land and ecosystems. Three chapters use quantitative methods and are primarily restoration ecology studies, which ask questions about how humans can support the flourishing of desert ecosystems. The other one is qualitative methods studies, which will center on questions about how

systems of power operate in the ways people interact with the land and each other. In doing my dissertation work this way, I increased understanding around how to approach relationships with the land on many different scales and in many different ways. I hope to understand more about how systems of harm move through relationships with ecosystems in restoration ecology in the desert southwest, how to support the healing of ecosystems by deconstructing these systems of harm, and how to keep moving towards healing myself.

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CHAPTER 1 - INTRODUCTION

The practice of restoration ecology is rooted in a hope for a future in which ecosystems and people are flourishing. Though it often isn't articulated by restoration ecologists that this vision is an anti-colonial one, true flourishing of ecosystems would require the ceasing of land degradation, which would require the dismantling of the extractive patriarchal system born through settler colonialism. In the United States, under a colonial economy, capital is accumulated by the wealthy few through extraction of land which was violently dispossessed from Indigenous peoples and transformed by the labor of people along racialized, gendered, and classed lines (Mies, 1989). This system is predicated on the degradation of land, as it necessitates that land is objectified into "products" instead of beings. Therefore, the restoration of ecosystems globally requires the dismantling of systems that have and continue to dispossess, objectify, and extract from land and people. Here, I assert that an epistemological and ontological approach to restoration ecology that is explicit about dismantling systems of oppression, highly contextual, and community-led is needed for thriving ecological futures to be realized.

1.1 LAND DEGRADATION AND COLONIAL CAPITALISM

Systems of harm such as colonial capitalism, which is to say the specific frame of patriarchal capitalist economies that has been systematically imposed by colonialism, create land degradation through the

dividing of people and land and the degradation of land for products (Shiva, 2010). In Chapter 5, I explicitly outline the ways that several histories and logics of domination (Warren, 1990), which are oppressive logics that claim moral superiority of a group of beings to justify the oppression of another group, have been intertwined with the degradation of land. By historicizing the entanglement of systems of oppression with land degradation, a conceptualization of how logics of domination have inflicted harm on people and land in a deeply entangled way (Honkanen, 2005). This understanding is critical to any work in restoration ecology, because to support the healing of the land and understanding of the harm the land has undergone must be conceptualized. The material reality of the land and ecosystem is shaped by the historical, social, economic, and ecological contexts that surround it.

So many scholars, activists, and practitioners have extensively noted how, as Lee Maracle states, "violence to earth and violence between humans are connected" (Maracle, 2015, p. 53). This is not a new conception, and was fleshed out notably by Karl Marx, who discusses primitive accumulation as an initial violence in which capital comes into this world "dripping from head to foot, from every pore, with blood and dirt" (Marx et al., 1981). Marx used capitalistic agriculture as an example of how extractive industry both degrades land and workers, forcing the overproduction of soil until the nutrients are gone and forcing the work of the laborer until their health is also gone (Marx, 1992). Therefore the healing of soil after extractive agriculture must also be concerned with the healing of the worker's health, as they are inextricably linked. We must recognize that the body of the land is our

body and that we are the body of the land, and as scholars engaged in the Cuerpo Territorio movement state "there is no ontological difference between territory (land) and the body. Hence what is done to the body is done to the territory and vice versa" (Zaragocin & Caretta, 2021). Restoration ecology cannot address the healing of the body of the land while still subscribing to systems that harm people, because the two are not separate. The epistemological and ontological foundation of land degradation is the epistemological and ontological foundation of oppression of people.

The danger of not directly seeing and speaking to logics of domination when working with land can be seen when we examine the histories of biology and ecology as fields. As Vandana Shiva points out, "the Western patriarchal conceptualization of biology was based on robbing intelligence from organisms if they were female or nonhuman" (Shiva in Jaggar, 2016, pg. 223). This stealing of intelligences is motivated by the aspect of objectification or production. Often, quantification can be a tool for objectification, as many feminist scholars have noted in tracing the harm of western science (Smith et al., 2023). Quantitative restoration ecology has, as Jennifer Grenz states, "taken scientific understanding to create rules for ecological restoration such that it can be executed in a cookie-cutter fashion" (Grenz, 2024). But ecosystems are highly contextualized, nuanced in their histories, needs, and compositions, and therefore, actual restoration has to be highly contextual as well.

Ecological research in particular can play into the objectification and decontextualization of restoration. Many Indigenous scholars have outlined how "research during [the early colonial] phase was mainly observations of Europeans as they colonized Aboriginal [and Indigenous] lands," as Shawn

Wilson notes in their book, *Research is Ceremony* (Wilson, 2008). Scholar Banu Subramaniam sums the colonial origins of botanical and ecological research by stating "they claimed local knowledge and renamed plants after white scientists, explorers, and rulers....They decimated local knowledge systems, practices, and cultures to install a colonial, European system as universal science," (Subramaniam, 2024). Now, the academic system is the inheritor of these immense harms, and by conducting restoration ecology research within the academy, particularly without the knowledge of and direct opposition to these legacies, research can perpetuate and grow the legacy (Grenz & Armstrong, 2023).

Therefore, this work is particularly interested in historicizing, contextualizing, and centering community members in restoration ecology. It is this epistemological and ontological framing, that recognizes, as the Cuerpo Territorio movement articulates, the intertwinement between the bodies of people and the body of the land, that must guide restoration ecology research and projects ("Humus - Capítulo 2. Lorena Cabnal: El Cuerpo Como Territorio de Defensa | La Tinta," 2020). In this work, I began to learn how to do these things and disentangle them for myself and for the wider field. I employ methods from dryland restoration ecology, seed-based restoration to mechanistically work towards healing, while pulling from precision restoration for contextualization and historicization and community-based natural resource management for community participation.

1.2 FRAMING COMMUNITY-BASED DRYLAND RESTORATION ECOLOGY

This work is situated within the context of dryland ecological restoration, and particularly focuses on rangeland and agricultural landscapes on the Colorado Plateau. My longest running project (Chapter 4) is a comparative study of two sites in Montezuma County, CO, one which is less arid and post-agricultural, and the other, which is more arid and was grazed extensively by cattle and wild horses. This work tests different restoration strategies and the response of seeded native plants to them at the two sites, then compares between the sites. My other restoration-based studies are supportive of this research, and examine different seeding strategies and how a herbicide which is applied to reduce a common introduced grass (*Bromus tectorum*) impacts other organisms.

Dryland restoration ecology is a unique branch of restoration ecology because it works to support lands that are highly water limited (Bestelmeyer et al., 2015). These lands are particularly vulnerable to the crisis imposed by extractive systems because land degradation has decreased ecosystem biodiversity and resilience and has now led to less ability to regenerate as precipitation decreases and temperatures increase (Burrell et al., 2020). Desert and dryland ecosystems can often be misconceived as "wastelands" when they are in fact highly biodiverse and support critical global ecosystem functioning and balance (Dregne, 2002). Drylands face threats due to the climate crisis, introduced species encroachment, increased intensification of land degradation and subdivision of land, and feedback loops between these things (Hoover et al., 2020). These biotic and abiotic factors often exert pressure on restoration, as plants may not be able to establish in the face of these barriers.

Seed based restoration (SBR), or the distribution of seeds on the ground, is the only economically feasible way to distribute a large amount of plants on a landscape (RestoreNet, 2023). However, SBR is often not very successful in drylands because the seeds dessicate from heat or lack of precipitation, are eaten, or do germinate and then quickly perish because of the harsh conditions intensified by climate change (Shackelford et al., 2021). Restoration treatments like those I explore in Chapter 4 which decrease the barriers that seeds face through mechanistic support, and treatments like seed pelleting (Chapter 3) as well as the reduction of pressure from introduced species (Chapter 2) all can increase the establishment of native plants through seeding.

To overcome barriers to SBR, I often draw from precision restoration, which is a relatively new term in restoration ecology that argues for highly contextualizing restoration work. Though precision restoration has yet to be used for fully fleshing out site histories, including those which interplay with systems of harm, this strategy does incorporate nuanced understandings of ecosystems, which is a move away from "cookie-cutter" restoration. Precision restoration "targets critical biotic and abiotic barriers to restoration success and applies specific tools or methods based on barrier distribution in space and time," these barriers include large-scale land degradation and the ways that land degradation has played out at a particular site. This is particularly important in dryland restoration, as the strength of barriers can prevent restoration efforts that aren't highly contextualized from succeeding.

Contextualization and degradation of the concept that the scientist is the knower, while the community and land are the known, my research is particularly informed by community-based natural resource management. The questions asked across these chapters have been informed by people who are living and working with dryland ecosystems. Community-based natural resource management and research is a critical component of dismantling and untangling ecological research that re-inscribes colonial ways of being (David-Chavez et al., 2020). It is important that research be contextualized and close to the land and close to the people that steward the land. My work has been informed by stewards affiliated with the Ute Mountain Ute Tribe, Boulder County Parks and Open Space, and independent ranching and agricultural producers. These land stewards have been extensively consulted, consistently informed, and reported to throughout the process of this work.

Through incorporating these principles of precision restoration and community-based natural resource management into seed-based dryland restoration, I hope to grow towards a restoration ecology that works to dismantle systems of harm instead of reinscribing them. As supporting the healing of the land also requires supporting the healing of people, these things not being separate, but an intertwined journey, dismantling these systems is crucial. In naming this epistemological and ontological framing at the beginning, the invisibilization of these harms is reduced, and a move towards a holistic land healing practice is incorporated.

1.3 REFERENCES

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., & Herrick, J. E. (2015). Desertification, land use, and the transformation of global drylands. Frontiers in Ecology and the Environment, 13(1), 28–36. https://doi.org/10.1890/140162

Burrell, A. L., Evans, J. P., & De Kauwe, M. G. (2020). Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. Nature Communications, 11(1), 3853. https://doi.org/10.1038/s41467-020-17710-7

David-Chavez, D. M., Valdez, S., Estevez, J. B., Meléndez Martínez, C., GarciaJr, A. A., Josephs, K., & Troncoso, A. (2020). Community-based (rooted) research for regeneration: Understanding benefits, barriers, and resources for Indigenous education and research. AlterNative: An International Journal of Indigenous Peoples, 16(3), 220–232. https://doi.org/10.1177/1177180120952896

Dregne, H. E. (2002). Land Degradation in the Drylands. Arid Land Research and Management, 16(2), 99–132. https://doi.org/10.1080/153249802317304422

Grenz, J. (2024). Medicine wheel for the planet: A journey toward personal and ecological healing (First University of Minnesota Press edition). University of Minnesota Press.

Honkanen, K. (2005). 'It is Historically Constituted': Historicism in Feminist Constructivist Arguments. European Journal of Women's Studies, 12(3), 281–295. https://doi.org/10.1177/1350506805054269

Hoover, D. L., Bestelmeyer, B., Grimm, N. B., Huxman, T. E., Reed, S. C., Sala, O., Seastedt, T. R., Wilmer, H., & Ferrenberg, S. (2020). Traversing the Wasteland: A Framework for Assessing Ecological Threats to Drylands. BioScience, 70(1), 35–47. https://doi.org/10.1093/biosci/biz126

Jaggar, A. M. (Ed.). (2016). Just methods: An interdisciplinary feminist reader (Second edition). Routledge. https://doi.org/10.4324/9781315636344

Maracle, L. (2015). Memory Serves: Oratories. NeWest Press.

Mies, M. (1989). Patriarchy and accumulation on a world scale: Women in the international division of labour (3. imp). Zed Books.

RestoreNet: Collaboration to Improve Success of Seed-Based Restoration | U.S. Fish & Wildlife Service. (n.d.). Retrieved February 16, 2026, from https://www.fws.gov/project/restorenet-collaboration-improve-success-seed-based-restoration

Shackelford, N., Paterno, G. B., Winkler, D. E., Erickson, T. E., Leger, E. A., Svejcar, L. N., Breed, M. F., Faist, A. M., Harrison, P. A., Curran, M. F., Guo, Q., Kirmer, A., Law, D. J., Mganga, K. Z., Munson, S. M., Porensky, L. M., Quiroga, R. E., Török, P., Wainwright, C. E., … Suding, K. L. (2021). Drivers of seedling establishment success in dryland restoration efforts. Nature Ecology & Evolution, 5(9), 1283–1290. https://doi.org/10.1038/s41559-021-01510-3

Shiva, V. (2010). Staying alive: Women, ecology, and development. South End Press.

Smith, C., Diver, S., & Reed, R. (2023). Advancing Indigenous futures with two-eyed seeing: Strategies for restoration and repair through collaborative research. Environment and Planning F, 2(1–2), 121–143. https://doi.org/10.1177/26349825221142292

Warren, K. J. (1990). The Power and the Promise of Ecological Feminism: Environmental Ethics, 12(2), 125–146. https://doi.org/10.5840/enviroethics199012221

Zaragocin, S., & Caretta, M. A. (2021). Cuerpo-Territorio: A Decolonial Feminist Geographical Method for the Study of Embodiment. Annals of the American Association of Geographers, 111(5), 1503–1518. https://doi.org/10.1080/24694452.2020.1812370

CHAPTER 2 - PLANT AND SOIL MICROBIAL COMPOSITION LEGACIES FOLLOWING INDAZIFLAM HERBICIDE TREATMENT[2]

2.1 ABSTRACT

Land stewards in dryland ecosystems across the western U.S. face challenges to manage the exotic grass Bromus tectorum (cheatgrass), which is a poor forage, is difficult to remove, and increases risk of

catastrophic fire. Managers may consider using indaziflam (Rejuvra™), a relatively new pre-emergent herbicide, which may reduce cheatgrass cover within drylands. However, few studies have explored the effects of indaziflam on non-target organisms. We tested how indaziflam application impacted cover and biomass of native and exotics within the plant community and composition and diversity of the soil microbiome by comparing untreated and treated arid shrubland sites in Boulder County, Colorado, USA. We found that indaziflam application decreased cheatgrass cover by as much as 80% and increased native plant cover by the same amount. Indaziflam application also was associated with increased soil nitrate (NO_3^-), decreased soil organic matter, and had a significant effect on the composition of the soil microbiome. Microbial community composition was significantly related to soil NO_3^-, soil organic matter, soil pH, and native species and cheatgrass biomass. An indicator species analysis suggested that indaziflam application shifted microbial communities. In untreated sites, ammonia-oxidizing bacteria Nitrosomonadaceae and nitrogen-digesting Opitutaceae and the fungi Articulospora proliferata were

found. While in treated sites, ammonia-oxidizing archaea, which are associated with intact drylands, Nitrososphaeraceae and toxin digesters, and acidic-soil species Sphingomonas and Acidimicrobiia were significantly associated. Overall, these results demonstrate that indaziflam application can increase native plant recruitment while also affecting soil properties and the soil microbiome. The findings from this study can be used to inform decision-making during the dryland restoration planning process as indaziflam use may have benefits and unknown long-term consequences for the biogeochemistry and microbial ecology of the system.

2.2 INTRODUCTION

Cheatgrass now occupies over 54 million acres in the Intermountain West (the region of the United States between the Rocky Mountains, Cascades, and Sierra Nevada's but not including the Pacific Coast) after its introduction as a contaminant in grain during the 1900s (Pierson and Mack, 1990; Sebastian et al., 2017). Cheatgrass is an early seeding grass which outcompetes native plant species, resulting in loss of diversity, disruptions of historic grazing regimes, and increased risk of catastrophic wildfire (Balch et al., 2013; Pilliod et al., 2017). These impacts have driven land managers

to seek strategies for reducing cheatgrass populations, but targeted grazing, prescribed burning, and use of other herbicides have all had limited success (Lehnhoff et al., 2019; Mack, 2010; Perryman et al., 2020).

Indaziflam (marketed as Rejuvra®/Esplanade® by Bayer CropScience) is a relatively new herbicide that was approved in 2020 for use to control invasive annual grasses on rangeland and open space. Indaziflam is a fluoroalkyl triazine-containing herbicide that inhibits cellulose synthesis (Brabham et al., 2014). Indaziflam application has shown reduction of cheatgrass (Clark et al., 2023; Meyer-Morey et al., 2021; Sebastian et al., 2017). However, weed control with indaziflam may also impact non-target taxa (Meyer-Morey et al., 2021; Sebastian et al., 2020; Strilbytska et al., 2022). Thus far, treatment with indaziflam has shown positive (Clark et al., 2023; Seshadri et al., 2018) and negative (Clenet et al., 2019; Fowers and Mealor, 2020; Meyer-Morey et al., 2021) effects on native plant cover and diversity. While Seshadri et al. (2018) found that indaziflam increased native forb diversity and floral resources for pollinators, Meyer-Morey et al. (2021) saw reduction in cover of [1]target invasive annual mustards (Alyssum spp.) and also decreased native forb diversity 2 years following treatment in a sagebrush steppe ecosystem. Given these limited and conflicting results, additional study about indaziflam effects on native plant communities and non-target organisms following treatment is needed.

[1] Published in Frontiers in Microbiology, https://doi.org/10.3389/fmicb.2024.1450633

Herbicides may also impact soil microbial communities and nutrient cycling (Asad et al., 2017; Caggìa et al., 2023; Sebastian et al., 2020; Van Bruggen et al., 2021), although few studies have investigated indaziflam's effect on these processes. Soil microbes mediate key ecosystem functions (Fierer et al., 2021; Neilson et al., 2017; Wang and Li, 2019), and herbicide treatments can have variable effects on them (e.g., Van Bruggen et al., 2021). For example, the broad-spectrum systemic herbicide glyphosate interferes with nitrogen metabolism in some soil bacteria, while others can digest it (Helander et al., 2012; Huang et al., 2017; Ruuskanen et al., 2023). In a study that examined indaziflam impacts on soil properties, application shifted soil carbon and nitrogen mineralization rates 11 days after treatment (Koçak et al., 2021). However, to our knowledge, there have been no studies of how indaziflam impacts soil microbial community composition in natural grassland systems.

The central goal of this study was to explore the effects of indaziflam on soil microbial and native plant communities to improve management planning and practice. The major research objectives of this project were to:

1. Observationally evaluate the effects of indaziflam on non-target soil microorganisms and native plants by comparing community composition in areas that have been treated with indaziflam herbicide with untreated controls.
2. Assess whether indaziflam effects on soil microbes and native plants vary across
    a. Ecological gradients (e.g., soil texture, ecological site type, and pre-treatment exotic grass cover)

b. Time since application.

3. Explore relationships among exotic plant, native plant, and soil community composition in treatment versus control plots to infer potential mechanisms whereby indaziflam could affect the soil microbial communities.

Incomplete understanding of the effects of indaziflam on non-target organisms in natural systems currently limits the capacity of land stewards to weigh the potential benefits and risks of indaziflam. The findings from this study can support land manager decision-making by increasing understanding of indaziflam effects on native plant and soil microbial communities relative to controls.

2.3 METHODS

2.3.1 Site description

We collected soil samples and data describing soil physical characteristics and plant communities from seven sites within arid foothill shrubland 7,000 ft. above sea level in Boulder County Parks and Open Space (BCPOS) in Boulder, Colorado USA in June 2022 (Caudle et al., 2013; Soil Survey Staff, 2024). Soil and vegetation data were collected at seven sites spanning a 5-year gradient of time since indaziflam treatment (2017–2022). Each site contained two paired plots [50×50-m plots one treated with indaziflam (T) and one untreated (U)] for a total of 16 plots. Paired plots were selected to have similar potential vegetation (ESD), soil texture, and slope (Table 1) to each

plot. All sites had an average annual temperature of 7.9°C and an average annual precipitation of 516 mm (PRISM Climate Group, Oregon State University, 2014).

Table 1. Site characteristics and herbicide application information for each site. Soil texture information from USDA Web Soil Survey tool (Soil Survey Staff, 2024).

Site ID	Site Name	Year Treated	Average Soil pH	Soil Texture
RABB22	Rabbit Mountain	2022	6.60	Very stony sandy loam and clay loam
DORO21	Dorothy Ellen	2021	7.08	Very stony sandy loam
DORO20	Dorothy Ellen	2020	7.13	Very stony sandy loam
TREVA22	Trevarton	2022	7.16	Gravelly sandy loam
TREVA19	Trevarton	2019	6.35	Gravelly sandy loam
TREVA18	Trevarton	2018	5.75	Gravelly sandy loam
TREVA17	Trevarton	2017	6.46	Gravelly sandy loam

2.3.2 Plant community monitoring

To explore how plant communities responded to herbicide treatment, we collected plant cover and biomass data for native and exotic plant communities from indaziflam-treated and untreated plots. Vegetation data were collected from three, 1×1-m subplots within each plot using a quadrat

(Figure 1, Supplementary Figure S1, found in Appendices section 1). Subplots were first photographed, and a general description of the plant community and site type was recorded. Within each subplot, we collected plant data on (1) species-level native plant cover (% cover) using a cover estimator and visual estimate and biomass (ounces) for grasses, forbs, shrubs, and bare ground, (2) exotic plant cover and biomass, (3) native plant diversity (e.g., species richness and Shannon diversity) through identification of each species present by a trained botanist and using the USDA, NCRS (2022) database citation,1 and (4) ground level thatch biomass, depth, and cover for native plants and cheatgrass (mm measured at thickest point with a ruler). Data were collected from all plots in June 2022. Some of the sites shared the same control plots, so vegetation monitoring was conducted only once for the shared sites.

Figure 1. Example photographs of untreated (left) and treated (right) plots taken within the Trevarton site. Untreated plots were generally noticeably covered in cheatgrass (yellow arrow pointing to an example), while treated plots usually had fallen cheatgrass, but mostly native grasses and forbs growing within the plot.

2.3.3 Soil physical sampling and analyses

Three soil samples (500 g) were collected to a depth of 10 cm from each subplot within each plot using a sterilized trowel (Supplementary Figure S1). Soil samples collected from each subplot (n = 3 each) were then pooled and homogenized. All samples were air-dried and stored in paper bags at room temperature prior to analysis. Samples were then sent to the Colorado State University Soil and Plant Testing Lab2 where organic matter content, electrical conductivity, pH, and nitrate (NO_3^-) were measured. Organic matter was measured using the loss on ignition method (Mehlich, 1984; Ball, 1964). Bulk density was measured with a mass per volume calculation using intact oven-dried 200 mL subsampled cores (Håkansson, 1990; Håkansson and Lipiec, 2000). Electrical conductivity and pH were measured using a 1:1 soil to water suspension (Sparks, 1996). Finally, nitrate was measured using a 2 M KCl extraction (Matsumura and Witjaksono, 1999).

2.3.4 Soil microbial sampling

Soil samples for microbial analysis were collected from the same subplots (Supplementary Figure S1). For these samples, 10 g of soil was collected from three points within each subplot to a depth of 10 cm using a metal trowel that was rinsed in ethanol between plot sampling events (Penton et al., 2016). All samples were collected in sterile Whirl-Paks™ after sifting roots and debris out and homogenized on site, placed on dry ice during transport, and then stored in a −40°C freezer until further analysis. Before conducting microbial analysis, soils were sieved through a 3.35 mm sieve.

2.3.5 Soil DNA extraction, PCR, and gene amplicon sequencing

See Appendix 1 for a full microbial analysis methodology. First, DNA was extracted from 0.25 g of soil using the Qiagen DNeasy PowerSoil Pro Kit (Qiagen, Hilden, Germany) following the manufacturer's instructions. Blank samples were used as negative controls. Next, we used primers (515F/806R 16S and ITS1-F/ITS2 ITS) to amplify the V4 region of the 16S rRNA gene for bacteria and archaea, and the ITS gene region for fungi (Bellemain et al., 2010; Iwen et al., 2002; Parada et al., 2016; Walters et al., 2016). Each sample was assigned a 12-bp barcode, homogenized, and then randomly assigned a location on a 96-well plate. The reactions were run in duplicate and then combined. SequalPrep Normalization Kit was used to normalize. DNA extraction was done in the

Dryland Ecology and Management Lab at Colorado State University, while PCR and sequencing were done at the CIRES Microbial Community Sequencing Laboratory at the University of Colorado Boulder. Samples were then sequenced with the Illumina MiSeq platform. For 16S, a 300-cycle kit and, for ITS, a 500-cycle kit were used, paired-end (PE) for both. After sequencing, idemp (idemp3) was used to demultiplex the samples according to their specific barcodes. We used cutadapt (Martin, 2011) for cleaning. We then used the dada2 package in R (Callahan et al., 2016) to characterize the microbial communities in each sample. After using the filertaAndTrim() function (settings: 16S truncLen = c(150,150), ITS truncLen = c(200,220), maxEE = (2,2), truncQ = 2, rm.phix = T) (see Supplementary Figure S3 for quality read plots), learning error rates, and merging pairs, we used a Bayesian taxonomic identifier (Wang et al., 2007) as implemented in the dada2 package to assign a taxonomy based on UNITE (Oct. 2021 release for ITS) and Silva (v 138.1 for 16S).

2.3.6 Statistical analyses

Soil microbiome data were filtered and rarified prior to statistical analysis. Amplicon sequence variants (ASVs) that were highly abundant in negative control samples were filtered out after verifying that these ASVs were not highly abundant in the sample data.

All statistical analyses were performed in R version 4.2.2 (R Core Team, 2023). We used generalized linear mixed effects models (GLMMs) with the lme4 package (Bates et al., 2014). Separate models were built for the following response variables: cheatgrass cover

(%), cheatgrass biomass (ounces per m2), cheatgrass thatch depth (cm), total native herbaceous plant cover (%), total native forb cover (%), total native shrub cover (%), native species richness, and soil mineral nutrient levels of interest (i.e., organic matter, NO3- (ppm), pH, and others). In each model, indaziflam treatment (i.e., treated vs. control) was included as fixed effects, and Site_ID was included as a random effect. The significance of individual terms ($p < 0.05$) included in final models was estimated using a Wald Type II X2 test ('ANOVA' function, car package; Fox and Weisberg, 2011). For significant variables, we used planned contrasts to explore differences in group means among levels using the 'emmeans' function (package emmeans; Lenth, 2017).

Permutational analysis of variance (PERMANOVA) tests were then conducted using the vegan (Oksanen, 2020), pairwiseAdonis(Arbizu, 2020), and smartsnp packages (Herrando-Pérez et al., 2021). In these models, treatment (treated with indaziflam or not treated) was the predictor variable, and Bray–Curtis dissimilarity matrices of vegetation and soil variables were the response variables. PERMANOVAs were nested by site. We first calculated the Shannon index and species richness using the diversity() and specnumber() functions of the vegan package (Oksanen, 2020).

We then used ANOVA (analysis of variance) tests to compare the Shannon indices and species richness (Fox and Weisberg, 2011). To parse apart if soil and ecological variables had a related effect on microbial diversity and community composition, we also conducted a multiple regression on distance matrices (MDRM) test (Goslee and Urban, 2007). Finally, we performed an indicator species analysis to determine taxa indicative of treated and untreated conditions. For this analysis, we used the multipatt() function of the indicspecies package (De Cáceres et al., 2010).

2.4 RESULTS

2.4.1 Cheatgrass versus native plant species responses to indaziflam treatment

The results from generalized linear mixed models comparing herbicide treated vs. control plots showed striking differences in plant community composition (Figure 2). Overall, plots treated with indaziflam herbicide had substantially lower cheatgrass cover (Figures 2A–C) and higher native plant cover (Figures 2E–H) relative to untreated controls. These differences also varied in magnitude in paired plots observed 0–5 years following herbicide treatment (Figure 2). For cheatgrass cover, treated plots on average had ~75% lower cheatgrass percent cover, with an average of 0 % cheatgrass cover, relative to untreated controls (which at a significance level of $p < 0.001$ had a mean of 51–83% cover; Figure 2A). Cheatgrass thatch cover was also significantly lower in treatment plots overall ($p < 0.001$) and decreased slightly with increasing time since treatment ($p = 0.086$; Figure 2C). Total percent cover

of other non-native weeds was also lower in treatment plots, reduced on average by 37% cover ($p < 0.001$; Figure 2D).

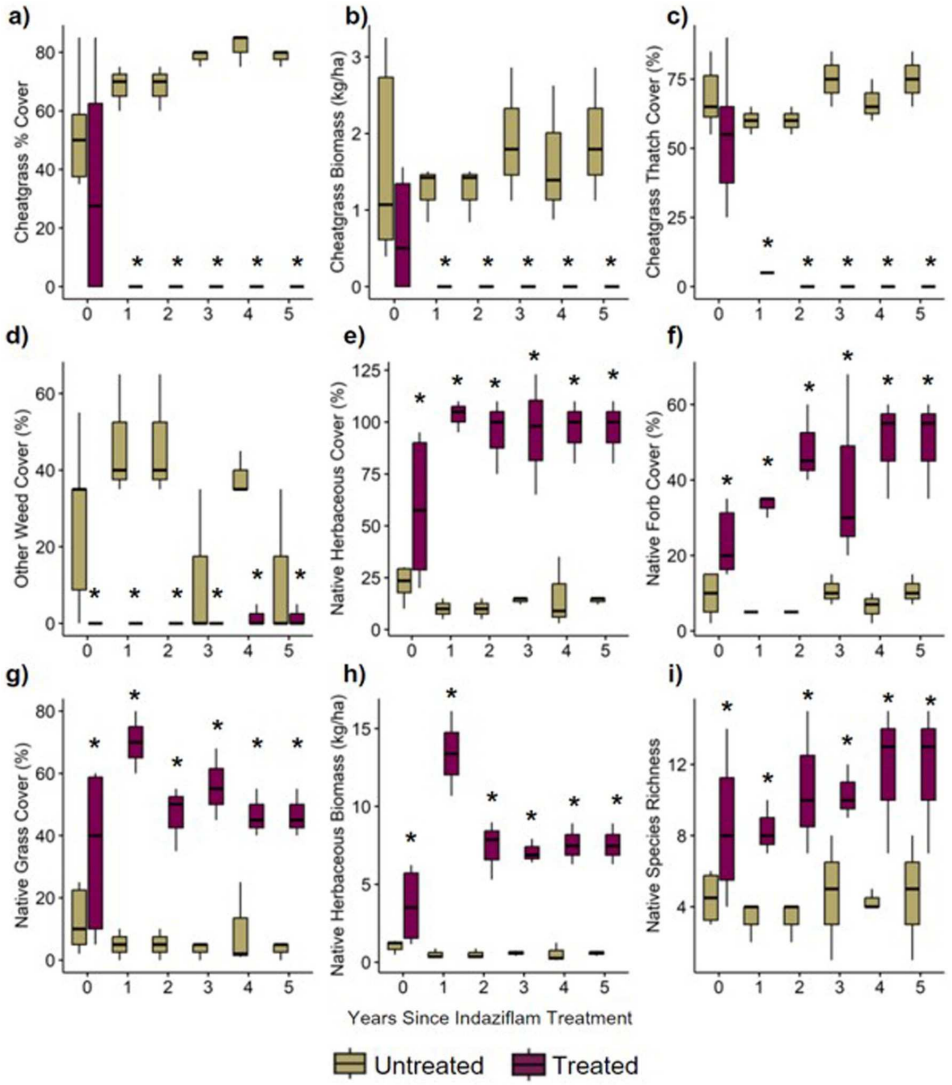


Figure 2. (A) percentage of the plot covered by cheatgrass, (B) biomass of cheatgrass collected in plot, (C) percentage of the plot covered by thatch (living and dead plant material) from cheatgrass, (D) percentage of the plot covered by weeds other than cheatgrass, (E) percentage of the plot covered by all native herbaceous material, (F) percentage of the plot covered by native forbs (subset of native

herbaceous cover), (G) percentage of the plot covered by native grasses (subset of native herbaceous cover), (H) biomass of native biomass collected in plot, (I) count of native species in plot.

Treated plots on average had ~6-fold greater total native herbaceous plant cover relative to untreated controls ($p < 0.001$; treated average cover = >100%, control average cover = 20%; Figure 2E), with over 4-fold greater native forb cover ($p < 0.001$; Figure 2F) and 11-fold greater cover of native grasses in treated plots ($p < 0.001$; Figure 2G). Total herbaceous plant biomass (lb./ac) was higher ($p < 0.001$; Figure 2H) in treated plots. Native species richness was also substantially higher in indaziflam-treated plots (~10 versus ~4 native species per plot, respectively; $p < 0.001$; Figure 2I). Together, these results show steep declines in cheatgrass and weed cover in indaziflam-treated plots and increases in native plant cover and biomass in years following indaziflam application. All data from this project can be found at doi: 10.5061/dryad.7m0cfxq4r and in the NCBI database under the BioProject ID PRJNA1171444.

2.4.2 Responses of soil physical characteristics to indaziflam treatment

Soil physical characteristics also differed between indaziflam treatment versus control plots. For soil properties, soil organic matter (SOM) was lower in indaziflam-treated plots ($p = 0.033$; Figure 3A) ($p = 0.013$; Figure 3A). While there were no significant differences in SOM in Year 0-1, in Years 2-5 SOM was significantly lower in treated plots. In contrast, soil nitrate ($NO3-$) was higher

in indaziflam-treated plots ($p < 0.001$; Figure 3B). Although the magnitude of NO3- ppm difference between treated and untreated plots was not consistent in time since treatment ($p < 0.001$; Figure 3B), soil NO3- was significantly higher in treatment plots spanning all years since treatment except for in Year 5 (2022) where it was equivalent between treated and untreated plots. Finally, soil pH also differed across plots, although differences were variable across time since treatment ($p = 0.010$; Figure 3C). Soil pH was highly variable across years (Figure 3C). Soil physical characteristics and plant community data are indicated in the file "FINAL_BCPOSVeg.csv."

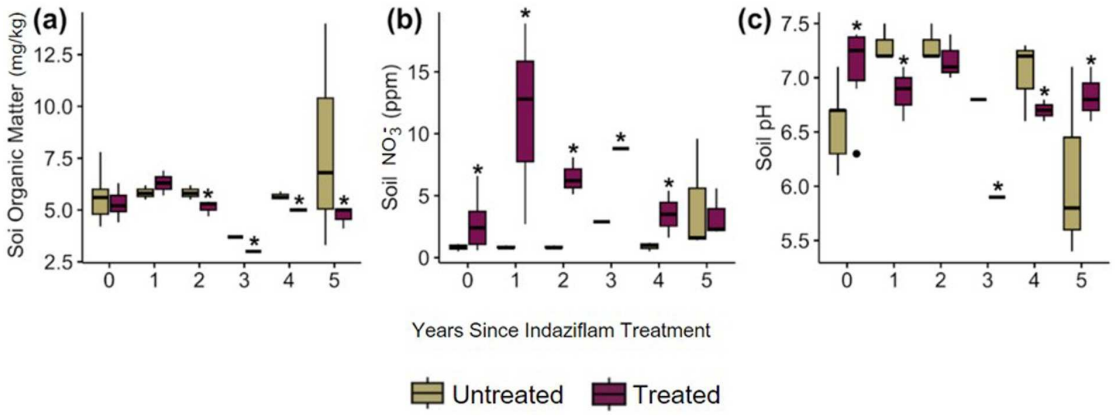


Figure 3. (A) concentration of soil organic matter (mg/kg) in soil samples from plot, (B) concentration of soil nitrate (ppm) in soil samples from the plot, (C) pH of the soil samples from plot.

2.4.3 Microbial database results

16S data from this project resulted in 9,042 ASVs across all samples and treatments. Treated samples had 4,567 ASVs, and untreated samples had 4,589 ASVs in total (see file "FINAL16S_ASVs_ID.csv"). The most abundant phylum included the genus was Nitrososphaeraceae that represents ammonia-oxidizing archaea such as Candidatus Nitrosocosmicus, which are common in most soils (Sauder et al., 2017; Tourna et al., 2011). The second most abundant group were a part of the general Bacillales order, members of the Firmicutes phylum, which are also highly abundant and common soil microorganisms (Setlow and Doona, 2023).

ITS data resulted in 3,128 ASVs across all samples and treatments. Treated samples had 1,539 ASVs, and untreated samples had 1,450 ASVs in total (see file "FINALITS_ASVs_ID.csv"). The most abundant ASV was Solicoccozymaeria, a common soil fungus (Rui et al., 2022). Mortierella, another common soil fungus implicated in decay and organic matter cycling, was also abundant (Ozimek and Hanaka, 2021). Other information about community composition can be found in the Supplementary materials (file "Bradbury_BCPOS_SupplementaryMaterials.docx").

2.4.5 Microbial community composition variance

PERMANOVA testing nested by site demonstrated that plots treated with indaziflam significantly differed in microbial community composition from untreated plots for both bacteria/archaea (16S; $p = 0.008$; Table 2; Figure 4) and fungi (ITS; $p = 0.001$; Table 2; Figure 4).

Table 2. P-value and significance level of each soil and biomass variable in the MDRM test for 16S and ITS data showing that pH, organic matter, nitrate, and native forb biomass are significantly related to 16S and organic matter to ITS composition. Significance amount marked by symbols, * = <0.05, ** = <0.005, *** = <0.001.

16S MDRM Results

Variable	Coefficient	p	Significance
pH	-0.024	0.040	**
OM	0.025	0.033	**
NO3-	0.006	0.084	*
Cheatgrass Biomass	-0.011	0.418	
Native Grass Biomass	0.008	0.062	
Native Forb Biomass	-0.014	0.080	*
Native Shrub Biomass	0.009	0.638	

ITS MDRM Results

Variable	Coefficient	p	Significance
pH	-0.002	0.708	
OM	0.008	0.068	*
NO3-	-0.002	0.202	
Cheatgrass Biomass	0.009	0.259	
Native Grass Biomass	0.004	0.151	
Native Forb Biomass	0.006	0.198	
Native Shrub Biomass	0.009	0.343	

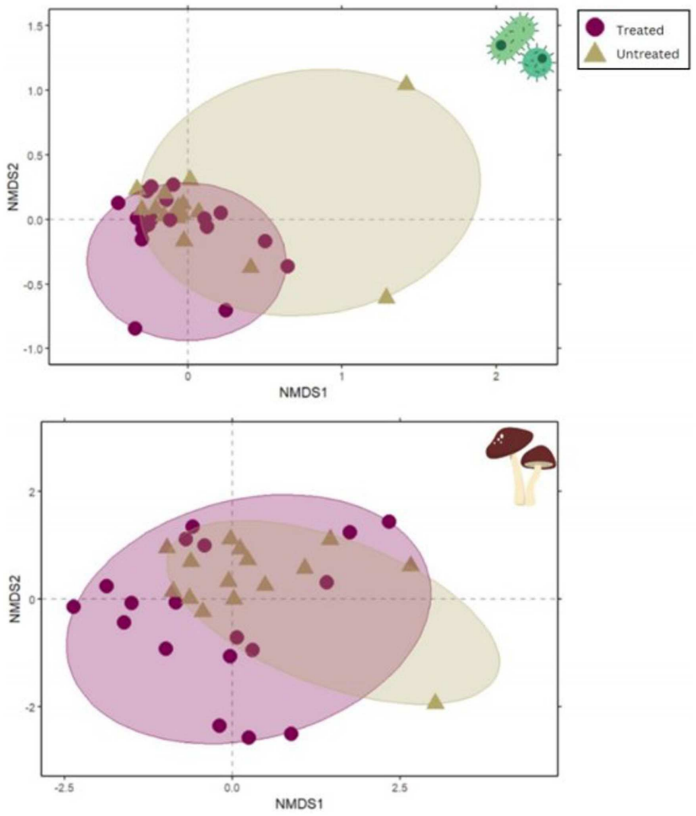


Figure 4. NMDS plots demonstrate the significant difference between treated and untreated sample microbial community composition. The plot on the top shows results from 16S and the lower plot shows ITS results. NMDS differences are visualized by distance between points. Circles represent 95% confidence intervals.

Differences in Shannon diversity of bacterial/archaeal communities were also tested with ANOVAs and did not show a significant difference between treated and untreated sites in both 16S and ITS (Supplementary Table S1, $p = 0.845$). However, 16S had a much higher diversity overall than ITS.

2.4.6 Multiple regression on distance matrices (MDRM)

The MDRM test indicated that soil pH ($p = 0.040$), OM ($p = 0.033$), $NO3^-$ ($p = 0.084$), and native forb biomass ($p = 0.080$) were all significantly related to the difference in bacterial and archaeal community composition between treated and untreated plots. Only soil OM ($p = 0.068$) was marginally significantly related to the difference in fungal community composition (Table 2).

2.4.7 Indicator species analysis results

Analysis of indicator species demonstrated that there were many ASVs significantly associated with indaziflam-treated and untreated plots. For 16S, 26 ASVs were indicative of treated sites, while 24 ASVs were indicative of untreated sites (see file "IndicSpecResults16S.csv"). ITS results had 4 ASVs significantly associated with treated sites and 24 ASVs associated with untreated sites (see file "IndicSpecResultsITS.csv").

2.5 DISCUSSION

Cheatgrass invasion in dryland ecosystems across the western U.S. presents many challenges and considerations for land stewards. Indaziflam (Rejuvra™) has recently been approved for use to control cheatgrass. Yet, to date, there have been few studies of the herbicide's effects on non-target

organisms. Through plant surveys, soil physical analysis, and soil microbiome 16S/ITS amplicon sequencing, we found that treatment of cheatgrass with indaziflam had varied effects on different ecosystem actors in an arid foothill shrubland in Boulder County, USA.

This study found that plant community composition, soil physical characteristics, and soil microbiome shifted dramatically after indaziflam application. Cheatgrass cover was reduced by up to 80% in plots that had been sprayed just 1 year before monitoring, and native plants almost fully recovered in these plots. Organic matter was lower in treated plots than untreated plots, and soil nitrate (NO_3^-) was higher in treated plots than untreated plots, while pH was variable between treatments. Soil microbial communities were also impacted by indaziflam treatment, with bacterial and fungal communities being significantly different in composition between treated and untreated sites. Statistical analysis in this study also demonstrated a relationship between microbiome composition and soil organic matter, NO_3^-, pH, and native forb biomass.

These results show that indaziflam changes plant and soil dynamics in ecosystems, but more work is necessary to fully understand the mechanisms behind these shifts. This study showed that soil

microbial communities were different between treated and untreated sites but did not parse out if the soil microbial communities were responding to the application or if they responded to plant community shifts. Based on the PERMANOVA statistical analysis that demonstrated soil microbiome is linked with soil physical characteristics and treatment, it is likely that both are true. However, understanding the mechanism of the soil microbiome shift, and the wider impacts of indaziflam through continuous monitoring, is critical for future research.

2.5.1 Plant community composition and nutrient cycling shift in response to indaziflam treatment

Above ground, we found that application of indaziflam on cheatgrass-dominated plots successfully reduced cheatgrass cover by 80% on average. Native grasses and forbs recruited in plots that had been treated as recently 1 year prior, and native herbaceous plants covered up to 100% of treated plots. This response aligns with previous literature that has found similar dramatic decreases in cheatgrass and increases in native plant cover after indaziflam application (Alba et al., 2024; Courkamp et al., 2022; Arathi and Hardin, 2021; Kainrath et al., 2022; Meyer-Morey et al., 2021; Sebastian et al., 2017; Seedorf et al., 2022). Kainrath et al. (2022) showed that direct reduction of cheatgrass, as opposed to modifying soil physical and microbial characteristics, was the most effective restoration strategy for invaded areas and that native plants quickly recruited after removal in sagebrush habitat (Kainrath et al., 2022). Therefore, the dramatic reduction of cheatgrass after indaziflam application suggests that this tool could be useful for opening space for restoration to occur. Arathi and Hardin (2021) also found that native and pollinator-friendly plant species richness

doubled a year after indaziflam application in another study conducted in Boulder, CO (Arathi and Hardin, 2021). This study, taken with the results of our study, demonstrates that the goal of native plant recruitment after cheatgrass invasion may be met with indaziflam application.

Belowground, we found that soil NO_3^- increased after application and that SOM significantly decreased. Although Weber et al. (2015) also found that nitrate was significantly higher in native perennial rangeland than in cheatgrass-dominated areas, many prior studies have found more NO_3^- after invasion, due to cheatgrass root exudation and leaf senescence (e.g., Baughman et al., 2016; Weber et al., 2015). Therefore, our more novel result that nitrate increased in the soil after indaziflam application could be due to either legacy effects of cheatgrass invasion or of increased nitrogen-synthesizing fungi that native plants partner within the rhizosphere. If nitrogen-synthesizing fungi are driving the increase in NO_3^- after indaziflam application, this could point toward the restoration of relationships between native plants and microbes after cheatgrass removal.

The findings surrounding soil carbon have also been contradictory, and a recent review by Maxwell and Germino (2022) found that the carbon dynamics of sites across the Great Basin that have

been invaded by cheatgrass vary from site to site and have high heterogeneity in the magnitude and direction of carbon change (Maxwell and Germino, 2022). Our study adds to the complex story of soil nutrient dynamics as cheatgrass invades and is removed, and native plants revegetate. Our result that soil organic matter decreased when cheatgrass was removed (Figure 3A) is likely because cheatgrass cover and thatch decreased so dramatically, and therefore, soil organic matter that had been previously added by the cheatgrass thatch, growth, and decomposition cycle was no longer present. Previous studies have shown that when plant cover decreases, soil organic carbon decreases, and as soil organic carbon comprises a large portion of SOM, our result that a decrease in cheatgrass cover may have led to a decrease in SOM agrees with this (Fekete et al., 2012; Koçak et al., 2021; Wan et al., 2019). These soil physical property and plant changes were also related to soil microbial community composition and shifts.

2.5.2 Soil microbial community composition, but not diversity, differed significantly between treated and untreated sites

The results from soil community composition analyses (i.e., PERMANOVA and ANOVA Shannon diversity) demonstrate that indaziflam treatment significantly changed microbial community composition but not overall diversity. PERMANOVA testing showed a statistically significant difference in community composition between treated and untreated plots, indicating that microbes in the community are different in abundance and composition. Previous studies have shown that cheatgrass encroachment itself can shift soil microbial communities when compared to native states

and that N2 fixing and uratolytic bacteria increasing while denitrifiers decrease is particularly indicative of cheatgrass dominance (Reitstetter et al., 2022). The indicator species analysis in this study mirrored this shift, meaning that cheatgrass removal was likely a major driver of nitrogen microbial dynamics. Furthermore, chiral herbicides such as indaziflam have been shown to move soil microbiomes toward aromatic compound digestion and affect nitrogen dynamics, which the results of our indicator species analysis also support (Asad et al., 2017; Pertile et al., 2021).

The results of the MDRM analysis provide insight into the ecological dynamics surrounding the difference in treated and untreated bacterial communities. Differences in bacterial and archaeal community composition were correlated with differences in soil organic matter, soil nitrate, soil pH, and native forb biomass, suggesting that associated ecosystem changes with indaziflam application are drivers of microbiome shift. This is a critical finding as it means that indaziflam application shifts ecosystem relationships, especially soil physical characteristics, which may have a cascading impact throughout the system. In contrast to bacterial communities, differences in soil fungal communities were only due to soil organic matter. The fact that soil fungal community composition was not significantly correlated with nitrate amount may mean that the observed nitrogen dynamics were related to native forb presence or that bacterial communities were doing the majority of fixation in the system. The decrease in organic matter that is potentially due to thatch cover reduction could be a key indicator of microbial community shift for both bacteria and archaea as well as fungi. Considering thatch cover and compensation for organic matter may be important for overall ecological restoration

and management practices as this decrease having ripple effects on the microbial community could hinder restoration efforts. Furthermore, bacteria could be more sensitive to these shifts because of the number of variables that are associated with bacterial community change. Therefore, indaziflam's effect on each of these variables may be critical for land managers to consider for ecosystem health post-application.

2.5.6 Microbial indicator species differ between treated and untreated sites

Indicator species analysis demonstrated that the nitrogen metabolism, soil microbial characteristics, and community composition shifted after indaziflam application. Although the PERMANOVA and MDRM tests demonstrated the differences in microbial communities, the indicator species analysis showed key organisms that are significantly different between indaziflam-treated and untreated sites. In our indicator species analysis, ammonia-oxidizing bacteria, Nitrosomonadaceae, were found to be associated with untreated sites, while ammonia-oxidizing archaea, Nitrososphaeraceae, were found to be associated with indaziflam treatment. This could point to the soil microbiome becoming more similar to native community composition after cheatgrass is removed as Chen et al. (2021) found that ammonia-oxidizing bacteria were associated with disturbance and urbanization in the Southwestern U.S., while ammonia-oxidizing archaea were associated with undisturbed ecosystems. Other nitrogen dynamics of indaziflam application in the soil microbiome were indicated by the association of Opitutaceae and the fungi Articulospora proliferata, which engage in nitrate digestion and assimilation, in untreated sites, and of Chloroflexi TK10 in

treated sites, which digests N2 to nitrate (Chin et al., 2001; Johnston et al., 2019; Pöritz et al., 2015). Microvirga which are an unconventional root-associated nitrogen-fixing root-associated bacteria (Maheshwari and Sankar, 2022) were associated with treatment. Cheatgrass utilizes high amounts of nitrogen but does not make associations with nitrogen-fixing bacteria on their roots (Reitstetter et al., 2022). Therefore, Microvirga's presence indicates that native plants that have grown after cheatgrass removal by indaziflam are likely associating with microbes, especially bacteria, to fix nitrogen in the soil (Erlacher et al., 2015). These differences in nitrogen metabolism of key taxa in the soil microbiome may give clues about nitrate dynamics of cheatgrass invasion as the nitrogen-fixing bacteria could be the drivers of our different result from past literature.

Other indicator species also shed light on the microbial community differences between treated and untreated sites. In treated sites, many significant indicator species specialize in different forms of chemical digestion. Sphingomonas, for instance, has been used in detoxification efforts because of its ability to digest organometals and support plant growth, while Acidobacteriales have been associated with acidic mining-contaminated soils (Kishimoto and Tano, 1987; Leys et al., 2004). Indaziflam is an aromatic compound, meaning that these organisms could be metabolizing the chemical itself. Furthermore, indaziflam is a fluoroalkyl triazine-containing compound. Previous study has tied Acidobacteriales to fluoroalkyl chemicals, and this order of bacteria's presence could support the notion that some toxicity to the soil microbiome is occurring with cheatgrass application (Wang et al., 2023).

Finally, some ASVs associated with untreated and cheatgrass-dominated sites are indicative of ecological pH stress. Two of the bacterial indicator species for untreated sites, namely, Blastocatellia and Acidimicrobiia, both from the phylum Acidobacteriota, have been found to thrive in acidic soil (Tables 3, 4; Hazarika and Thakur, 2020; Huber and Overmann, 2018). Our results from soil testing showed that untreated sites had more acidic soil than treated sites on average, and the indicator species analysis showed that microbes may be responding to this pH shift. A connection between soil pH and indaziflam treatment is also supported by the MDRM analysis, which showed pH as significantly associated with bacterial and archaeal community composition. Ecologically, acidic soil can often be a cause for concern if it inhibits symbiosis between microorganisms and native plants or it changes plant recruitment (Zama et al., 2022), but since our result showed that native forbs grew well after treatment and made association with nitrogen-fixing bacteria, this may not be the case for our specific study system.

Table 4a. Indicator species analysis of key 16S ASV differences between treated and untreated plots. Significance amount marked by symbols, * = <0.05, ** = <0.005, *** = <0.001.

Significant 16S Indicator Species

Phylum	Class	Order	Family	Genus	p	Significance	Ecological.Function
Treated							
Acidobacteriota	Acidobacteriae	Acidobacteriales	NA	NA	0.010	**	Found in acidic mine drainage, chemoorganotroph (Kishimoto, 1991)
Actinobacteriota	Thermoleophilia	Solirubrobacterales	67-14	NA	0.049	*	Decomposition of organic matter, (Foesel, 2015)
Chloroflexi	TK10	NA	NA	NA	0.006	**	Nitrogen digestion, (Speirs, 2019)
Crenarchaeota	Nitrososphaeria	Nitrososphaerales	Nitrososphaeraceae	NA	0.007	**	Archea, ammonia oxidation. (Chen, 2021)
Proteobacteria	Alphaproteobacteria	Rhizobiales	Beijerinckiaceae	Microvirga	0.006	**	Lichen symbiosis, nitrogen fixation, (Erlacher, 2015)
Proteobacteria	Alphaproteobacteria	Sphingomonadales	Sphingomonadaceae	Sphingomonas	0.020	*	Polycyclic aromatic hydrocarbon digestion, (Leys, 2004)
Untreated							
Acidobacteriota	Blastocatellia	45254	NA	NA	0.019	*	Characteristic of acidic soil, (Huber, 2018)
Actinobacteriota	Acidimicrobiia	NA	NA	NA	0.009	**	Indicative of acidic soil, (Hazarika & Thakur, 2020)
Bacteroidota	Bacteroidia	Chitinophagales	Chitinophagaceae	NA	0.025	*	Ureolysis production, chitin digestion (Hasan, 2000, Wieczorek, 2019)
Proteobacteria	Gammaproteobacteria	Burkholderiales	SC-I-84	NA	0.001	***	Plant growth promotion, (Yurgel, 2022)
Proteobacteria	Gammaproteobacteria	Burkholderiales	Nitrosomonadaceae	Ellin6067	0.031	*	Bacteria, ammonia oxidation, (Chen, 2021)
Verrucomicrobiota	Verrucomicrobiae	Opitutales	Opitutaceae	Opitutus	0.033	*	Conversion of nitrate to nitrite, (Chin, 2001)

Table 4b. Indicator species analysis of key ITS ASV differences between treated and untreated plots. Significance amount marked by symbols, * = <0.05, ** = <0.005, *** = <0.001.

Significant ITS Indicator Species

Phylum	Class	Order	Family	Genus	Species	p	Significance	Function
Treated								
Basidiomycota	Agaricomycetes	Agaricales	Entolomataceae	Entoloma	byssisedum	0.050	*	Associated with wood decay, (He, 2019)
Ascomycota	Lecanoromycetes	NA	NA	NA	NA	0.009	**	Lichen indicative (Erlacher, 2015)
Untreated								
Basidiomycota	Agaricomycetes	Cantharellales	Ceratobasidiaceae	Rhizoctonia	NA	0.050	*	Plant pathogen, (Termorshuizen, 2007)
Ascomycota	Dothideomycetes	Pleosporales	Lentitheciaceae	Darksidea	NA	0.039	*	Associated with plant invasion in the desert southwest, (Williams, 2021)
Ascomycota	Dothideomycetes	Pleosporales	Phaeosphaeriaceae	Phaeosphaeria	NA	0.005	**	Lignin degradation, (Ferrari, 2021)
Ascomycota	Dothideomycetes	Pleosporales	Pleosporaceae	Pyrenophora	sieglingiae	0.001	***	Plant pathogen, (Masi, 2022)
Ascomycota	Leotiomycetes	Helotiales	Helotiaceae	Articulospora	proliferata	0.001	***	Nitrogen assimilation, decomposition (Johnston, 2019)
Ascomycota	Orbiliomycetes	Orbiliales	Orbiliaceae	Orbilia	NA	0.013	*	Nematophagy, (Kavitha, 2020)

Fungi indicator species suggest improvements to soil health following indaziflam application. Untreated sites were associated with several fungi that are plant pathogens and associated with plant invasion in the desert southwest, such as Darksidea and Pyrenophora, while treated sites were

associated with lichen-indicative fungus (Erlacher et al., 2015; Masi et al., 2022; Termorshuizen, 2007; Williams et al., 2022). The fact that plant pathogens were associated with untreated sites may mean that indaziflam treatment lowers plant pathogen presence, although the mechanism by which this occurs is unclear. The indication of lichen-associated fungi after treatment may be particularly important as lichen was visually observed to be growing on the soil more frequently in treated sites. Lichens have been shown to be important for soil stability, moisture, and overall health, and therefore, this association may demonstrate an increase in soil condition after treatment (Finger-Higgens et al., 2022).

2.5.7 Study limitations and future research opportunities

Although this study is among the first to evaluate critical non-target impacts of indaziflam, it has several limitations. First, this study sampled sites within a relatively small spatial extent, with limited replicates and spatial homogeneity. More repetition, ecosystem representation, and in-depth sampling are needed in the future. Furthermore, this study was retrospective in its temporal aspect, and a continuous monitoring effort is needed for changes over time to be characterized. We suggest that future studies investigate impacts on other non-target organisms, nitrogen mechanics after application, and how the soil microbiome may be processing indaziflam.

2.5.8 Indaziflam application shifts soil microbiome, physical characteristics, and plant community composition: implications for dryland management and restoration

As cheatgrass dominance in the Intermountain West poses increasing risks to human and ecological communities, informed management decisions about restoration of cheatgrass-dominated communities have become increasingly important. This study found that indaziflam did successfully remove cheatgrass from an arid foothill shrubland ecosystem and that native plant communities grew back after this removal. However, this study also found that decreases in organic matter and increases in soil nitrate may be related to indaziflam treatment. These soil physical property changes have relationships with the soil microbiome. The results suggest that the soil microbiome was significantly altered by indaziflam application and that these changes may be related to changes in soil organic matter, nitrate, pH, and native forb biomass associated with indaziflam treatment, meaning that land managers may consider assessing soil biogeochemistry before application. Finally, indicator species analyses showed that nitrogen dynamics may particularly change after indaziflam application. The shift in microbial community may be beneficial, as indicated by the presence of lichen-associated and pH-neutral microbes in treated sites, but further research is needed to assess long-term impacts of the observed microbial shift. These results are critical for land managers trying to restore and steward lands that have been invaded with cheatgrass, as assessing whether to use indaziflam to reduce cheatgrass cover may have nuanced effects on the soil biogeochemistry and microbial ecology of the ecosystem.

2.6 REFERENCES

Alba, C., DePrenger-Levin, M., & Hufft, R. (2024). Incorporation of Indaziflam into Natural Areas Management of Cheatgrass and Other Short-Lived Invasive Species: Post-Fire Assessment in a Semi-Arid Colorado Grassland. *Natural Areas Journal*, *44*(1), 9–20. https://doi.org/10.3375/2162-4399-44.1.9

Asad, M. A. U., Lavoie, M., Song, H., Jin, Y., Fu, Z., & Qian, H. (2017). Interaction of chiral herbicides with soil microorganisms, algae and vascular plants. *Science of The Total Environment*, *580*, 1287–1299. https://doi.org/10.1016/j.scitotenv.2016.12.092

Bellemain, E., Carlsen, T., Brochmann, C., Coissac, E., Taberlet, P., & Kauserud, H. (2010). ITS as an environmental DNA barcode for fungi: An in silico approach reveals potential PCR biases. *BMC Microbiology*, *10*(1), 189. https://doi.org/10.1186/1471-2180-10-189

Brabham, C., Lei, L., Gu, Y., Stork, J., Barrett, M., & DeBolt, S. (2014). Indaziflam Herbicidal Action: A Potent Cellulose Biosynthesis Inhibitor. *Plant Physiology*, *166*(3), 1177–1185. https://doi.org/10.1104/pp.114.241950

Caggìa, V., Waelchli, J., Chiaia-Hernandez, A. C., Weihermueller, L., Grosjean, M., Spielvogel, S., & Schlaeppi, K. (2023). Glyphosate and terbuthylazine effects on soil functions, microbiome composition and crop performance. *Applied Soil Ecology*, *191*, 105036. https://doi.org/10.1016/j.apsoil.2023.105036

Caudle, D., DiBenedetto, J., Sanchez, H., Talbot, C., & Sherm. (2013). *Interagency Ecological Site*

Handbook for Rangelands. USDA. https://jornada.nmsu.edu/files/InteragencyEcolSiteHandbook.pdf

Clark, P. E., Porter, B. A., Pellant, M., Dyer, K., & Norton, T. P. (2023). Evaluating the Efficacy of Targeted Cattle Grazing for Fuel Break Creation and Maintenance. *Rangeland Ecology & Management*, *89*, 69–86. https://doi.org/10.1016/j.rama.2023.02.005

Courkamp, J. S., Meiman, P. J., & Nissen, S. J. (2022). Indaziflam reduces downy brome (Bromus tectorum) density and cover five years after treatment in sagebrush-grasslands with no impact on perennial grass cover. *Invasive Plant Science and Management*, *15*(3), 122–132. https://doi.org/10.1017/inp.2022.21

Fekete, I., Kotroczó, Z., Varga, C., Hargitai, R., Townsend, K., Csányi, G., & Várbiró, G. (2012). Variability of Organic Matter Inputs Affects Soil Moisture and Soil Biological Parameters in a European Detritus Manipulation Experiment. *Ecosystems*, *15*(5), 792–803. https://doi.org/10.1007/s10021-012-9546-y

Fierer, N., Wood, S. A., & Bueno De Mesquita, C. P. (2021). How microbes can, and cannot, be used to assess soil health. *Soil Biology and Biochemistry*, *153*, 108111. https://doi.org/10.1016/j.soilbio.2020.108111

H. S., A., & Hardin, J. (2021). Pollinator-friendly flora in rangelands following control of cheatgrass (*Bromus tectorum*): A case study. *Invasive Plant Science and Management*, *14*(4), 270–277. https://doi.org/10.1017/inp.2021.33

Helander, M., Saloniemi, I., & Saikkonen, K. (2012). Glyphosate in northern ecosystems. *Trends in Plant Science*, *17*(10), 569–574. https://doi.org/10.1016/j.tplants.2012.05.008

Huang, X., He, J., Yan, X., Hong, Q., Chen, K., He, Q., Zhang, L., Liu, X., Chuang, S., Li, S., & Jiang, J. (2017). Microbial catabolism of chemical herbicides: Microbial resources, metabolic pathways and catabolic genes. *Pesticide Biochemistry and Physiology*, *143*, 272–297. https://doi.org/10.1016/j.pestbp.2016.11.010

Iwen, P. C., Hinrichs, S. H., & Rupp, M. E. (2002). Utilization of the internal transcribed spacer regions as molecular targets to detect and identify human fungal pathogens. *Medical Mycology*, *40*(1), 87–109. https://doi.org/10.1080/mmy.40.1.87.109

Kainrath, N. B., Dijkstra, P., Gehring, C. A., Updike, C., & Grady, K. C. (2022). Water as the key to sagebrush restoration success in cheatgrass-invaded ecosystems. *Restoration Ecology*, *30*(7), e13473. https://doi.org/10.1111/rec.13473

Koçak, B., Cenkseven, Ş., Kizildağ, N., Aka Sağliker, H., & Darici, C. (2021). How did the Addition of Indaziflam Affect on Carbon and Nitrogen Mineralizations in a Vineyard Soil? *International Journal of Life Sciences and Biotechnology*, *4*(1), 1–12. https://doi.org/10.38001/ijlsb.751731

Lehnhoff, E. A., Rew, L. J., Mangold, J. M., Seipel, T., & Ragen, D. (2019). Integrated Management of Cheatgrass (Bromus tectorum) with Sheep Grazing and Herbicide. *Agronomy*, *9*(6), 315. https://doi.org/10.3390/agronomy9060315

Mack, R. N. (2010). Fifty years of 'Waging war on cheatgrass': Research advances, while meaningful control languishes. In D. M. Richardson (Ed.), *Fifty Years of Invasion Ecology* (1st ed., pp. 253–265). Wiley. https://doi.org/10.1002/9781444329988.ch19

Meyer-Morey, J., Lavin, M., Mangold, J., Zabinski, C., & Rew, L. J. (2021). Indaziflam controls nonnative *Alyssum* spp. But negatively affects native forbs in sagebrush steppe. *Invasive Plant Science and Management*, *14*(4), 253–261. https://doi.org/10.1017/inp.2021.31

Neilson, J. W., Califf, K., Cardona, C., Copeland, A., van Treuren, W., Josephson, K. L., Knight, R., Gilbert, J. A., Quade, J., Caporaso, J. G., & Maier, R. M. (2017). Significant Impacts of Increasing Aridity on the Arid Soil Microbiome. *mSystems*, *2*(3), 10.1128/msystems.00195-16. https://doi.org/10.1128/msystems.00195-16

Ozimek, E., & Hanaka, A. (2021). Mortierella Species as the Plant Growth-Promoting Fungi Present in the Agricultural Soils. *Agriculture*, *11*(1), Article 1. https://doi.org/10.3390/agriculture11010007

P, M., & Perumal, M. S. (2022). *Culture-independent and culture-dependent approaches in symbiont analysis: In proteobacteria* (pp. 743–763). https://doi.org/10.1016/B978-0-323-99334-0.00018-9

Parada, A. E., Needham, D. M., & Fuhrman, J. A. (2016). Every base matters: Assessing small subunit rRNA primers for marine microbiomes with mock communities, time series and global field samples: Primers for marine microbiome studies. *Environmental Microbiology*, *18*(5), 1403–

1414. https://doi.org/10.1111/1462-2920.13023

Perryman, B. L., Schultz, B. W., Burrows, M., Shenkoru, T., & Wilker, J. (2020). Fall-Grazing and Grazing-Exclusion Effects on Cheatgrass (Bromus tectorum) Seed Bank Assays in Nevada, United States. *Rangeland Ecology & Management*, *73*(3), 343–347. https://doi.org/10.1016/j.rama.2020.01.012

Pierson, E. A., & Mack, R. N. (1990). The population biology of Bromus tectorum in forests: Distinguishing the opportunity for dispersal from environmental restriction. *Oecologia*, *84*(4), 519–525. https://doi.org/10.1007/BF00328169

PRISM Climate Group, & Oregon State University. (2014). *PRISM Gridded Climate Data* [dataset]. https://prism.oregonstate.edu

Reitstetter, R., Yang, B., Tews, A. D., & Barberán, A. (2022). Soil microbial communities and nitrogen associated with cheatgrass invasion in a sagebrush shrubland. *Plant and Soil*, *479*(1–2), 325–336. https://doi.org/10.1007/s11104-022-05523-0

Rui, Y., Jackson, R. D., Cotrufo, M. F., Sanford, G. R., Spiesman, B. J., Deiss, L., Culman, S. W., Liang, C., & Ruark, M. D. (2022). Persistent soil carbon enhanced in Mollisols by well-managed grasslands but not annual grain or dairy forage cropping systems. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(7), e2118931119. https://doi.org/10.1073/pnas.2118931119

Ruuskanen, S., Fuchs, B., Nissinen, R., Puigbò, P., Rainio, M., Saikkonen, K., & Helander, M. (2023).

Ecosystem consequences of herbicides: The role of microbiome. *Trends in Ecology & Evolution*, *38*(1), 35–43. https://doi.org/10.1016/j.tree.2022.09.009

Sauder, L. A., Albertsen, M., Engel, K., Schwarz, J., Nielsen, P. H., Wagner, M., & Neufeld, J. D. (2017). Cultivation and characterization of Candidatus Nitrosocosmicus exaquare, an ammonia-oxidizing archaeon from a municipal wastewater treatment system. *The ISME Journal*, *11*(5), 1142–1157. https://doi.org/10.1038/ismej.2016.192

Sebastian, D. J., Clark, S. L., Nissen, S. J., & Lauer, D. K. (2020). Total vegetation control: A comprehensive summary of herbicides, application timings, and resistance management options. *Weed Technology*, *34*(2), 155–163. https://doi.org/10.1017/wet.2019.94

Sebastian, D. J., Fleming, M. B., Patterson, E. L., Sebastian, J. R., & Nissen, S. J. (2017). Indaziflam: A new cellulose-biosynthesis-inhibiting herbicide provides long-term control of invasive winter annual grasses: Indaziflam: a new cellulose-biosynthesis-inhibiting herbicide. *Pest Management Science*, *73*(10), 2149–2162. https://doi.org/10.1002/ps.4594

Seedorf, R. H., Clark, S. L., & Nissen, S. J. (2022). Prescribed burning followed by indaziflam enhances downy brome (Bromus tectorum) control. *Invasive Plant Science and Management*, *15*(2), 72–80. https://doi.org/10.1017/inp.2022.11

Setlow, P., & Doona, C. J. (2023). Chapter Three—High pressure thermal sterilization technology for bacterial spore inactivation and the production of sterile, ambient-stable, low-acid foods. In K. Knoerzer & R. Sevenich (Eds.), *High Pressure Thermal Processing* (pp. 41–53). Academic

Press. https://doi.org/10.1016/B978-0-12-823872-1.00001-6

Soil Survey Staff. (n.d.). *Web Soil Survey* [dataset]. National Resources Conservation Service. Retrieved March 10, 2024, from https://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx

Strilbytska, O. M., Semaniuk, U. V., Strutynska, T. R., Burdyliuk, N. I., Tsiumpala, S., Bubalo, V., & Lushchak, O. (2022). Herbicide Roundup shows toxic effects in nontarget organism *Drosophila*. *Archives of Insect Biochemistry and Physiology*, *110*(4), e21893. https://doi.org/10.1002/arch.21893

Tourna, M., Stieglmeier, M., Spang, A., Könneke, M., Schintlmeister, A., Urich, T., Engel, M., Schloter, M., Wagner, M., Richter, A., & Schleper, C. (2011). Nitrososphaera viennensis, an ammonia oxidizing archaeon from soil. *Proceedings of the National Academy of Sciences*, *108*(20), 8420–8425. https://doi.org/10.1073/pnas.1013488108

Van Bruggen, A. H. C., Finckh, M. R., He, M., Ritsema, C. J., Harkes, P., Knuth, D., & Geissen, V. (2021). Indirect Effects of the Herbicide Glyphosate on Plant, Animal and Human Health Through its Effects on Microbial Communities. *Frontiers in Environmental Science*, *9*, 763917. https://doi.org/10.3389/fenvs.2021.763917

Walters, W., Hyde, E. R., Berg-Lyons, D., Ackermann, G., Humphrey, G., Parada, A., Gilbert, J. A., Jansson, J. K., Caporaso, J. G., Fuhrman, J. A., Apprill, A., & Knight, R. (2016). Improved Bacterial 16S rRNA Gene (V4 and V4-5) and Fungal Internal Transcribed Spacer Marker

Gene Primers for Microbial Community Surveys. *mSystems*, *1*(1). https://doi.org/10.1128/mSystems.00009-15

Wan, Q., Zhu, G., Guo, H., Zhang, Y., Pan, H., Yong, L., & Ma, H. (2019). Influence of Vegetation Coverage and Climate Environment on Soil Organic Carbon in the Qilian Mountains. *Scientific Reports*, *9*(1), 17623. https://doi.org/10.1038/s41598-019-53837-4

Wang, L., & Li, X. (2019). Steering soil microbiome to enhance soil system resilience. *Critical Reviews in Microbiology*, *45*(5–6), 743–753. https://doi.org/10.1080/1040841X.2019.1700906

CHAPTER 3 - COMPARING THE EFFECT OF TWO SEED PELLET CREATION METHODS UNDER DIFFERING WATERING TREATMENTS ON EMERGENCE OF NATIVE PLANT SPECIES

3.1 ABSTRACT

Restoring native plant biodiversity is critical to reversing dryland degradation. Yet, seed-based restoration (SBR) is often unsuccessful in drylands due to extreme and worsening drought. Seed pellets may support SBR in drylands by protecting seeds from desiccation and granivory and increasing resource availability to emerging seedlings. However, evaluation of effects of seed pellet creation strategies and pellet interaction with watering regimes on seedling emergence is needed. We conducted a greenhouse experiment to test two seed pellet treatments (seed pellets produced with a seed-pellet bike versus handmade seed pellets) against a broadcast seeding control under two experimental watering regimes (low frequent and pulse) to determine emergence rates and community composition of a seed mix comprised of 19 native dryland plant species. mechanically-made pellets significantly increased total seedling emergence relative to handmade pellets and the control and particularly promoted forb recruitment. These effects may be attributable to increased microsite heterogeneity, reduced compaction, and longer pellet dissolution time in mechanically-made pellets. Further, emergence in mechanically-made pellets significantly increased under higher volume, lower frequency watering

(pulse) as opposed to lower volume, higher frequency watering. These results indicate that mechanically-made seed pellets may be a way to increase native plant recruitment in dryland restoration efforts, especially when seeding is timed with high-volume (pulse) watering events, and that they may particularly promote the emergence of forbs like *Linum lewisii* (Blue Flax) and *Asclepias tuberosa* (Butterfly Milkweed). Because forb establishment is often limited in dryland systems, these findings highlight the potential of mechanically-made pellets to improve restoration outcomes. Seed pellets represent a tool for precision restoration, in which dispersal is spatially and temporally timed to increase the likelihood of native plant emergence and establishment. Further work identifying mechanisms behind seed pellet promotion of emergence and optimal planting timing with seasonality is needed to continue to inform manager decision-making.

3.2 INTRODUCTION

Dryland ecosystems cover more than 40% of Earth's terrestrial surface (Vicente-Serrano, et al., 2024) and include rangeland and agricultural systems. Drylands are experiencing land degradation and biodiversity losses associated with land use and climate change, and slowing their destruction and restoring ecological function is crucial (Burrell et al., 2020). Seed-based restoration is used to reverse dryland degradation by reestablishing native plant species but is often unsuccessful because of high temperatures, erratic and limited precipitation, and granivory (Shackleford et al., 2021). Precision

restoration, or choosing targeted restoration treatments based on abiotic and biotic barriers that vary across space and time, (Copeland et al., 2021) may improve seed-based restoration success

Seed pellets are a seed enhancement technology that are leveraged in precision restoration under water limitation, as they may protect seeds until a precipitation event (Munro et al., 2024). In pellets, seeds are combined with clay, straw, and other additions (e.g., organic matter), and water, then dried (Gornish et al., 2019). Pellets may increase seedling emergence by supplying seeds with increased water and nutrient availability and protecting against desiccation and granivory (reviewed in Gornish et al., 2019). Seed pellets have been widely used by Indigenous peoples across the globe for up to 3,000 years, with evidence of ancient Egyptian cultures using them for restoring the Nile's flood plains (Kannan et al., 2021). Later, they were popularized by Masanobu Fukuoka, who used them to seed crops without disturbing the soil (Fukuoka, 2009). Recently, ecological studies of seed pellets have demonstrated their potential efficacy in dryland restoration (Gornish et al., 2019), but research around making seed pellets and timing planting is limited.

Seed pellets are commonly made by hand but recently, innovative mechanical methods like the "seed ball bike," a stationary bicycle with a barrel attachment as it is turned (Gornish et al., 2018) and the multispecies pelleting method, which pellets small seeds together while maintaining singulation (Pedrini, 2025), have emerged. Others have shown that seed pelletization with activated carbon may protect seeds from herbicide application (Swartz et al., 2026). However, Gornish et. al (2019) note that seed pellet creation methods are frequently not well recorded. Further, little information is published

about pellet responses to different precipitation regimes, which may be important for decision-making about when and where to use seed pellets in precision restoration frameworks in drylands, which are characterized by low, episodic, and/or pulse precipitation dynamics (Copeland et al., 2021; Wei et al., 2024).

In a greenhouse study, we compared seedling emergence and the resulting community composition of a seed mix comprised of 19 plant species commonly used in dryland restoration projects in the Southwestern US to three seeding treatments (i.e., handmade and mechanically-made pellets and a broadcast seeding control) under two watering treatments, a more frequent low volume (low, frequent) and a less frequent high volume (pulse). This study aims to improve understanding of how to match seed pellet deployment strategies to watering conditions and support dryland precision restoration efforts. We hypothesized that seed pellets increase seedling emergence by providing favorable microsites for developing seedlings and that mechanically-made pellets may increase plant emergence and shift community composition due to their heterogeneity in size and limited compaction. Further, we predicted that all treatments would have higher plant density under the pulse watering treatment, as this treatment mimics the monsoon rainfall pattern of our focal dryland system.

3.3 METHODS

3.3.1 Experimental design

We conducted a fully crossed greenhouse experiment to test how three seeding treatments (i.e., broadcast seeding (control), handmade pellets (homogenous in size, more compact), and mechanically-made pellets (size heterogenous, less compact)) deployed under two watering treatments (i.e., low frequent and pulse) impacted native plant emergence. Each seeding and watering method cross (broadcast x low frequent, broadcast x pulse, etc.) had four experimental replicates, resulting in 24 experimental units in total. Plant emergence was tracked for six weeks from April to May 2023 at the Colorado State University Plant Growth Facility.

3.3.2 Seed mix and seed pellet treatments

Each experimental mesocosm was seeded with 19 native plant species that are commonly used in field restoration studies in the Colorado Plateau Ecoregion and/or identified as culturally important species to engaged land stewards in the region (Havrilla et al., 2020). Seeds were acquired from Southwest Seed (https://www.southwestseed.com) or Granite Seed (https://nativeseedgroup.com), and emergence tests were conducted prior to seeding (Table S1). Species were seeded by the producer-recommended rate calculated for a 13.25-liter tub. Handmade pellets were made by emptying a seed packet into a container and gently mixing them with 350 g of red clay, ~23 g of chopped weed-free straw, and sprayed water to create a consistency like a soft dough (Gornish et al., 2018). A quarter of this mixture was then rolled into a sphere by hand (Jawahar & Umarani, 2020). mechanically-made pellets ingredients (same recipe) were loaded into the barrel of a bicycle-powered seed pelletizer (Gornish et al., 2018). The sides of the barrel were scraped, and water was sprayed as the barrel was turned. Once pellets

aggregated, they were taken out of the barrel. mechanically-made pellets ranged in size from ~1.27 cm to ~2.54 cm and handmade pellets were approximately 5.08 cm in diameter. Pellets were left to dry under a fume hood until dried (~24 hours) before seeding.

3.3.3 Mesocosm seeding

Mesocosms were prepared by puncturing six small holes into the bottom of a 13.25-liter Sterilite Latching Storage Box and covering the bottom with weed cloth, ensuring the growing medium (approximately 13 quarts of Quikrete Premium play sand per mesocosm) did not leak out. Bins were then watered to help the sand settle evenly and left to dry. Seeding treatments were randomly assigned and deployed to mesocosms. Handmade pellets were evenly placed around the bin. Mechanically-made pellets and broadcast seeding (control) treatments were distributed randomly by hand (Meyer et al., 2008).

3.3.4 Watering treatments

After seeding, watering treatments were implemented with a custom-made pressure-gauge-controlled spot sprinkler attached to a box-shaped frame that fit over each bin (Swartz et al., 2026). Watering treatments were calibrated prior to implementation by watering an empty bin and calculating time to reach the treatment amount. Two watering treatments were chosen to mimic different precipitation regimes common in drylands on the Colorado Plateau, which has a bimodal precipitation pattern relying on the North American Monsoon (heavy rainstorms) and winter snow but also receives lighter precipitation in the spring and fall transition periods (U.S. Geological Survey, 2002). As such,

the two precipitation patterns we tested were: (1) a low frequent watering treatment, with 25 mm of water applied four times per week (low frequent); (2) a high-intensity pulse watering treatment of 50 mm applied twice per week (pulse). The frequency of treatments was adjusted so both would receive the same amount of water, thereby only mimicking the size of events, but not the temporal spacing of precipitation in a field experiment setting.

3.3.5 Data collection

Mesocosms were monitored every two days for six weeks by counting the density of forb and grass seedlings. Once a week, we recorded species-level identification and the average height of seedlings for each species. If a seedling was too small to be identified, it was labeled as unknown and revisited as it developed. Each time a new plant emerged in a bin, a toothpick was placed next to it. Toothpicks were color-marked for each species to track seedling mortality and emergence.

3.3.6 Data Analysis

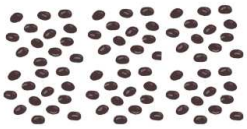
Data analysis was conducted in R version 4.2.2 (R Core Team, 2023). We used a combination of linear modeling and multivariate community analyses to test for treatment effects on seedling density and community composition. To compare density between seeding method and watering treatments, we used generalized linear mixed-effects models (GLMMs) with the lme4 package (Bates et al., 2014). We used multivariate community analyses to test for differences in plant community composition among treatments with PERMANOVA (permutational analysis of variance) conducted with the adonis2() and pairwise.adonis2() functions from the vegan and pairwiseAdonis packages (Arbizu, 2020;

Oksanen, 2020). When significant differences in community composition were found among groups, we conducted an indicator species analysis to identify species that were most associated with treatment types, with the multipatt() function of the indicspec package (De Cáceres et al., 2010). All data visualizations were created using the ggplot2 package (Wickham, 2016). See supplement (Text S1) for more detailed methods.

3.4 RESULTS

3.4.1 Plant density responses to seed pellet and watering treatments

Seed pellet method and watering treatment both affected seedling density (Figs. 1, 2, 3). mechanically-made pellets resulted in significantly greater seedling density (*std. = +0.43, z = +8.73, p = <2e-16,* Fig. 2), while handmade pellets resulted in significantly less emergence (*std. = -0.74, z = -10.96, p = 0.0138*) compared to the control. mechanically-made pellets also emerged more quickly, reaching a greater average of germinants at day 15 than broadcast did at day 40. Seeding treatment effects on plant density were influenced by watering treatments. Handmade pellets produced fewer germinants in the pulse treatment than in the low frequent treatment (*std. = -0.29, z = -3.37, p = 0.0150;* Fig. 3, Fig. S4), while mechanically-made pellets had significantly greater emergence in the pulse treatment than the low frequent (*std. = +0.36, z = +9.05, p = 2.7e-09*). Forb and grass density followed similar patterns overall (Figures S1 and S2).

	Broadcast	Handmade	Mechanically-made
Seeding Method			
Watering Effect	No Effect	No Effect	Pulse precipitation significantly higher germination ($p<0.001$)
Variation*	N/A	Homogenous	Heterogenous
Melting Rate*	N/A	Slower melting	Faster melting
Compaction*	N/A	More compact	Less compact

*indicates conceptual understanding not supported by quantitative data

Figure 1. Conceptual comparison of seed pellet treatments by average grass and forb density between both watering treatments with visual representation of method. Lower table shows if the watering treatments were significantly different, then conceptualization around the variation of size and shape of pellet, the melting speed of the pellet, and the compaction of clay, straw, and seeds.

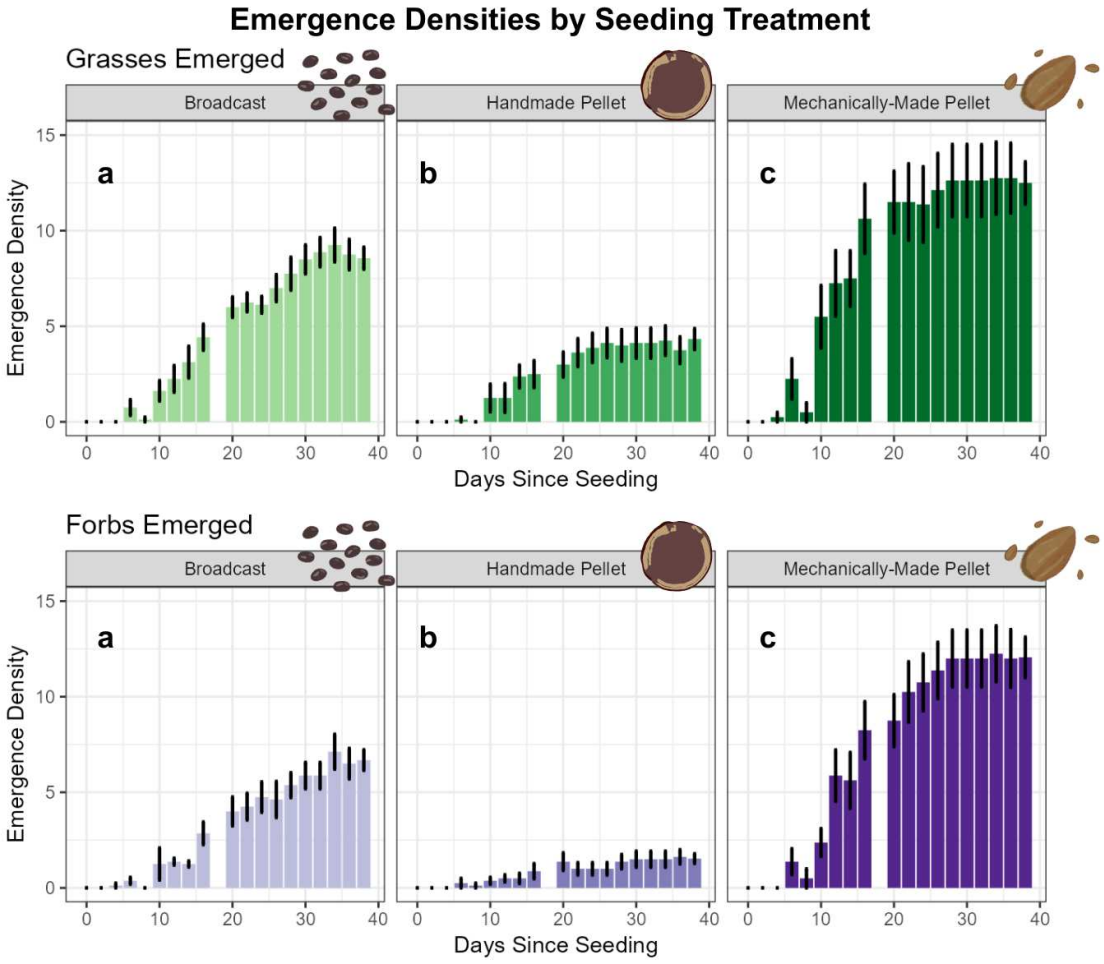


Figure 2. Differences in mean grass and forb seedling density between seed pellet treatments at each monitoring timepoint averaged within treatment groups (n = 24 bins, n = 8 broadcast, n = 8 mechanically-made, n = 8 handmade). Letters indicate statistically significant differences from other groups, a shared letter would indicate no statistically significant difference (ex. “a” is significantly different from “b”) . Error bars represent standard deviation from the mean. Watering was conducted on Day 18 but the monitoring count was not taken.

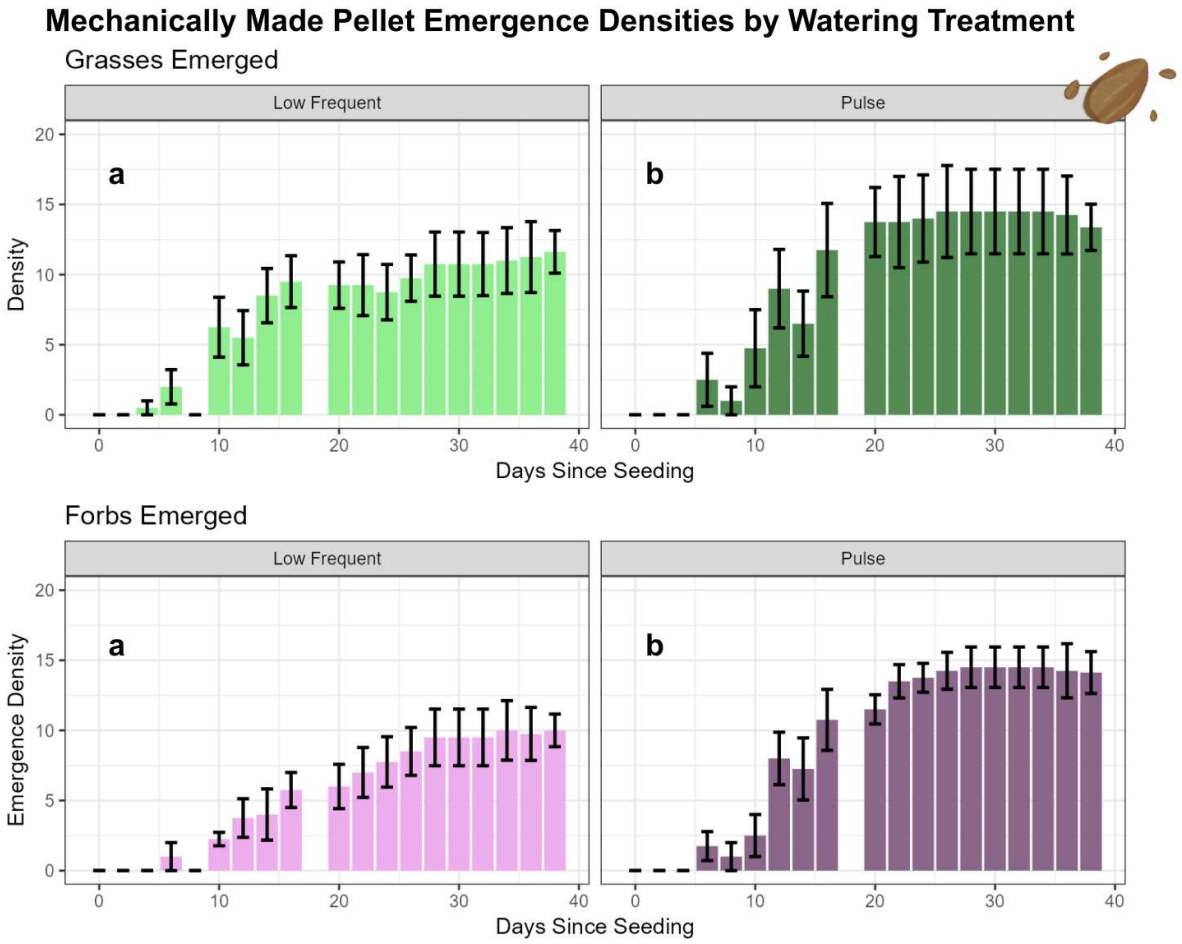


Figure 3. Differences in grass and forb seedling density emergence means between watering treatments in mechanically-made pellets (n = 8 mechanically-made pellet bins total, n = 4 low frequent, n = 4 pulse). Letters indicate statistically significant differences from other groups, a shared letter would indicate no statistically significant difference (ex. "a" is significantly different from "b"). Error bars represent standard deviation from the mean. Watering was conducted on the 18th day but the monitoring count was not taken.

3.4.2 Seeding pellet treatments resulted in distinct plant community composition

Seed pellet and watering treatments resulted in distinct plant community compositions (Figure S5) (*p=0.001)* and watering treatments (*p=0.001*). We conducted a pairwise contrast of the

PERMANOVA and found that every seeding method was significantly different from the others, meaning that the 19 species assembled into distinct communities depending on their seeding method *(F = 7.443, p = 0.001*). The pairwise contrast between watering methods also showed different community compositions (*F = 3.895, p = 0.003*) (Fig S3). To visualize differences, we created NMDS plots in which the distance between centroids demonstrates the difference between communities (Figure S3).

To understand which species may be driving community differences among seeding treatments, we conducted an indicator species analysis. We found that *Linum lewisii* (blue flax; IndVal = 0.679 ; p = 0.009) and *Asclepias tuberosa L.* (butterfly milkweed, IndVal = 0.660; p = 0.018) were indicative of the mechanically-made pellet communities (Table S4). Handmade pellets had no indicator species. In the indicator species analysis comparing watering treatments, we found that *Achillea millefolium* (yarrow, IndVal = 0.795; p = 0.001) was significantly associated with pulse watering. Full indicator species analysis results can be found in the supplement (Table S4).

3.5 DISCUSSION

Dryland restoration is critical for the conservation of biodiversity and ecological and economic global health (United Nations Convention to Combat Desertification, 2024). However, seed-based restoration in dryland systems is challenged by water limitation, granivory, and ongoing, intensifying aridification (Shackelford et al., 2021). Seed pellets show promise in supporting emergence despite these pressures (Gornish et al., 2019). Here, we tested how different seed pellet creation methods useful for

precision restoration under two watering treatments impact seedling emergence. We found that mechanically-made pellets produced by a custom-made seed pellet bike had significantly higher counts of both grass and forb seedlings and differed in community composition from broadcast seeding, particularly promoting two native forb species. This suggests smaller, more heterogeneous seed pellets might support recruitment of dryland seedlings, possibly by increasing soil nutrient and/or moisture availability. We observed that mechanically-made pellets seemed to be holding water and broke down ("melted") much faster and more completely than handmade pellets (Figure S3). mechanically-made pellets watered in pulses particularly increased seedling emergence; therefore, planting at times of year when larger pulses of water are likely (e.g., monsoons) could assist seedballs in melting and seedlings in obtaining water and nutrients (Gornish et al., 2018; Madsen et al., 2016). In drylands, which are generally water and nutrient limited, mechanically-made pellets may be especially advantageous, as they add microsites favorable for emergence and may be a useful tool for precision restoration frameworks.

3.5.1 Mechanically-made seed pellets increased seedling recruitment

We speculate that the almost double seedling establishment in mechanically-made pellets compared to broadcasting was due to their size heterogeneity and limited compaction, as water may have been able to permeate the entire mechanically-made pellet, while handmade pellets may only have absorbed water in the surface layer due to their greater compaction and size. If this is true, a greater number of seeds in mechanically-made pellets would receive moisture than in the handmade pellets. This may have been the case particularly in the pulse watering treatment, in which water was delivered

in fewer, larger events, as mechanically-made pellets in this treatment seemed to melt faster. Further, the majority of seeds used in this study have an optimal planting depth of 0.6 cm (Table S1), and as handmade pellets were approximately 5 cm in diameter, seeds at the center may have been embedded too deeply to receive necessary water and light cues.

Previous studies have discussed relationships between size and water retention of seed pellets. Jones (2014) found that seed pellets had a negative effect on emergence of seeded species, but smaller and flatter pellets that had less clay germinated more than their larger counterparts, which is consistent with our findings (Jones et al., 2014). Similarly, Mueller (2021) found that smaller pellets (under 3 cm) were more effective for small and medium seed-sized species, which most in our study tended to be (Mueller et al., 2021). Mechanically-made pellets being more heterogeneous and generally smaller than handmade pellets could have provided more microsite variety, increasing the likelihood of the ideal microsite for a given species while promoting the recruitment of species with small and medium seeds. Further, Madsen (2016) suggests that seed pellets are able to "swell" with water and may improve emergence of species that need to be seeded at shallow depths because the swelling creates water space for the seedling (Madsen et al., 2016). Madsen et al. also suggest that pellets that absorb more water may distribute it more evenly throughout the pellet (Madsen et al., 2016), and if mechanically-made pellets were able to absorb more water, they may have been able to support seedlings in accessing water resources at an early critical life stage, while if handmade pellets were less absorbent due to compaction, they may not have had this ability.

Both seeding pellet treatments potentially increased nutrient availability to developing seedlings with clay, which has a high cation exchange capacity compared to inert sand and contains important micronutrients (Mg, Ca, K) that may have been more available in the mechanically-made pellets with water infiltration (Lagaly, 1981). Nutrient addition may have been a reason that seeds in the mechanically-made pellets emerged more than broadcast, as broadcast seeds were only on sand, but these nutrients were likely less available in the handmade pellets if water was not permeating them. Other work has suggested that the inherent addition of nutrients from the clay and binding material can support seedling establishment, particularly in soils that are nutrient-poor like sand (Madsen et al., 2016). Studies have also tested adding different nutrients into seed pellets and have shown that manure increased seedling emergence from pellets (Mueller et al., 2021).

3.5.2 Mechanically-made pellets favored the recruitment of forbs and differed community composition

Forb restoration is particularly challenging in dryland systems (Dumroese et al., 2015), and as our community analyses found that seeding treatment communities differed with three forb species as indicators of pulse and mechanically-made pellet conditions, planting these species in mechanically-made pellets may be a promising strategy to support native forb restoration in systems with a high likelihood of receiving pulse precipitation (e.g., monsoons). *L. lewisii* (blue flax) and *A. tuberosa L.* (butterfly milkweed) were most indicative of mechanically-made pellets, and these two species are both commonly used forbs in dryland restoration, which have a similar seed size, shape, and recruitment niches (Innes et al., 2022; Kephart, 1987). Mechanically-made seed pellets may encourage this specific

kind of plant morphology to emerge, as both of these species are small- to medium-seeded, and smaller-seeded species prefer smaller pellets (Mueller et al., 2021). *A. millefolium* (yarrow), a perennial forb, was indicative of pulse watering treatment, and this plant is generally considered to be beneficial in restoration in the arid west due to its ability to quickly establish in highly degraded areas (Winslow, 2014). However, the difference in community found between different seed pellet treatments may have been purely driven by the fact that more seedlings emerged in mechanically-made pellets overall (Figure 2).

3.5.3 Next steps for seed pellet research and restoration practice

Seed pellets may improve seed-based restoration outcomes in dryland systems by protecting seedlings, absorbing water, and increasing micronutrient availability. This greenhouse study demonstrated that mechanically-made seed pellets resulted in increased recruitment of native dryland species, particularly under a pulse watering treatment. This result can inform practitioners working to restore dryland areas within precision restoration frameworks that aim to spatially and temporally time restoration treatments to maximize success (Copeland et al., 2021). Insights between seed pellet creation techniques and watering treatment differences gleaned here add to the baseline knowledge around seed pellet creation and deployment mechanics. However, additional comparisons of seed pellet methods are needed under field conditions to make recommendations for dryland restoration project seed pellet treatments, as these plants were grown under ideal conditions without the water limitations and seed predation common in dryland ecosystems (Havrilla et al., 2020; Shackelford et al., 2021; Vincent-

Serrrano, et al., 2024). Further, additional experiments that test different seed pellet recipes and additions (e.g., compost, biochar, activated charcoal, etc.) under a variety of precipitation regimes are needed to determine the feasibility for deploying mechanically-made seed pellets under a variety of ecological conditions. However, that mechanically-made pellets increased germination and promoted forb recruitment is promising for their future use in dryland restoration projects.

3.6 REFERENCES

Arbizu, P. M. (2020). *pairwiseAdonis: Pairwise Multilevel Comparison Using Adonis*. [Dataset]. https://github.com/pmartinezarbizu/pairwiseAdonis

Arid and Semi-arid Region Landforms—Geology (U.S. National Park Service). (n.d.). Retrieved October 6, 2025, from https://www.nps.gov/subjects/geology/arid-landforms.htm

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). *Fitting Linear Mixed-Effects Models using lme4*. https://doi.org/10.48550/ARXIV.1406.5823

Burrell, A. L., Evans, J. P., & De Kauwe, M. G. (2020). Anthropogenic climate change has driven over 5 million km2 of drylands towards desertification. *Nature Communications*, *11*(1), 3853. https://doi.org/10.1038/s41467-020-17710-7

Copeland, S. M., Baughman, O. W., Boyd, C. S., Davies, K. W., Kerby, J., Kildisheva, O. A., & Svejcar, T. (2021). Improving restoration success through a precision restoration framework.

Restoration Ecology, *29*(2), e13348. https://doi.org/10.1111/rec.13348

De Cáceres, M., Legendre, P., & Moretti, M. (2010). Improving indicator species analysis by combining groups of sites. *Oikos*, *119*(10), 1674–1684. https://doi.org/10.1111/j.1600-0706.2010.18334.x

Dumroese, R. K., Luna, T., Richardson, B. A., Kilkenny, F. F., & Runyon, J. B. (2015). Conserving and restoring habitat for Greater Sage-Grouse and other sagebrush-obligate wildlife: The crucial link of forbs and sagebrush diversity. *Native Plants Journal*, *16*(3), 276–299. https://doi.org/10.3368/npj.16.3.276

Fox, J. (2023). *Package 'car.'* https://cran.r-project.org/web/packages/car/car.pdf

Fukuoka, M. (2009). *The one-straw revolution: An introduction to natural farming*. New York Review Books.

Gornish, E., Arnold, H., & Fehmi, J. (2019). Review of seed pelletizing strategies for arid land restoration. *Restoration Ecology*, *27*(6), 1206–1211. https://doi.org/10.1111/rec.13045

Gornish, E., Simpson, A., & Caballero-Reynolds, M. (n.d.). *A Bicycle-Powered Seed Pelletizer for Use in Gardening and Restoration*.

Havrilla, C. A., Munson, S. M., McCormick, M. L., Laushman, K. M., Balazs, K. R., & Butterfield, B. J. (2020). RestoreNet: An emerging restoration network reveals controls on seeding success across dryland ecosystems. *Journal of Applied Ecology*, *57*(11), 2191–2202. https://doi.org/10.1111/1365-2664.13715

Innes, P., Gossweiler, A., Jensen, S., Tilley, D., St. John, L., Jones, T., Kitchen, S., & Hulke, B. S. (2022). Assessment of biogeographic variation in traits of Lewis flax (Linum lewisii) for use in restoration and agriculture. *AoB PLANTS*, *14*(2), plac005. https://doi.org/10.1093/aobpla/plac005

Jawahar, R., & Umarani, R. (2020). Development of Seed Cube Technology for Successful Afforestation Through Direct Seeding of Thespesia Populnea Trees. *Journal of Tropical Forest Science*, *32*(1), 52–57.

Jones, L. C., Schwinning, S., & Esque, T. C. (2014). Seedling Ecology and Restoration of Blackbrush (Coleogyne ramosissima) in the Mojave Desert, United States. *Restoration Ecology*, *22*(5), 692–700. https://doi.org/10.1111/rec.12128

Kannan, R., Dhivya, V., & Janani, T. S. K. (2021). Future Perspective of Seed Ball Technology For Creating New Ecosystem. *INTERNATIONAL JOURNAL OF PLANT AND ENVIRONMENT*, *7*(04), 293–296. https://doi.org/10.18811/ijpen.v7i04.9

Kephart, S. R. (1987). Phenological Variation in Flowering and Fruiting of Asclepias. *The American Midland Naturalist*, *118*(1), 64–76. https://doi.org/10.2307/2425629

Lagaly, G. (1981). Characterization of clays by organic compounds. *Clay Minerals*, *16*(1), 1–21. https://doi.org/10.1180/claymin.1981.016.1.01

Lenth, R. V. (2017). *emmeans: Estimated Marginal Means, aka Least-Squares Means* (p. 1.10.5) [Dataset]. https://doi.org/10.32614/CRAN.package.emmeans

Madsen, M. D., Hulet, A., Phillips, K., Staley, J. L., Davies, K. W., & Svejcar, T. J. (2016). Extruded seed pellets: A novel approach for enhancing sagebrush seedling emergence. *Native Plants Journal*, *17*(3), 230–243. https://doi.org/10.3368/npj.17.3.230

Mueller, P., Mendivil, E., Jonas, J., Kline, A., & Gornish, E. S. (n.d.). *Seedball Design to Optimize Germination*.

Munro, T. P., Erickson, T. E., Nimmo, D. G., & Price, J. N. (2024). Assessing seed pellet formulations to improve native plant restoration under water-limited conditions. *Restoration Ecology*, *32*(7), e14217. https://doi.org/10.1111/rec.14217

Oksanen, J. (2020). *Package 'vegan.'*

Pedrini, S. (2025). A novel multi-species seed pelleting method to improve the efficiency of seed-based ecological restoration. *Frontiers in Environmental Science*, *13*. https://doi.org/10.3389/fenvs.2025.1595530

Precipitation History of the Colorado Plateau Region, 1900–2000. (n.d.). Retrieved January 9, 2026, from https://pubs.usgs.gov/fs/2002/fs119-02/

Shackelford, N., Paterno, G. B., Winkler, D. E., Erickson, T. E., Leger, E. A., Svejcar, L. N., Breed, M. F., Faist, A. M., Harrison, P. A., Curran, M. F., Guo, Q., Kirmer, A., Law, D. J., Mganga, K. Z., Munson, S. M., Porensky, L. M., Quiroga, R. E., Török, P., Wainwright, C. E., ... Suding, K. L. (2021). Drivers of seedling establishment success in dryland restoration efforts. *Nature Ecology & Evolution*, *5*(9), 1283–1290. https://doi.org/10.1038/s41559-021-01510-3

Swartz, E. H., Caldwell, B., & Havrilla, C. A. (n.d.-a). Seed pellets containing activated carbon increase emergence of native plant species used in dryland restoration following herbicide application. *Restoration Ecology*, *n/a*(n/a), e70316. https://doi.org/10.1111/rec.70316

Swartz, E. H., Caldwell, B., & Havrilla, C. A. (n.d.-b). Seed pellets containing activated carbon increase emergence of native plant species used in dryland restoration following herbicide application. *Restoration Ecology*, *n/a*(n/a), e70316. https://doi.org/10.1111/rec.70316

The global threat of drying lands: Regional and global aridity trends and future projections. (2024, December 9). UNCCD. https://www.unccd.int/resources/reports/global-threat-drying-lands-regional-and-global-aridity-trends-and-future

Wei, F., Wang, S., Fu, B., Li, Y., Huang, Y., Zhang, W., & Fensholt, R. (2024). Quantifying the precipitation supply of China's drylands through moisture recycling. *Agricultural and Forest Meteorology*, *352*, 110034. https://doi.org/10.1016/j.agrformet.2024.110034

Wickham, H. (with Sievert, C.). (2016). *ggplot2: Elegant graphics for data analysis* (Second edition). Springer international publishing.

Winslow, S. R. (n.d.). *WESTERN YARROW Achillea millefolium var. Occidentalis*.

Vicente-Serrano, S. M., N. G. Pricope, A. Toreti, E. Morán-Tejeda, J. Spinoni, A. Ocampo-Melgar, E. Archer, A. Diedhiou, T. Mesbahzadeh, N. H. Ravindranath, R. S. Pulwarty and S. Alibakhshi (2024). The Global Threat of Drying Lands: Regional and global aridity trends and future projections. A

Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD). Bonn, Germany.

CHAPTER 4 - PRECISION RESTORATION STRATEGIES THAT PROMOTE WATER CAPTURE AND RETENTION INCREASE SEED-BASED RESTORATION SUCCESS IN TWO SEMI-ARID AREAS IN COLORADO

4.1 ABSTRACT

Seed-based restoration (SBR) in drylands is constrained by high temperatures and low and variable precipitation regimes. Precision restoration treatments that aim to alleviate key abiotic barriers to seedling recruitment in drylands by increasing water capture, soil moisture retention, and/or soil nutrients may increase the success of SBR. We compared restoration treatments targeting moisture and nutrient dynamics at two areas in semiarid southwestern Colorado that differed in aridity and land-use history. Treatments included those trialed across a regional restoration network study (RestoreNet) and those selected by county land stewards. We also tested two climate-adaptive seed mixes across these treatments to inform seed mix selection. We investigated three research questions: Q1) How do two climate-adapted seed mixes differ from each other and unseeded controls in resultant seeded plant density and cover? Q2) How do locally chosen (county-level) versus regional, network-chosen (regional-level) restoration treatments differ in their impact on seeded plant density and cover? Q3) How do treatment effects differ among climate-adapted seed mixes in their impact on seeded plant density and cover? After monitoring plant establishment for four years after seeding, we

found that unseeded controls led to almost no native recruitment. Relative to unseeded controls, the cooler-adapted seed mix resulted in greater seeded plant density and cover overall, but the maximum cover and density across four years were found in the warmer-adapted mix paired with the mulch treatment. Network treatments resulted in the highest seeded plant cover overall, but locally chosen treatments had significantly higher cover in the first year. Across the eight treatments tested, compost, soil pitting, and pine mulching resulted in significantly higher seeded density or cover than seeded controls. However, these conclusions were only drawn from the less arid post-agricultural site, as the drier post-grazing area had almost zero seedling establishment throughout the study, suggesting potential climatic thresholds beyond which these treatments are insufficient to support SBR. Results provide support for using precision restoration frameworks in degraded drylands, as findings from this highly contextualized and locally informed study demonstrate the nuanced effects of land use history and precision restoration treatments on SBR outcomes.

4.2 INTRODUCTION

Dryland ecosystems are uniquely vulnerable to physical land degradation coupled with increased aridification posed by the climate crisis. Currently, up to 20% of drylands are degraded (Burrell et al., 2020; Hoover et al., 2020). Dryland degradation is characterized by decreased native plant cover and diversity (Yang et al., 2022a), increased soil erosion (Dregne, 2002), increased salinity (Stavi et al., 2021), and decreased microbial and biological activity (Reynolds et al., 2007), all of which

impact the ecosystem's ability to maintain critical biodiversity and functioning (Zdruli et al., 2010) and recover following disturbance (Miguel et al., 2020a). Drylands support over two billion people (Yirdaw et al., 2017) and comprise 44% of global cropland and 70% of grazing lands, making their degradation both an ecological and socioeconomic crisis (IUCN CEM Dryland Ecosystems Specialist Group | IUCN; Laban et al., 2018). Many people who live in drylands experience disproportionate harm from the climate crisis, including peoples and nations that pollute the least and have primarily pastoralist lifeways, but who are burdened with the effects of pollution and climate stress that large industrial polluters and countries initiated (Ahmed et al., 2022; Metternicht, 2025). Therefore, the restoration of drylands and the implementation of adaptation and resilience strategies are critical to slow and potentially reverse the harm that has been done to the communities and ecosystems of drylands globally (Hoover et al., 2020; Laban et al., 2018).

As plants are the basis of ecosystem productivity, establishing diverse native plant communities is a key goal of dryland restoration (Biancari et al., 2026). Seed-based restoration (SBR) is one of the most widely-used restoration techniques because distributing seed by hand or machine is often less expensive and time-consuming than other methods. However, SBR in drylands is challenging due to limited or variable precipitation and extreme temperatures (Eldridge et al., 2020). Shackelford et al. (2021) found that 17% of restoration projects attempting to grow native plants from seed in drylands resulted in none of the species seeded establishing. As land use histories (Bestelmeyer et al., 2015), area type and aridity index (Shackelford et al., 2021), soil and water dynamics (Kimmel et

al., 2023), and seed selection (Barr et al., 2017) all influence plants recruitment, utilizing precise supportive restoration techniques like altering surface topography to increase water capture or adding soil amendments, and carefully selecting seed mixes are critical for improving the likelihood of plant establishment through SBR. Precision restoration requires the layering of careful, locallyinformed selection of seed mix with restoration treatments, as seed size, plant traits, and amendment actions can all impact SBR success (Balazs et al., 2020; Naupu et al., 2026; Shackelford et al., 2021).

Ecological network studies aim to understand similarities and differences across a wider land area or ecological system and can serve to answer questions about ecological restoration to both inform precision restoration at specific sites and generate wider regional knowledge (Poisot et al., 2016). RestoreNet is a networked restoration field trial network that tests precision restoration strategies to alleviate barriers to SBR across ecological gradients in the southwestern US. RestoreNet is a collaborative effort between dryland restoration scientists and land stewards, and restoration treatments trialed include those selected by the network and by local stewards, aiming to support knowledge around SBR across scales in the region (Havrilla et al., 2020; Yang et al., 2022). Past RestoreNet studies have focused on exploring the effects of core dryland restoration strategies across ecological gradients in the southwestern US (e.g., Balazs et al., 2020; Farrell et al., 2023; Havrilla et al., 2020); however, no studies to date have compared the efficacy of these network-selected treatments to those selected by local land stewards within the network. Here, we compared restoration outcomes (i.e., seeded species density and cover) from two RestoreNet areas in southwestern Colorado, which

vary greatly in their land use histories and biophysical characteristics despite being within 40 miles of each other, to explore how different seeding and treatment activities may affect restoration outcomes across climatic characteristics and conditions.

Specifically, to examine the interplay between restoration treatments, treatment provenance (locally chosen or network chosen), seed mix, and area characteristics, we tested locally-chosen and network-chosen restoration treatments which previous literature has shown to increase water capture, moisture retention, and nutrient addition, and compared them across two seed mixes informed by species climatic niches (i.e., a "cooler-" vs "warmer-" adapted seed mix; (Balazs et al., 2020)). We tested three research questions: Q1) How do two climate-adapted seed mixes differ from each other and unseeded controls in resultant seeded plant density and cover? Q2) How do locally-chosen versus regional network-chosen restoration treatments differ in their impact on seeded plant density and cover? Q3) How do treatment effects differ among climate-adapted seed mixes in their impact on seeded plant density and cover? By answering these questions, we provide more understanding of regional dryland restoration practices and explore how regional and local partnerships can inform precision restoration strategies.

4.3 METHODS

4.3.1 Area Descriptions

We established two RestoreNet areas in southwestern Colorado in May-June 2021 using the RestoreNet protocol (Laushman et al. 2021). RestoreNet is a distributed dryland restoration field trial network founded by the U.S. Geological Survey that involves collaboration between scientists and local land managers, which tests seed mixes and treatments to promote native plant growth and restoration across the 35 areas within the network (*RestoreNet*, 2024). Of the two areas in Colorado, one is located at the Southwestern Colorado Research Center (SWCRC), an agricultural experimental research station managed by Colorado State University in Yellowjacket, Colorado (approximately 37° 32 '28.6"N 108° 44' 43.2"W). The second is located on tribal lands managed by the Ute Mountain Ute Tribe in the Ute Mountain Ute Tribal Park (UMUT), which is a culturally significant ecological area located near Towaoc, Colorado, approximately 40 miles south of the SWCRC (approximately 37°05'04.3"N 108°42'40.7"W). Prior to area installation, SWCRC was row-cropped with wheat and safflower, and UMUT was grazed by cattle and wild horses and had a high cover of non-native annual plants. Both areas were 50 m x 50 m and were fenced to exclude large herbivores and were cleared using a mechanical trimmer and herbicide (glyphosate; RangerPro: 41% glyphosate, applied in a 3% mixture). Herbicide application was conducted on June 19th, 2022, and seeding happened two weeks later in early July. SWCRC is in the loamy foothills area type with loamy soil, and UMUT is in the alkali bottom area type with very fine sandy loam and silt loam (websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

Table 1. Area descriptions of the two restoration research areas (SWCRC and UMUT). Ecological area type and soil type retrieved from (websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx), elevation from (The National Map), and mean-annual precipitation and mean-annual temperature from (Oregon State Prism, cite).

Area	**Area Type**	**Soil Type**	**Elevation (m)**	**Mean-annual precipitation (cm)**	**Mean-annual temperature (°C)**
SWCRC	Loamy foothills	Loamy	2,123	37.82	8.8
UMUT	Alkali bottom	Very fine sandy loam	1,627	17.91	13.1

4.3.2 Seed Mixes and Restoration Treatments

We tested eight restoration treatments (Table 2) designed to reduce barriers to SBR through increasing water capture, soil water retention, and adding nutrients and organic matter to the soil and compared them against a) unseeded and b) seed-only controls (seed mix information found in Table S1). Four treatments were the same at each area (RestoreNet networked treatments and one shared local treatment), and four were chosen by local stewards and therefore differed between SWCRC and UMUT. For strategy 1) increasing water capture, we dug four 0.5 x 0.5m c) soil pits in a grid in the 4 m^2 plots (Johnston & Mann, 2024), or raked d) 26 g of super absorbent polymer beads 10 cm into the soil (Roots® Terra-Sorb Fine Grade Hydrogel™). Soil pitting is a method that is the Indigenous knowledge of the A:shiwi (Zuni) Puebloan people, who are the ancestral stewards of what is now the Colorado Plateau sections of western New Mexico and eastern Arizona (Pueblo of Zuni) (See Table 2 for restoration strategy sources). Other dryland restoration researchers have been inspired by this

technique and have shown that it can have beneficial effects on native plant establishment in dryland systems (Johnston & Mann, 2024). Superabsorbent polymer beads also have been used to support SBR through capturing moisture during precipitation events and slowly release moisture into the soil even after the event is passed (Garbowski et al., 2016). Treatments were fully crossed with two climate-informed seed mix treatments (Table 2).

Table 2. Treatment descriptions with the restoration strategy they target, as well as which group proposed the treatment (treatment provenance) and the research area they were installed at. References which demonstrate their efficacy in implementing the listed restoration strategy included.

Treatment	**Restoration Strategy**	**Treatment Provenance**	**Area Installed**	**References demonstrating treatment efficacy or strategy**
Unseeded control	Control/NA	Control	Both	NA
Seed only (control)	Propagule addition only	Control	Both	(Miguel et al., 2020b)
Soil pitting ("pits")	1) Increase water capture	Network	Both	(Havrilla et al., 2020; Johnston & Mann, 2024)
Mulch	2) Increase water retention, 3) add nutrients and organic matter to soil	Network	Both	(Havrilla et al., 2020; Leger et al., 2022; Luna et al., 2018)
Connectivity modifiers ("ConMods")	3) Add nutrients and organic matter to soil	Network	Both	(Turk et al., 2024; Young et al., 2025)
Polymer beads	1) Increase water capture	Local Managers	Both	(Bai et al., 2010; Garbowski et al., 2016; Yu et al., 2017)
Biochar	2) Increase water retention	Local Managers	SWCRC	(Phillips et al., 2020; Razzaghi et al., 2020)
Compost	2) Increase water	Local	SWCRC	(Amari et al., 2026; Luna et al., 2018)

	retention, 3) add nutrients and organic matter to soil	Managers		
Tamarisk mulch	2) Increase water retention, 3) add nutrients and organic matter to soil	Local Managers	UMUT	(Harms & Hiebert, 2006; Shafroth et al., 2008)
Polymer beads & tamarisk mulch	1) Increase water retention, 2) increase water capture, 3) add nutrients and organic matter to soil	Local Managers	UMUT	(Harms & Hiebert, 2006; Shafroth et al., 2008)

For treatments targeting increased water capture and/or retention, we applied 2.5 cm of e) pine wood chip mulch evenly spread across the plot surface to increase water retention and raked ~1 cm into the soil; at SWCRC only, we spread 2.5 cm of f) industrial cow manure and aspen bark compost and g) biochar on the soil surface, and at UMUT only, we spread 2.5 cm of h) tamarisk mulch and i) a combination of tamarisk mulch and polymer beads on the soil surface. The introduced shrub tamarisk (Tamarix sp.) is highly prevalent in the area surrounding UMUT, as the Ute Mountain Ute Tribe is actively removing the shrub through mastication, thereby creating potential opportunity to use this material in restoration efforts (Ute Mountain Ute Tribe Natural Resources Office, personal communication). Seeds were raked into the soil prior to treatment installation for mulch, biochar, tamarisk mulch, compost, and ConMods, and after treatment installation for pits and superabsorbent polymer beads. To support soil nutrient addition, we placed four j) connectivity modifiers evenly in

the 4 m^2 plots, which are small mesh crosses that mimic nurse plant action through providing shade and catching litter ('ConMods'; e.g., Okin et al., 2015). Many of the treatments that may retain soil moisture also act to add nutrients and organic matter to the soil. Each 2-m x 2-m study plot had one treatment and was seeded with one of the seed mixes. Mulch, biochar, compost, and polymer beads were evenly distributed throughout the plots at a depth of 2.54 cm - 5.08 cm (1 - 2 in) and then incorporated before seeding and raking, but since ConMods and pits are discrete, four replicates of each were evenly spaced throughout the plot. Each treatment was replicated 8 times throughout each area, 4 plots per seed mix (cooler-adapted and warmer-adapted) for a total of 60, 4 m^2 plots per area.

4.3.3 Data collection

After installation, we monitored area plant density (number of plants) to the species level and average species height (in mm) annually in between late May and early June for four years post-treatment (2022 – 2025). To make this intensive monitoring feasible, count and height data were only taken within a 25 cm x 25 cm (0.25 m^2) subplot located in the bottom right corner of each plot and marked permanently with railroad nails (as in Laushman et al. 2021). In ConMod and pit plots, this smaller quadrat was located within the ConMod or pit. Then, we estimated the cover of seeded and unseeded species within the full 2x2m plot using ocular estimation (Popham & Baker, 1987). The seeded or unseeded seedling designation was determined through comparison with seed mix planted in each plot (e.g., only cooler-adapted species designated as seeded in cooler-adapted mix plots). Dormant perennial plants were included in counts and cover estimates. To estimate annual precipitation

conditions, data records were downloaded from the Oregon State University PRISM project for the coordinates of each area of the monthly average precipitation and temperature across the three study years (https://prism.oregonstate.edu/).

4.3.4 Data analysis

All analyses were conducted in R version 4.3.3 "innocent and trusting" (R Core Team, 2024). To explore plant establishment across areas, treatments, and seed mixes, we utilized a combination of linear modeling and multivariate community analyses. Specifically, we tested how seeded species density in 0.25 m^2 subplots and full plot seeded species cover differed in their response to seed mix, treatment provenance, and restoration treatments. We utilized a mixed modeling approach. Prior to running models, data exploration revealed that the data from the UMUT area was overwhelmingly zero values (91%). We were unable to conduct linear model statistical testing on UMUT data because the data was so right-skewed that there was no guarantee of accuracy in the model findings. We created visualizations from this dataset, but none of the findings from this area have statistical power behind them. SWCRC had only 25% zero values, and after fitting models to this data, we selected GLMMs using the glmmTMB package (McGillycuddy et al., 2025). The models for the SWCRC area findings included either seeded species density or seeded species cover as response variable and seed mix (control, cooler-adapted, or warmer-adapted), treatment provenance (local or network), treatment (see Figure #) as fixed-effect predictor variables. Plot ID and monitoring year were included as random effects in each model to account for repeat measures. In many cases we were also interested in how

effects varied across monitoring years, and in these models, monitoring year was included as a fixed-effect predictor variable. To account for seed mixes differences, we modeled treatment effects within subset data by seed mix (Figure 1) and seed mix effects across treatments. Only results from seeded species data are included here. We then created visualizations for both areas with the ggplot2 package (Wickham, 2016).

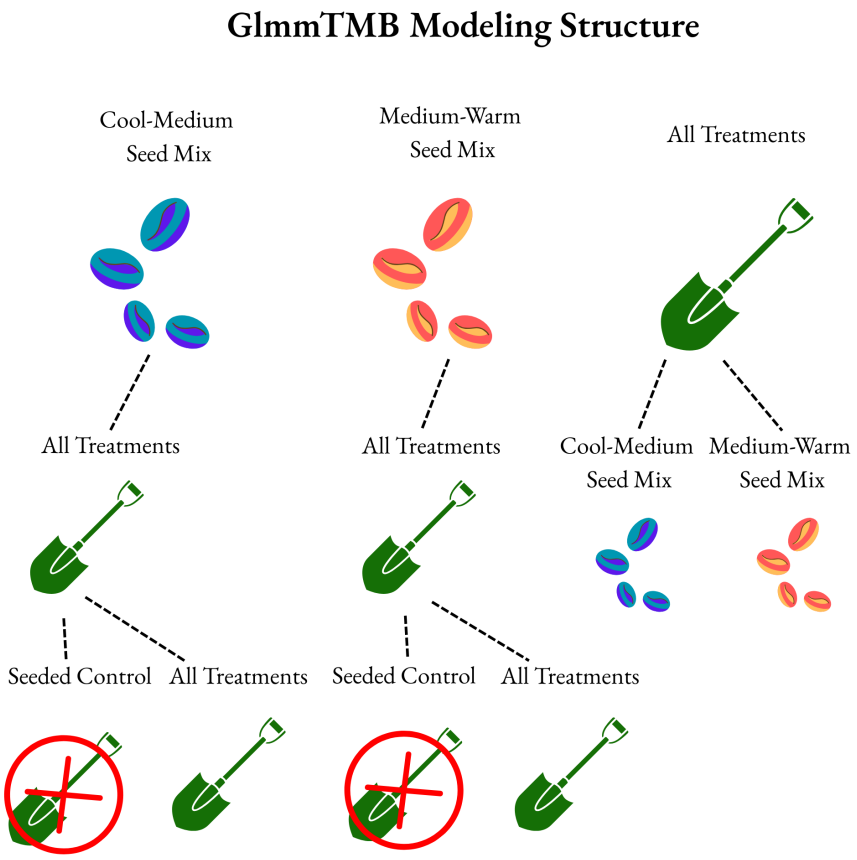


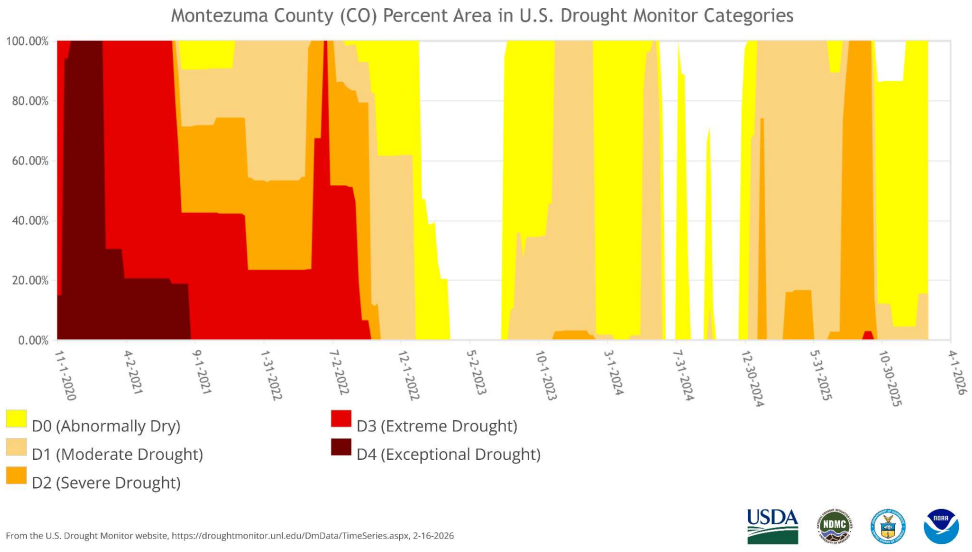
Figure 1. Modeling structure for GLMMs we conducted. Shovel indicates restoration treatments, while a shovel with "x" indicates seeded controls (no treatment). Blue seeds indicate the cool-medium seed mix, while red and yellow seeds indicate the medium-warm seed mix. Data was first separated by area, then seeded and unseeded species. Then from the seeded species data, treatments were compared

within seed mixes to each other and then in pairwise contrasts to the seeded controls. Finally, seed mixes were compared to each other within treatments.

4.4 RESULTS

4.4.1 Climate during the study period

Averages from the PRISM database (https://prism.oregonstate.edu/) information revealed that the research areas were in exceptional drought in the winter leading up to and first growing season post-seeding, extreme drought in the second, with periods of moderate to severe drought in 2024-2025 (Figure 2). Therefore, the areas were unanimously dry throughout the study period.



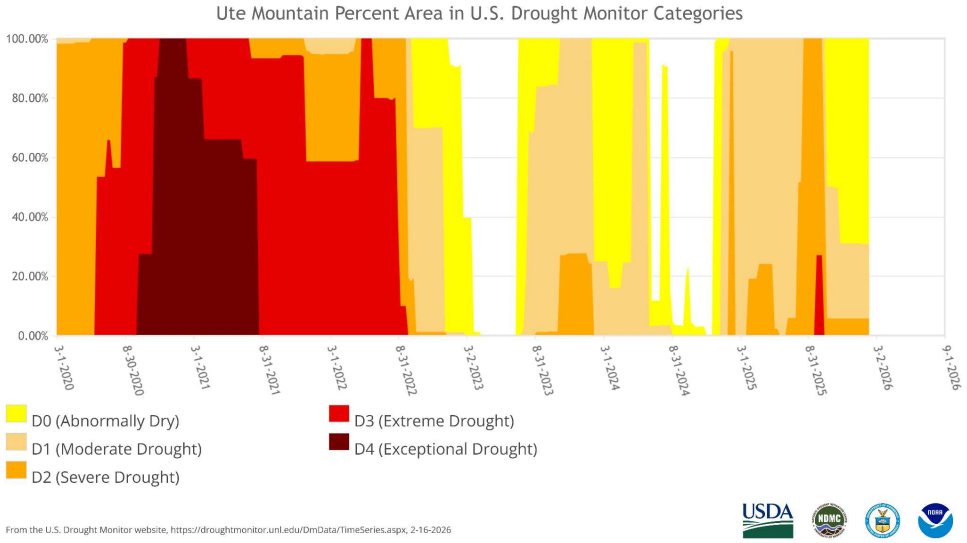


Figure 2. USDA Drought Monitor levels for November, 2020 through April, 2026 for Montezuma County, CO (SWCRC) and on Ute Mountain Ute Tribal Land (UMUT). Seeds were planted in spring of 2021 during a period of exceptional drought.

4.4.2 Seedling density and cover greatly differed between two research areas, with UMUT having majoritively zero seedlings established

Seedling recruitment differed greatly at the post-agricultural area (SWCRC) versus the drier, post-grazing, more arid area (UMUT). Over the course of the four years of monitoring at UMUT (post-grazing, more arid area) there was a severe , and seedling recruitment was exceptionally low (average cover = <0.5%, average density = 0). Too few seedlings established at UMUT for a formal analysis to be conducted using linear models. The maximum average seeded species cover at UMUT across the four years was less than <1%, while at SWCRC, it was 25%. Therefore, statistical significance for results could only be reported for SWCRC, as models were not able to run with UMUT data.

4.4.3 The cooler-adapted seed mix had higher cover across all treatments, but seed mixes resulted in no significant differences in seeded species density. While unseeded controls resulted in almost zero seeded species density and cover.

SWCRC - Unseeded controls had almost zero seeded seedling density (avg = 0) and subsequent seeded species cover. Across all treatments and the four years of the experiment, the cooler-adapted seed mix led to significantly higher seeded species cover (warmer-adapted seed mix Est = -2.033 e-01 compared to cooler-adapted, p = 1.23e-05) (Figure 3). There was no significant difference between the seed mixes in species density, only cover.

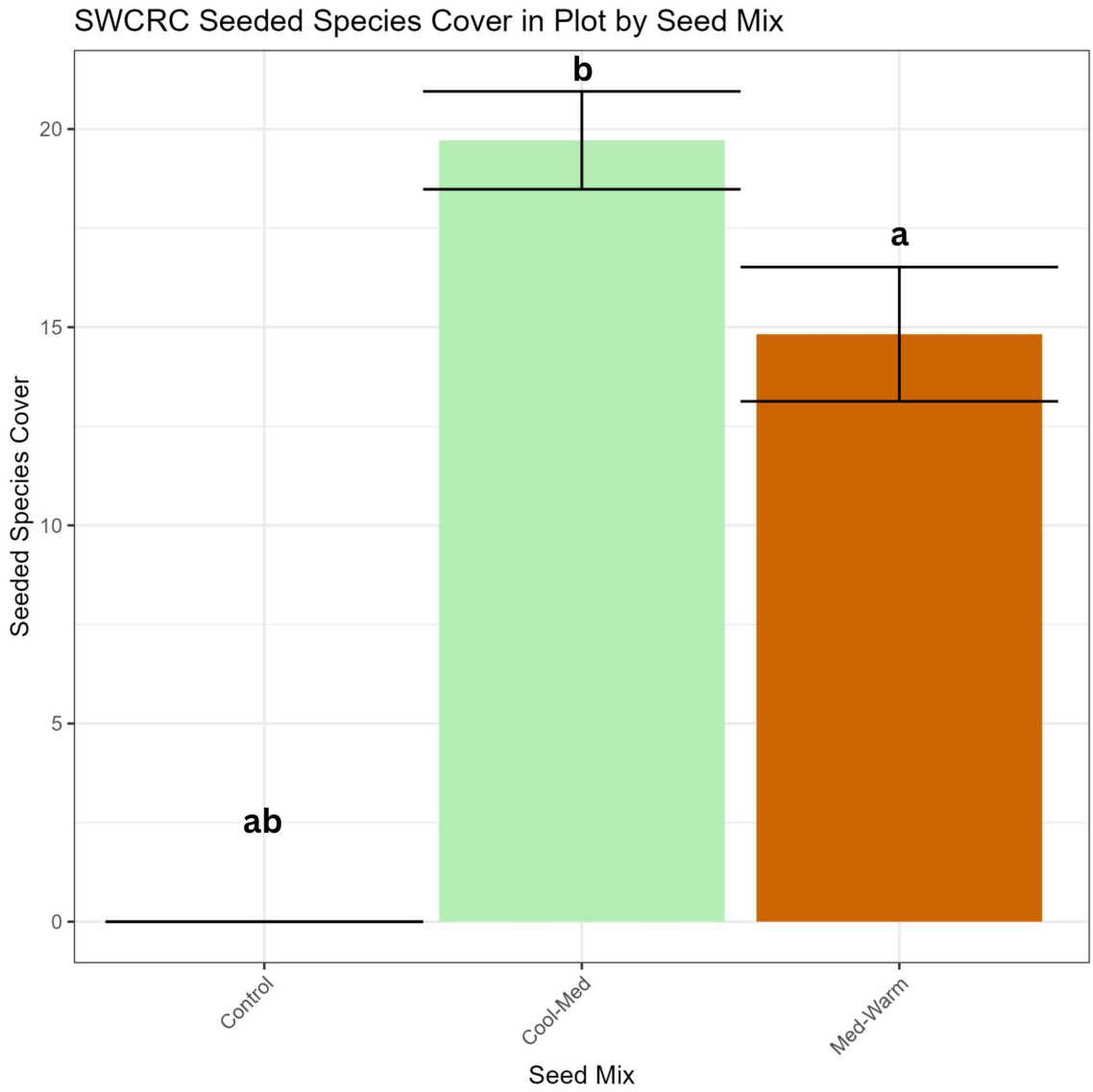


Figure 3. Comparison of seeded species cover by seed mix at SWCRC across all four years monitored and all treatments. Significance denoted by letters, with shared letters denoting no proven statistical difference and different letters denoting significant statistical difference ($p < 0.05$).

UMUT - There were no statistically significant results for UMUT due to the dataset demonstrating almost no seedling establishment (91% zero seeded species, all averages <0.5% seeded cover across seed mixes). Therefore, only plotted results were created (Figure S1). The warmer-adapted

mix resulted in a higher average (avg = 0.31%, sd = 0.97) seeded cover than the cooler-adapted mix (avg = 0.23%, sd = 0.78) .

4.4.4 Locally chosen treatments resulted in higher covers in the first year but network treatments increased cover more overall

SWCRC - Regional network-chosen treatments (avg = 21.5%, sd = 20.76) resulted in significantly higher species cover across both seed mixes and four years of monitoring than locally-chosen treatments (avg = 15.1%, sd = 15.4) and seeded controls (avg = 19.32%, sd = 19.3), (Est =0.4077, p =0.0893, EMM = 2.55, SE = 0.447) (Figure 4). However, in the first year, treatments that were locally chosen had significantly higher seeded species cover (Est = 1.5266 in pairwise comparison with network treatments during the first year, p = <.0001) (Figure 5). This effect decreased over time, as in the second (Est = local -0.9001 less than network in pairwise comparison, p = <.0001) and fourth year (Est = local -0.4816 less than network in pairwise comparison, p = 0.0207). In these years (2023 and 2025), network chosen treatments resulted in significantly higher plant density (EMM = 1.088, SE = 1.80e-01, p = 0.07213) as indicated by the compact letter display (Tukey adjusted). Plant density across all years was not significantly impacted by treatment provenance.

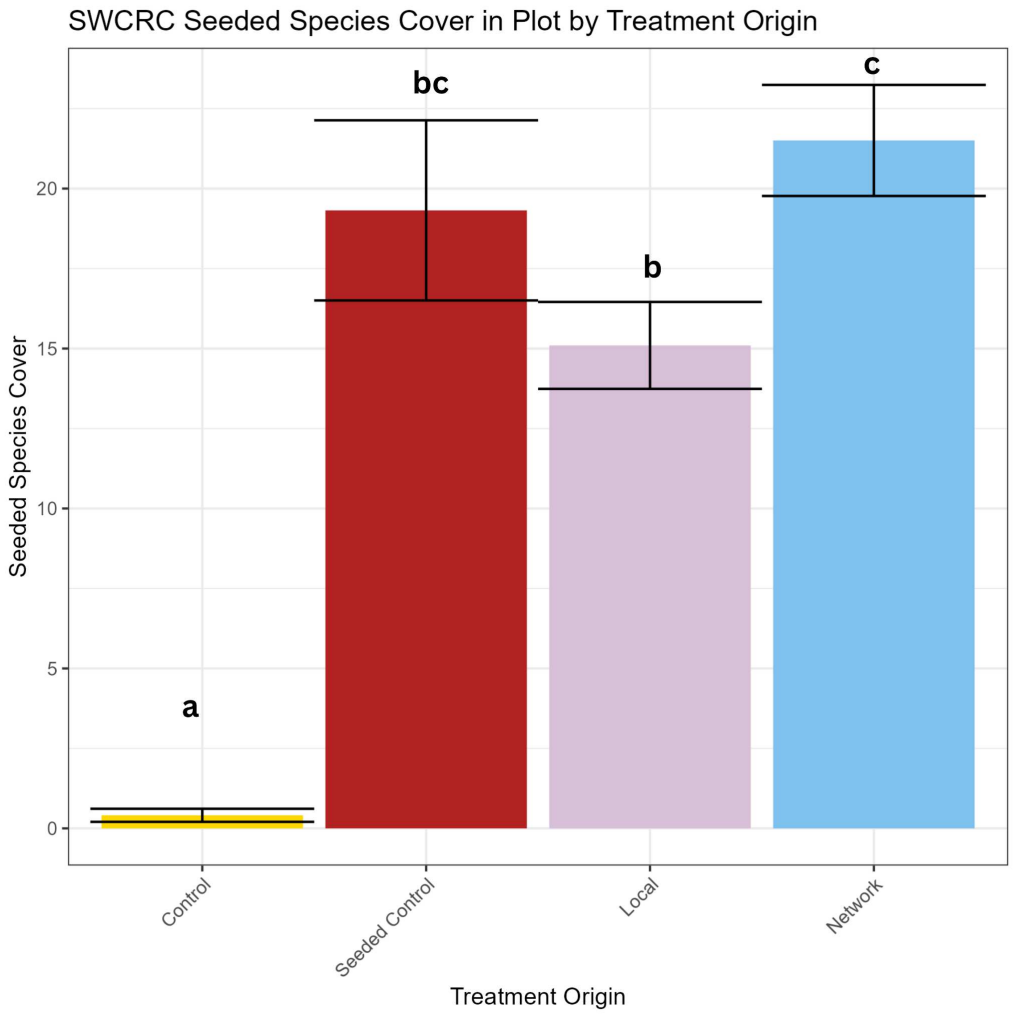


Figure 4. Comparison of seeded species cover by treatment provenance at SWCRC across all treatments, seed mixes, and monitoring pushes. Significance denoted by letters, with shared letters denoting no proven statistical difference and different letters denoting significant statistical difference ($p < 0.05$).

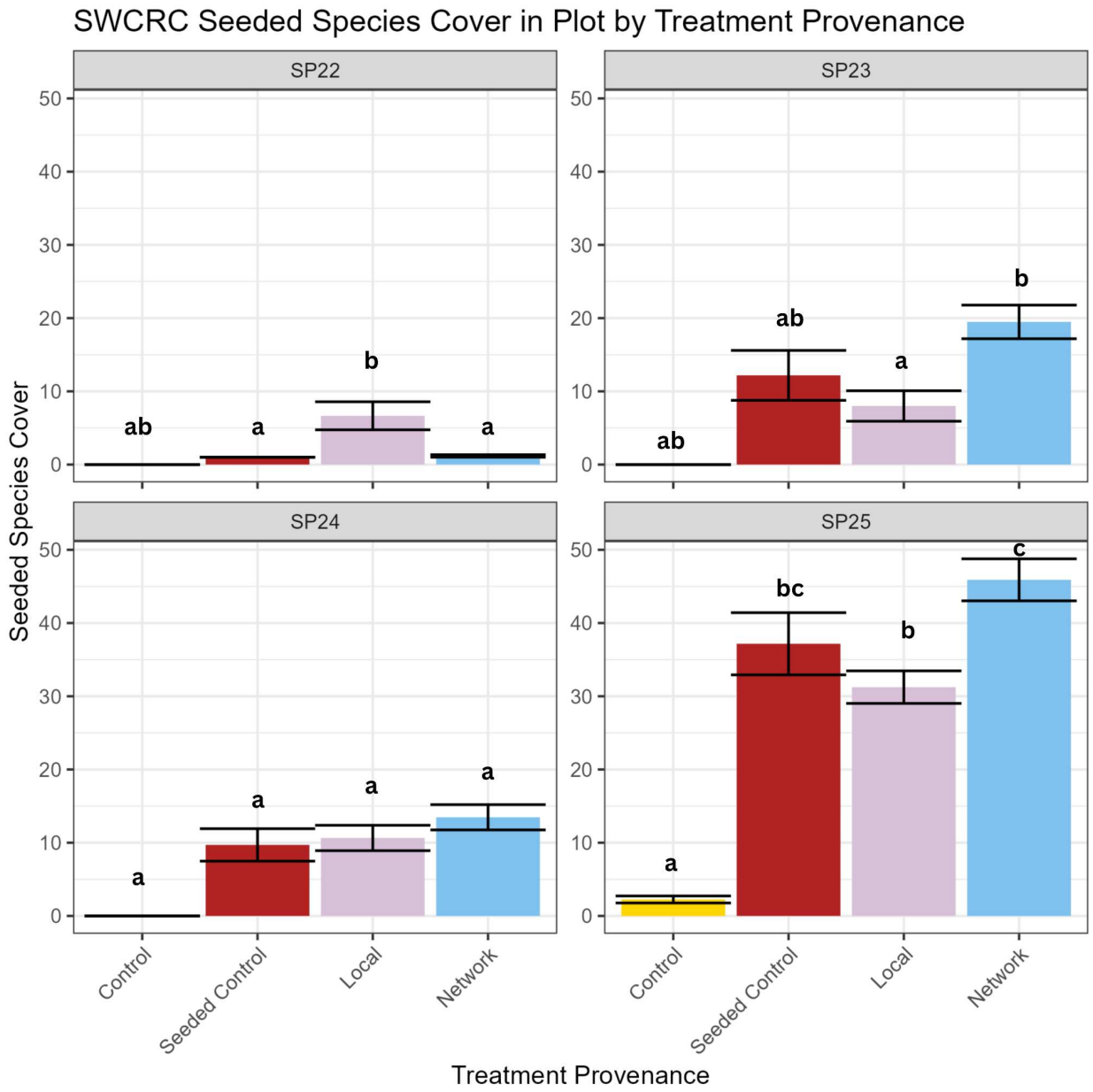


Figure 5. Comparison of seeded species cover by treatment provenance at SWCRC during each monitoring push (spring annual data collection, where SP23 = Spring 2023 and so on). Significance denoted by letters, with shared letters denoting no proven statistical difference and different letters denoting significant statistical difference ($p < 0.05$).

UMUT - Though data from the UMUT area was not analyzed with linear models, calculated averages of seeded cover in network treatments (avg = 0.36%, sd = 1.01) were marginally higher than locally-selected treatments (avg = 0.25%, sd = 0.87) and seeded controls (avg = 0.03%, sd = 0.18) (Figure S2).

4.4.5 Seed mix and treatment provenance questions are nuanced by treatment differences, with compost, mulch, and pits resulting in statistically significant increases in seeded cover and density

SWCRC - Treatment results further nuance and explain wider trends across seed mixes and treatment provenance. Though the cooler-adapted seed mix (cool-medium) resulted in higher species cover across all treatments and years, the warmer-adapted seed mix had a higher maximum cover in the mulch treatment. The seeded control in cooler-adapted mix resulted in higher species cover than the warmer-adapted mix, and almost all treatments were either statistically the same or resulted in significantly less cover in the cooler-adapted seed mix than the unseeded control. However, in the warmer-adapted mix, the mulch treatment resulted in significantly higher seeded species cover, but the mulch treatment was not significantly different from seeded controls in the cooler-adapted seed mix. Pits, a water capture treatment, resulted in the highest seeded species density in the medium-warm seed mix (Est = 1.64523, p = 0.000155). In the cooler-adapted seed mix, compost resulted in a two-fold higher seeded species density relative to seeded control at SWCRC (Figure 6). Compost was a locally-selected treatment at SWCRC, while mulch was a network-selected treatment. Compost had significantly higher density of seeded species (Est = 1.602, p = 0.0009) in the cool medium seed mix

model as well as a significantly greater coverage of seeded species in 2022 and 2024 across both seed mixes (Est = 2.5811, Est = 0.663; p <0.001, p = 0.081) (Figure 7). This is reflected in our result that local treatments had higher seeded species cover in 2022, and further analysis suggested that compost was the treatment primarily driving this result (Figure S3). Both compost and mulch are strategies that minimize barriers to SBR that increase water retention. Compost and mulch treatments were able to support SBR at the post-agricultural less arid area, while they did not reduce barriers enough at UMUT to allow for seeded species to establish.

Compost, a local treatment, was the most effective treatment across all models, doubling plant density in the full model comparing both seed mixes (Est =2.369, p = 6.45e-05), the cooler-adapted model (Est = 2.003, p = 0.005), and in the warmer-adapted model (Est =2.369; p = 0.0004) (Figure 6). Mulch, on the other hand, is a network-chosen treatment and was the only significantly beneficial treatment than seeding alone other than pits in the second year (EMM = 3.0220) in the last three years of the warmer-adapted seed mix model only, increasing establishment density by 1.3x (2023, Est =1.341, p = 0.0107; 2024, 2.126, p = <0.0001; 2025, Est = 1.12; p = 0.0026). These results also provide insight into seed mix differences and interaction with treatments, indicating that compost and a cooler-adapted mix and mulch and a warm-medium mix were most effective. These results are reflected in the figures of the average covers and densities across treatments and seed mixes (Figures 6 and 7).

Though some treatments resulted in significantly higher seeded species cover and density compared to seeded controls, several treatments had the opposite effect, resulting in significantly less cover or density compared to seeding only. The seeded controls had particularly high seeded cover in the cooler-adapted mix, and compared to these, ConMods (EMM = 2.65), biochar (Est = -0.708, p = 0.007), and polymer beads (Est = -0.709, p = 0.006) all resulted in significantly less seeded species cover and density. These same treatments in the warmer-adapted mix were not significantly different than the seeded control, meaning that though they didn't decrease seeded species establishment, they also did not lead to any increases over seeding alone.

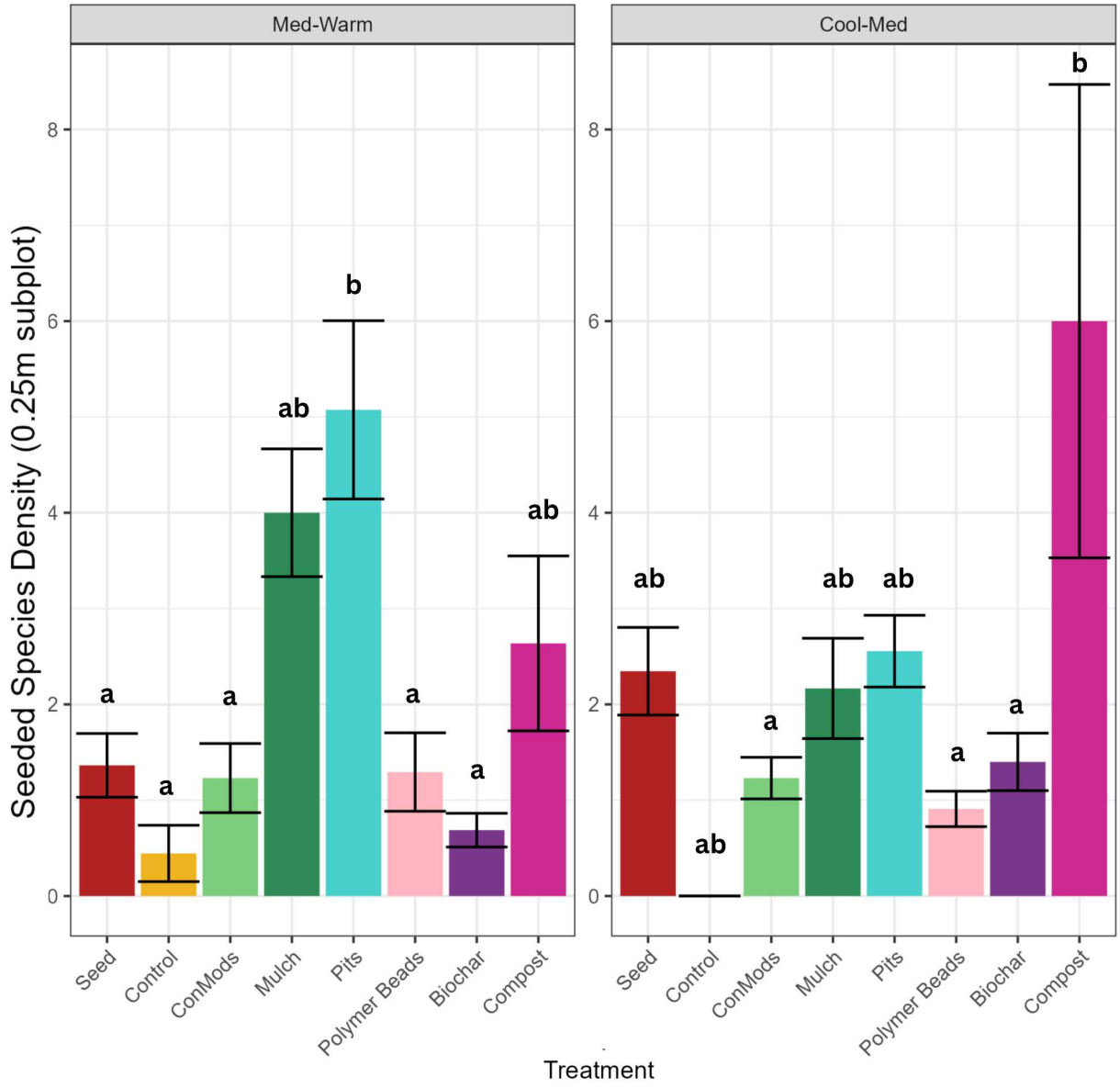


Figure 6. Comparison of seeded species density in the 0.25 m2 by treatment at SWCRC separated by climate adapted seed mix. Significance denoted by letters, with shared letters denoting no proven statistical difference and different letters denoting significant statistical difference ($p < 0.05$).

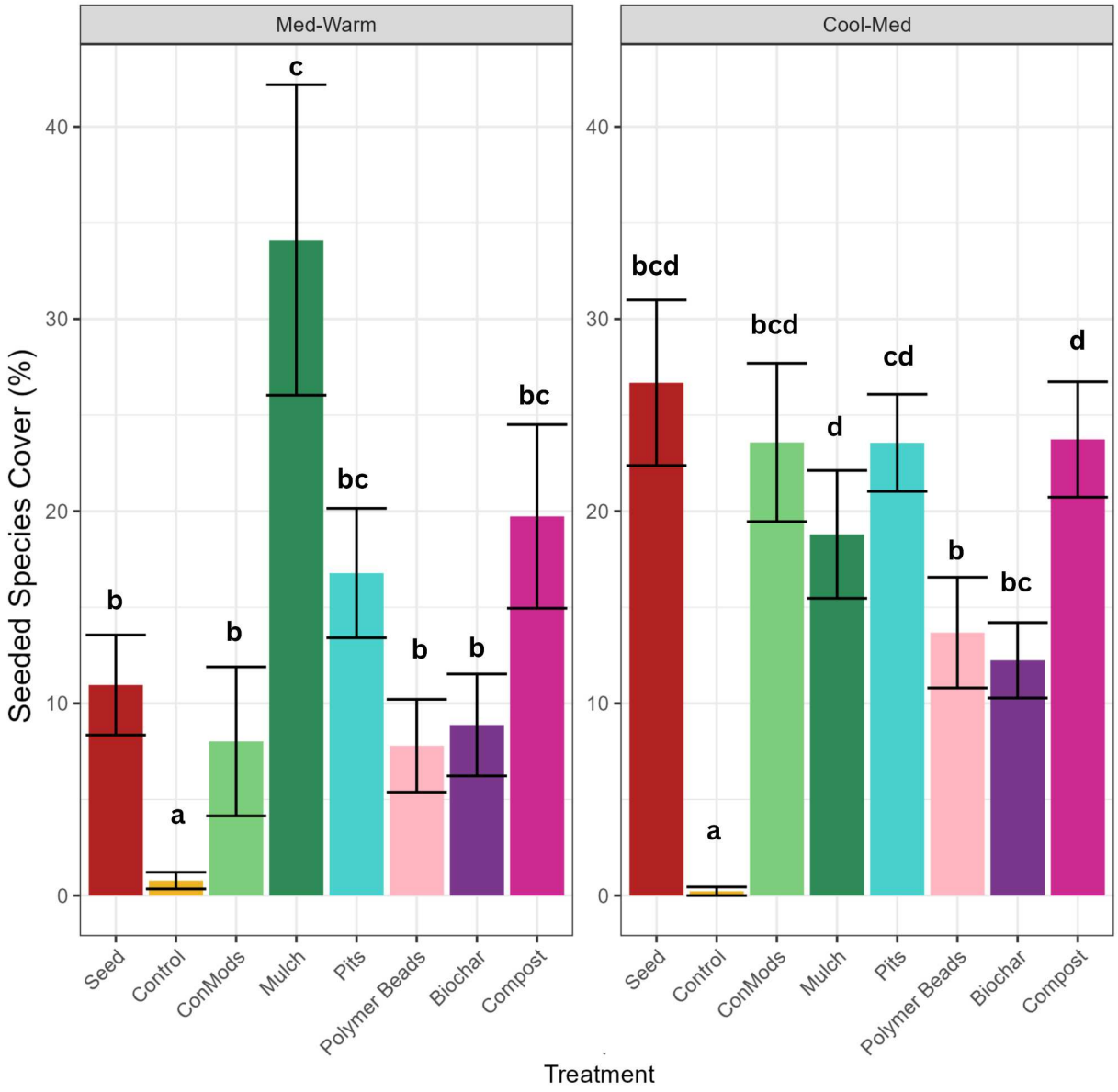


Figure 7. Comparison of seeded species percent cover in the full plot by treatment at SWCRC separated by climate adapted seed mix (warmer-adapted = Warm-Med, cooler-adapted = Cool-Med). Significance denoted by letters, with shared letters denoting no proven statistical difference and different letters denoting significant statistical difference ($p < 0.05$).

UMUT - No formal analysis could be conducted for UMUT due to the very low seeded species density (average 0% recruitment). Some slight differences between treatments were shown by averages, but these were not statistically significant (Figure S4). Pits resulted in the highest average seeded species cover (avg = 0.81%, sd = 1.60) and density (avg = 0.63, sd = 1.52).

Table 3. Average (avg) seeded cover and density as well as standard deviation for each treatment at the UMUT site.

UMUT Treatment Averages and SD

Treatment	Avg.Seeded.Density..count.	SD.Seeded.Density	Avg.Seeded.Cover....	SD.Seeded.Cover
Control	0.00	0.00	0.00	0.00
Seed	0.03	0.18	0.03	0.18
ConMods	0.06	0.25	0.23	0.43
Mulch	0.03	0.17	0.04	0.18
Pits	0.63	1.52	0.81	1.60
Polymer Beads	0.11	0.32	0.06	0.20
Tamarisk Mulch	0.24	0.66	0.52	1.39
Polymer Beads & Tamarisk Mulch	0.26	0.75	0.17	0.49

a)

b)

Figure 8. **a) Image of UMUT plots**. Growth in the image is primarily introduced non-native species *Salsola tragus* (Russian thistle) and *Eremopyrum triticeum* (annual wheatgrass) as well as unseeded native shrubs that were present at the area before plot installation. Image taken in September, 2023. **b) Image of SWCRC plots**. Growth in the image consists of planted species such as *Krascheninnikovia lanata* (winterfat), *Pascopyrum smithii* (western wheatgrass), *Achillea millefolium* (common yarrow),

and *Penstemon palmeri* (palmer's penstemon) as well as non-native introduced species such as Bromus tectorum (cheatgrass) and *Lactuca serriola* (prickly lettuce). Image taken in May, 2025.

4.5 DISCUSSION

Restoration of degraded drylands is critical for ecosystem health and biodiversity, global food security, and the protection of millions of human lives and livelihoods (UNCCD, 2024). To support learnings around dryland restoration, we tested precision restoration treatments across two climate-adapted seed mixes that varied by treatment provenance. These treatments aimed to address key limitations to seedling recruitment using the RestoreNet framework in southwestern Colorado at two dryland areas with differing characteristics and land use histories: a post-agricultural area (SWCRC) and a drier post-grazing area (UMUT). However, we were only able to statistically analyze data from the post-agricultural site, SWCRC, due to barriers to SBR being too high at UMUT. We found that both seed mixes resulted in significantly higher native seeded species cover and density than the unseeded control. The cooler-adapted seed mix resulted in significantly higher cover overall, while the warmer-adapted seed mix included the maximum seeded cover and density crossed with specific treatments (Q1). Further, we found that treatments selected by a regional network resulted in higher seeded species cover across full plots (though not density in the smaller 0.25 m^2 subplots) compared to local treatments overall (Q2). However, the effect of treatment provenance varied through time, with locally-chosen treatments initially resulting in higher seeded species cover, and network-chosen treatments having higher seeded cover in the fourth year. Within these treatments, mulch (network-

chosen) and pits (network-chosen) resulted in significantly higher seedling density or cover than the seeded control in the warmer-adapted seed mix, while only compost (locally-chosen) resulted in significantly greater seeded species cover than seeding only in the cooler-adapted mix (Q3). These results speak to the nuance of restoration practices, as not all restoration treatments were more effective than seeding alone at SWCRC, and despite some treatments increasing seeded species density and cover at one area, results from the UMUT area did not reflect the same trends. The highly limited recruitment at UMUT compared to SWCRC is likely due to higher barriers to restoration at the more arid area, and though these areas are geographically close to each other (~40 miles apart), they have very different restoration needs. Therefore, the results of this study demonstrate the need for highly precise and nuanced ecological restoration practice.

4.5.1 Species in the cooler-adapted seed mix established more cover and density overall, while species in the warmer-adapted mix established high cover and density in specific treatments

Seed mixes designed to be climate-adaptive can support the recruitment of more seeded species overall in SBR projects (Balazs et al., 2020; Briand et al., 2026; Good, 2025; Larson et al., 2023). After comparing seed mixes composed of species that are adapted to cooler arid climates (cooler-adapted) and warmer arid climates (warmer-adapted), we found that the cooler-adapted mix overall had significantly greater seedling establishment, seen in both cover and density on average at SWCRC. Both seed mixes resulted in higher seeded species cover and density than unseeded controls, demonstrating that not seeding this area did not result in a natural restoration of native species. Our

result that all seeding efforts increased native seeded species cover and density demonstrates that passive restoration (no human input) in this context may be less effective than active approaches (e.g., treatments, seeding), particularly on the plot scale. Previous work by Miguel et al. (2020c), found that passive restoration in dryland agricultural systems may result in some increased native plant establishment, but the outcome is more variable than active restoration and may result in minimal positive soil effects.

Though seeding both mixes led to increased seeded species cover and density compared to the unseeded control, the cooler-adapted mix resulted in a higher plot-wide cover of seeded species overall. The species included in the cooler-adapted mix may be particularly suited for this post-agricultural soil type and precipitation regime. Species observed during monitoring to be highly prolific were the grasses *Pascopyrum smithii* (Western wheatgrass) and *Elymus elymoides* (Squirrel-tail grass) as well as the forbs *Linum lewisii* (Blue flax) and *Achillea millefolium* (Common yarrow). The grasses were especially prolific, and *Pascopyrum smithii* (Western wheatgrass) was observed to be spreading outside of seeded plots across the area and into other plots due to its ability to reproduce rhizomatously (D. G. Ogle et al., 2009) (Figure S5). In contrast, species within the warmer-adapted species resulted in less overall cover and density but had very high cover and density in particular treatments, notably *Krascheninnikovia lanata* (winterfat) and *Poa secunda* (Sandberg bluegrass) in the mulch treatments (Figure S5). As time went on through the experiment, our research team noted that these two species began to spread throughout the study area, leading to these warmer-adapted species moving into the

cooler-adapted plots (Figure S5). Across the southwest United States, the climate is rapidly changing, growing warmer and decreasing in precipitation (MacDonald, 2010), which may change community compositions that are most favorable for the climate. Previous work within the RestoreNet framework has also found that cooler seed mixes had a higher density across treatments (Farrell et al., 2023), but similarly noted that warmer-adapted seed mixes may be more useful as predicted warming and drying futures occur (Seager et al., 2007).

Some nuance is introduced to the point that the warmer-adapted mix may not be establishing as well because of climatic conditions when we take into account that neither seed mix had high survival rates at UMUT. As UMUT is a warmer and drier climate than SWCRC, we might expect that the warmer-adapted mix would have a higher survival and establishment rate than the cooler-adapted mix if it was only climatically controlled. As neither of the mixes survived at UMUT, it may be either that the barriers to SBR for almost any species were too high for plant establishment or that many of the plants in the warmer-adapted mix are difficult to establish in the region overall.

4.5.2 Treatment provenance results suggest multi-scalar collaborative approaches to precision restoration

Precision restoration practices may require thoughtful consideration of scale and decision-making protocols, including the provenance of treatment decisions. Here, we compared how treatments chosen by county-scale land stewards differed in their resultant seeded species cover and density with treatments chosen by the regional-scale network. Our findings that locally-chosen treatments initially resulted in higher species cover in the first year, but were surpassed in the second

and fourth year by network-chosen treatments, demonstrate that collaboration, nuance, and multi-scalar decision-making may be important for positive restoration outcomes.

Both the regional network and the local land stewards made decisions and held insights that were invaluable to the establishment of native seeded species at the site. Though network-chosen treatments ultimately resulted in the highest cover of seeded species overall, the locally-chosen treatment compost increased native seeded species cover greatly, particularly in the first year (likely driving the first year treatment provenance results). Other work has shown that restoration efforts only led by scientists may be disconnected and not locally informed enough to be contextually applicable (Christensen, 2025). Community-based restoration (locally-led), on the other hand, has shown promise in increasing restoration buy-in and wider application (D. Brown & Gabrys, 2026). However, sometimes communities lack the resources or time to be plugged into wider restoration discourse. Precision restoration efforts may thrive best when there is collaborative decision-making that draws on researcher expertise but is community-led. Collaboration between researchers and community members that emphasizes local knowledge may lead to a more contextual framework for decision-making and therefore more SBR success (Toumbourou et al., 2025).

The significantly positive effect network-chosen treatments had on seeded species cover may demonstrate the possibility for these kinds of collaborative projects to lead to restoration success. RestoreNet is a highly collaborative, community-informed networked restoration trial, and the treatments the network chose were selected based on regional information and community-partner

discussions (Havrilla et al., 2020). Therefore, this regional networked study may have led to more favorable restoration outcomes because of its intertwinement of local and regional knowledge, instead of in spite of it. This finding suggests that precision restoration in dryland ecosystems in the southwestern United States may benefit from multi-scalar decision-making and intentional collaboration between applied practitioners and ecological researchers.

4.5.3 Treatments that target increasing moisture availability increase seeded species density and cover with variance across seed mix

Though treatment provenance and seed mix were shown to have effects, these findings are nuanced by differences between treatments. Compost, mulch, and pits were the treatments that increased seeded species density and cover compared to seeded controls. Biochar, polymer beads, and ConMods either significantly decreased species density and cover or were not statistically different from seeded controls. Both the treatments, which increased and significantly decreased seeded cover and density, aimed to mechanistically target water capture, moisture retention, and nutrient addition; however, half of these treatments were successful at promoting plant establishment, while the others were not. This result speaks to the importance of precision in how a specific treatment supports seedling access to water and nutrients in this ecological context and which species that seedling belongs to, as treatment effects vary by seed mix. In the cooler-adapted mix, compost treatments resulted in significantly higher seeded plant cover and density, but in the warmer-adapted seed mix, mulch resulted in significantly higher seeded cover, while pits resulted in significantly higher seeded species

density. Compost also showed some statistical signs of resulting in higher species density and cover in the warmer-adapted seed mix (as shown by CLD lettering) and therefore was the most effective across all treatments at increasing seeded establishment.

Elsewhere, particularly in cropping systems, compost has shown variable effects on soil health, water infiltration, and native plant establishment, in some dryland cases increasing restoration metrics like soil organic matter and native plant density, and in others not making a change in these metrics (Rayne & Aula, 2020; Singh & Burke, 2024). Here, compost was found to result in higher seeded species cover and density in our work, other dryland restoration studies have found that compost can dry-out quickly in arid environments, resulting in a thick, hydrophobic cover on the soil surface that decreases native species establishment (Alessi et al., 2023; Henry & Bergeron, 2005; Leger et al., 2022). Because of this variability in the literature, it may be important at this specific area and soil type to utilize a similar compost NPK nutrient ratio for the increased establishment that we observed as these nutrient ratios are critical in compost selection and performance (Alam et al., 2020). In a meta-analysis of the application of composts and similar organic amendments on arid rangelands, Graveur et al., (2019) found that on average these amendments increase plant productivity and soil health but that in some cases the increase in soil nutrients can cause runoff with too high a nitrate and phosphorus content and increase soil CO_2 emissions (Gravuer et al., 2019). Therefore, mindfulness of water runoff dynamics may be especially important for thinking about scaling up this treatment.

Though compost was most effective across all treatments, the other locally selected treatments (polymer beads and biochar) at SWCRC had no or negative effects compared to seeded controls. This may align with other work, as superabsorbent polymer beads in particular have been shown to have low success in supporting restoration treatments long-term, and this work adds to the body of knowledge cautioning their use in large-scale restoration (Garbowski et al., 2020). Further, biochar resulted in significantly less seeded species cover and density in the cooler-adapted mix and had no difference from the seeded control in the warmer-adapted mix. Biochar primarily adds carbon to the soil (Nogués et al., 2023; Phillips et al., 2020), while the compost we utilized was tested in a separate study and had a 1:1:2 ratio of NPK (nitrogen, phosphorus, and potassium) (Brueger, 2021). Theoretically, both biochar and compost work to improve water retention, and so the difference in their effect may be either due to their nutrient addition strategies or differences in the way they work to retain moisture (Henry & Bergeron, 2005; Razzaghi et al., 2020). That biochar was not as effective as compost suggests that macronutrient supplementation, rather than carbon addition alone, may have driven observed responses in these post-agricultural soils, which have grown thousands of annual plants that absorbed these nutrients, can be an effective addition. Further, drylands are often primarily nitrogen-limited, which may have driven the response to nitrogen addition but not carbon addition (R. F. Brown & Collins, 2024; Ramond et al., n.d.).

ConMods, a treatment selected by the regional network, also resulted in less seeded cover and density than other treatments. ConMods, or “connectivity modifiers” aim to act as a synthetic nurse

plant, increasing soil moisture and organic matter by capturing litter and plant debris which can protect the soil moisture from evaporation and add nutrients as the litter degrades (Young et al., 2025). However, here, ConMods resulted in almost three-times less seeded species cover than mulch in the warmer-adapted mix, and resulted in no significant difference from the seeded control across mixes.

In contrast to ConMods, the other network-selected treatments, mulch and pits, resulted in significantly higher seeded species cover or density in the warmer-adapted mix. Mulch aims to increase soil moisture retention, and also adds organic matter that is not yet decomposed and therefore is a less direct application of NPK (A. M. Leger et al., 2022). Pits work towards increasing water capture by retaining water that would have run-off of a flat soil surface, instead holding it in the basin the pit creates (Johnston & Mann, 2024). Other studies have found that pits may also decrease the competitive advantage of introduced species like the grass *Bromus tectorum* (cheatgrass), which was highly present at the site, where cheatgrass gets "trapped" in pits and decreases in seed viability and fitness weakening (Johnston & Mann, 2024). In the warmer-adapted mix, pits resulted in almost triple the seeded species density compared to seeded control, indicating that pitting created a more beneficial micro-site on the subplot level than other treatments. Across the 35 areas in the RestoreNet network, pits also have been found to increase seeded species cover and density more than other network-chosen treatments, demonstrating the regional benefit of this strategy (Havrilla et al., 2020). Mulch also resulted in higher seeded species density compared to the seeded control, but most notably, resulted in

the highest seeded species full plot cover than any other treatment in either seed mix (almost 3x more than seeded control).

The result that mulch increased establishment in species that are adapted to warmer climates may be important for practitioners thinking of using the species within the warmer-adapted mix like *Pleuraphis jamesii* (Galleta grass), *Krascheninnikovia lanata* (Winterfat), and *Penstemon palermi* (Palmer's penstemon), and *Poa secunda* (Sandberg bluegrass), all which were abundant at SWCRC (Figure S5). These species may be particularly suited to benefitting from mulch addition, as wood mulch can trap runoff and sediment and decrease the soil temperature as well as increase water retention (Luna et al., 2018; Wang et al., 2017). Seeds in the cooler-adapted seed mix didn't seem to get the same benefits from mulch, as there was not a significant difference in cover or seedling density between the seeded control and mulch.

Though compost, mulch, and pits improved seeded species cover and density compared to seeded controls at SWCRC, the lack of seeded species recruitment at the drier, post-grazing area (UMUT) demonstrates that these benefits were not substantial enough to overcome barriers to SBR without the precise climatic and biophysical contexts of the SWCRC area. The loamy soils that are present at SWCRC are likely able to hold water for longer than sandy loams at UMUT, due to loam having smaller particle sizes and more clay (Clark, 2022). The UMUT area also is almost 1.5x hotter on average than SWCRC (13.1°C compared to 8.8°C) and gets only half as much precipitation (17.91 cm compared to 37.82 cm), meaning that the barriers to seed establishment like heat and lack of moisture

are doubled at UMUT (PRISM Climate Group, Oregon State University, 2014). This is likely why we recorded almost no plant establishment from seed at UMUT and were not able to run statistical analyses. Further, a previously published analysis of the full network showed that precipitation in the weeks immediately following seeding was crucial to an area's overall establishment (Havrilla et al. 2020), and as at both of the areas studied here seeding happened during a period of drought, the lack of precipitation was likely a primary driver in the area's limited establishment, particularly at UMUT.

That mulch and compost significantly increased seeded species cover and density in these arid areas indicates that scaling up these treatments or testing them in tandem could be useful for larger dryland ecosystem restoration efforts. It is the establishment of native plants that increases wildlife and livestock forage value and biodiversity and has positive ripple effects on soil health and soil moisture. Therefore, leveraging our small-scale findings on a larger scale could have larger impacts.

From field observations and data trends, we saw that treatment differences may have been driven by a few key species. Importantly, 2025, the last year of our study, saw the most native seeded plant establishment, and though almost all of the treatments had greater amounts of plant establishment in the fourth year than other years, mulch was especially successful. When conducting data collection, we observed that in the fourth year, many of the *Krascheninnikovia lanata* (Winterfat, warmer-adapted) shrubs had grown to be quite large and starting to self-seed, with smaller seedlings emerging beneath their canopy. Further, several of the grasses including *Pascopyrum smithii* (Western wheatgrass, cooler-adapted), *Elymus elymoides* (Squirrel-tail grass, cooler-adapted), *Pleuraphis jamesii*

(Galleta grass, warmer-adapted), and *Poa secunda* (Sandberg's bluegrass, warmer-adapted) started to become so established that they were spreading into plots outside the ones they were planted in. The two plots with the highest seeded cover (85% and 90%) were in 2025 in warmer-adapted mulch plots, and the seeded species making up that cover were the shrub *Krascheninnikovia lanata* (Winterfat), grass *Poa secunda* (Sandberg bluegrass), and forb *Penstemon palermi* (Palmer's penstemon, warmer-adapted). Winterfat has a shorter-than-average viability window after planting (2 years), and as it seems to also particularly thrive in mulch, these large shrubs coupled with a well-established grass or forb could be the primary drivers of the data trends in species cover (Ogle et al., 2009). Winterfat is a good forage species, and its establishment with mulch could be highly useful for informing practice in the area (Schellenberg, 2005).

4.5.4 Study limitations

Our study results are limited by several factors that are critical to consider both as opportunities for further study and as variables in the interpretation of analyses. The exceptionally lowseeded species recruitment at the UMUT area is one of these, as comparisons of treatments between areas with different conditions were not able to be conducted. Further, treatments that resulted in higher seeded species cover and density at SWCRC did not have the same results at the nearby UMUT area, meaning that wider installation of restoration treatments that improved seeded plant establishment at SWCRC may only have similar outcomes when soil, land use history, and climatic conditions are similar to the SWCRC area. Further, the RestoreNet network is comprised of

sites across the Southwestern United States, which is a much larger scale than the research area specific local managers operate on, but is a very small area in the global context. Therefore, "network-chosen" treatments may be much more "local" than if they were chosen by a wider-spread network. This is critical to keep in mind in the discussion of treatment provenance and who may have expertise for local decision-making. Lastly, though we implied treatment mechanisms throughout our study, drawing from other literature, we did not measure characteristics that would prove these functions were being met. We did not take soil moisture or nutrient levels that would allow for a deeper comparison of how treatments were functioning in our context. This is an opportunity for future research.

4.5.5 Results highlight the need for precision restoration in drylands that combines local knowledge with restoration strategies that address key barriers to seedling recruitment

Dryland ecosystems and the people, plants, and animals whose lives are entwined with them face unique challenges of land degradation and increasing extremely variable temperature and precipitation. Therefore, understanding and aligning precision restoration strategies to local systems to increase ecosystem resilience, like climate-adaptive seed mix design (Barr et al., 2017) and the addition of restoration treatments (Morales-Márquez & Meloni, 2022), is critical to increasing success of restoration efforts in these important systems (Ahmed et al., 2022). RestoreNet is a networked study that tests restoration strategies across 35 areas in the Western United States, and data from two areas in Colorado was presented here. After testing Q1) how climate-adapted seed mixes and unseeded

controls, Q2) how treatment provenance, and Q3) restoration treatments themselves differed in their resultant seeded species cover and density, our findings both aligned with and varied from previous network-wide findings (presented in Farrell et al., 2023 and Havrilla et al., 2020). Notably, our study is the first to test the difference between locally-selected and regional network-selected treatments, adding to the body of work around community- and place-based restoration practice.

First, we found that not seeding resulted in almost no seeded native species cover or density, and that though the cooler-adapted mix resulted in higher seeded species cover overall, the warmer-adapted mix resulted in the maximum cover throughout the study when paired with the mulch treatment. The cooler-adapted mix has resulted in more cover and density than the warmer-adapted mix throughout the network, with our results confirming this finding on the singular research-area scale (Farrell et al., 2023). Second, that overall, regional network-selected treatments resulted in higher species cover than locally-selected treatments, but that there was nuance in this finding over time, with locally-selected treatments having a higher seeded cover in the first year. Lastly, though regionally-selected network treatments mulch and pits resulted in the max seeded species cover or density in the warmer-adapted mix, a finding that has been true across the 35 RestoreNet sites and seed mixes (Havrilla et al., 2020), the locally-chosen treatment compost resulted in the highest seeded species in the cooler-adapted mix.

These findings contribute to work around community-led precision dryland restoration. Particularly in our finding that both network and locally-selected treatments improved restoration

outcomes like seeded species cover and density the need for collaborative restoration, in which communities are supported by larger networks like extension and research programs to make decisions, but also lead restoration activities and are informed by their close knowledge of the ecosystems they live with is emphasized. Further, differences between the areas we studied and the larger network demonstrate that all restoration areas, even those nearby like our two areas were, have different needs depending on their specific barriers, contexts, and land-use histories. Future directions could be to compare locally-chosen and network-chosen restoration treatments on a network-wide scale, and to test restoration strategies that are potentially more suited to the barriers presented at UMUT to increase seeding success. This work offers guidance about community-based area-specific restoration, contextual results about potential treatments, seed mixes, and their effects on restoration outcomes, and future directions for practitioner implementation.

4.6 REFERENCES

Amari, K. N., Cueva, A., Blankinship, J. C., & Throop, H. L. (2026). Microbial and soil moisture responses to compost amendments and simulated rainfall pulses in degraded dryland soils. *Journal of Arid Environments*, *235*, 105625. https://doi.org/10.1016/j.jaridenv.2026.105625

Bai, W., Zhang, H., Liu, B., Wu, Y., & Song, J. (2010). Effects of super-absorbent polymers on the physical and chemical properties of soil following different wetting and drying cycles. *Soil Use and Management*, *26*(3), 253–260. https://doi.org/10.1111/j.1475-2743.2010.00271.x

Balazs, K. R., Kramer, A. T., Munson, S. M., Talkington, N., Still, S., & Butterfield, B. J. (2020). The right trait in the right place at the right time: Matching traits to environment improves restoration outcomes. *Ecological Applications*, *30*(4), e02110. https://doi.org/10.1002/eap.2110

Barr, S., Jonas, J. L., & Paschke, M. W. (2017). Optimizing seed mixture diversity and seeding rates for grassland restoration. *Restoration Ecology*, *25*(3), 396–404. https://doi.org/10.1111/rec.12445

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., & Herrick, J. E. (2015). Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment*, *13*(1), 28–36. https://doi.org/10.1890/140162

Biancari, L., Oñatibia, G. R., Le Bagousse-Pinguet, Y., Gross, N., Yahdjian, L., Aguiar, M. R., Saiz, H., Eldridge, D. J., Valencia, E., Moreira, X., Ochoa, V., Gozalo, B., Asensio, S., Plaza, C., Guirado, E., García-Gómez, M., Gaitán, J. J., Martínez-Valderrama, J., Mendoza, B. J., & Maestre, F. T. (2026). Plant diversity enhances ecosystem resistance to increasing grazing pressure in global drylands. *Nature Ecology & Evolution*, *10*(2), 258–266. https://doi.org/10.1038/s41559-025-02952-9

Briand, J. K., Hosler, S. C., Merchant, T. K., Vinebrooke, R. D., Ostertag, R., Symons, C. C., Cadotte, M. W., Eviner, V. T., Bracken, M. E. S., Carlson, R. R., Henn, J. J., Garbowski, M., Bauer, J. T., Luong, J. C., Atkinson, J., Hughes, A. R., Adams, C. R., Bates, A. E., Funk, J. L., … Green, S. J. (2026). Trait-based approaches to restoration ecology: Synthesizing insights from diverse systems. *Ecological Applications*, *36*(2), e70193. https://doi.org/10.1002/eap.70193

Brown, D., & Gabrys, J. (2026). Community-led landscape regeneration: A review of and framework for engagement in restoration initiatives. *Ambio*, *55*(2), 227–244. https://doi.org/10.1007/s13280-025-02236-3

Brown, R. F., & Collins, S. L. (2024). Revisiting the bucket model: Long-term effects of rainfall variability and nitrogen enrichment on net primary production in a desert grassland. *Journal of Ecology*, *112*(3), 629–641. https://doi.org/10.1111/1365-2745.14258

Clark, C. A. (n.d.). The important role of soil texture on water. *Crops and Soils*. Retrieved February 6, 2026, from https://cropsandsoils.extension.wisc.edu/articles/the-important-role-of-soil-texture-on-water/

Dregne, H. E. (2002). Land Degradation in the Drylands. *Arid Land Research and Management*, *16*(2), 99–132. https://doi.org/10.1080/153249802317304422

Farrell, H. L., Léger, A., Breed, M. F., & Gornish, E. S. (2020). Restoration, soil organisms, and soil processes: Emerging approaches. *Restoration Ecology*, *28*(S4), S307–S310. https://doi.org/10.1111/rec.13237

Farrell, H. L., Munson, S. M., Butterfield, B. J., Duniway, M. C., Faist, A. M., Gornish, E. S., Havrilla, C. A., Larios, L., Reed, S. C., Rowe, H. I., Laushman, K. M., & McCormick, M. L. (2023). Soil surface treatments and precipitation timing determine seedling development across southwestern US restoration sites. *Ecological Applications*, *33*(4), e2834. https://doi.org/10.1002/eap.2834

Garbowski, M., Brown, C. S., & Johnston, D. B. (2020). Soil amendment interacts with invasive grass and drought to uniquely influence aboveground versus belowground biomass in aridland restoration. *Restoration Ecology*, *28*(S1), A13–A23. https://doi.org/10.1111/rec.13083

Garbowski, M., Brown, C. S., Johnston, D. B., Hardegree, S. P., & Schipanski, M. E. (2016). *Restoring semi-arid lands with superabsorbent polymers under reduced precipitation and threat of Bromus tectorum invasion*. http://hdl.handle.net/10217/176790

Good, S. (2025). Maximizing Dryland Seed-Based Restoration Success Via Retrospective Analyses of Species-Use Patterns and Field Testing of Seed Mix Composition. *All Graduate Theses and Dissertations, Fall 2023 to Present*. https://doi.org/https://doi.org/10.26076/0e62-814f

Harms, R. S., & Hiebert, R. D. (2006). Vegetation Response Following Invasive Tamarisk (Tamarix spp.) Removal and Implications for Riparian Restoration. *Restoration Ecology*, *14*(3), 461–472. https://doi.org/10.1111/j.1526-100X.2006.00154.x

Havrilla, C. A., Munson, S. M., McCormick, M. L., Laushman, K. M., Balazs, K. R., & Butterfield, B. J. (2020). RestoreNet: An emerging restoration network reveals controls on seeding success across dryland ecosystems. *Journal of Applied Ecology*, *57*(11), 2191–2202. https://doi.org/10.1111/1365-2664.13715

Henry, C., & Bergeron, K. (2005). *Compost Use in Forest Land Restoration*.

Johnston, D. B., & Mann, R. K. (2024). Rangeland pitting for revegetation and annual weed control. *Rangelands*, *46*(1), 23–30. https://doi.org/10.1016/j.rala.2023.11.002

Larson, J. E., Agneray, A. C., Boyd, C. S., Bradford, J. B., Kildisheva, O. A., Suding, K. N., & Copeland, S. M. (2023). A recruitment niche framework for improving seed-based restoration. *Restoration Ecology*, *31*(7), e13959. https://doi.org/10.1111/rec.13959

Leger, A. M., Ball, K. R., Rathke, S. J., & Blankinship, J. C. (2022). Mulch more so than compost improves soil health to reestablish vegetation in a semiarid rangeland. *Restoration Ecology*, *30*(6), e13698. https://doi.org/10.1111/rec.13698

Luna, L., Vignozzi, N., Miralles, I., & Solé-Benet, A. (2018). Organic amendments and mulches modify soil porosity and infiltration in semiarid mine soils. *Land Degradation & Development*, *29*(4), 1019–1030. https://doi.org/10.1002/ldr.2830

MacDonald, G. M. (2010). Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences*, *107*(50), 21256–21262. https://doi.org/10.1073/pnas.0909651107

Miguel, M. F., Butterfield, H. S., & Lortie, C. J. (2020a). A meta-analysis contrasting active versus passive restoration practices in dryland agricultural ecosystems. *PeerJ*, *8*, e10428. https://doi.org/10.7717/peerj.10428

Miguel, M. F., Butterfield, H. S., & Lortie, C. J. (2020b). A meta-analysis contrasting active versus passive restoration practices in dryland agricultural ecosystems. *PeerJ*, *8*, e10428. https://doi.org/10.7717/peerj.10428

Miguel, M. F., Butterfield, H. S., & Lortie, C. J. (2020c). A meta-analysis contrasting active versus passive restoration practices in dryland agricultural ecosystems. *PeerJ*, *8*, e10428. https://doi.org/10.7717/peerj.10428

Morales-Márquez, J., & Meloni, F. (2022). Soil fauna and its potential use in the ecological restoration of dryland ecosystems. *Restoration Ecology*, *30*(6), e13686. https://doi.org/10.1111/rec.13686

Naupu, P. N., Wassenaar, T. D., Becker, R. W., & Kwembeya, E. (n.d.). Trait-based restoration in African dryland restoration projects: Overcoming systemic and scientific barriers for a viable future. *Restoration Ecology*, *n/a*(n/a), e70331. https://doi.org/10.1111/rec.70331

Nogués, I., Mazzurco Miritana, V., Passatore, L., Zacchini, M., Peruzzi, E., Carloni, S., Pietrini, F., Marabottini, R., Chiti, T., Massaccesi, L., & Marinari, S. (2023). Biochar soil amendment as

carbon farming practice in a Mediterranean environment. *Geoderma Regional*, *33*, e00634. https://doi.org/10.1016/j.geodrs.2023.e00634

Phillips, C. L., Meyer, K. M., & Trippe, K. M. (2020). Is biochar applied as surface mulch beneficial for grassland restoration? *Geoderma*, *375*, 114457. https://doi.org/10.1016/j.geoderma.2020.114457

Poisot, T., Cirtwill, A. R., Cazelles, K., Gravel, D., Fortin, M.-J., & Stouffer, D. B. (n.d.). *The structure of probabilistic networks*. Retrieved June 25, 2026, from https://besjournals.onlinelibrary.wiley.com/doi/10.1111/2041-210X.12468

Ramond, J.-B., Jordaan, K., Díez, B., Heinzelmann, S. M., & Cowan, D. A. (n.d.). Microbial Biogeochemical Cycling of Nitrogen in Arid Ecosystems. *Microbiology and Molecular Biology Reviews : MMBR*, *86*(2), e00109-21. https://doi.org/10.1128/mmbr.00109-21

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, 114055. https://doi.org/10.1016/j.geoderma.2019.114055

RestoreNet: Distributed Field Trial Network for Dryland Restoration | U.S. Geological Survey. (2024, November 20). https://www.usgs.gov/centers/southwest-biological-science-center/science/restorenet-distributed-field-trial-network

Reynolds, J. F., Maestre, F. T., Kemp, P. R., Stafford-Smith, D. M., & Lambin, E. (2007). Natural and Human Dimensions of Land Degradation in Drylands: Causes and Consequences. In J. G.

Canadell, D. E. Pataki, & L. F. Pitelka (Eds.), *Terrestrial Ecosystems in a Changing World* (pp. 247–257). Springer. https://doi.org/10.1007/978-3-540-32730-1_20

Schellenberg, M. P. (2005). *Comparison of production and nutritional value of two seed sources of winterfat*. http://hdl.handle.net/10388/etd-12012008-142726

Shackelford, N., Paterno, G. B., Winkler, D. E., Erickson, T. E., Leger, E. A., Svejcar, L. N., Breed, M. F., Faist, A. M., Harrison, P. A., Curran, M. F., Guo, Q., Kirmer, A., Law, D. J., Mganga, K. Z., Munson, S. M., Porensky, L. M., Quiroga, R. E., Török, P., Wainwright, C. E., ... Suding, K. L. (2021). Drivers of seedling establishment success in dryland restoration efforts. *Nature Ecology & Evolution*, *5*(9), 1283–1290. https://doi.org/10.1038/s41559-021-01510-3

Shafroth, P. B., Beauchamp, V. B., Briggs, M. K., Lair, K., Scott, M. L., & Sher, A. A. (2008). Planning Riparian Restoration in the Context of Tamarix Control in Western North America. *Restoration Ecology*, *16*(1), 97–112. https://doi.org/10.1111/j.1526-100X.2008.00360.x

Soil restoration increases soil health across global drylands: A meta-analysis—Kimmell—2023—Journal of Applied Ecology—Wiley Online Library. (n.d.). Retrieved December 11, 2025, from https://besjournals.onlinelibrary.wiley.com/doi/10.1111/1365-2664.14459

Stavi, I., Thevs, N., & Priori, S. (2021). Soil Salinity and Sodicity in Drylands: A Review of Causes, Effects, Monitoring, and Restoration Measures. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.712831

Sustainable restoration: Addressing critical challenges through university-led projects—Christensen—2025—Restoration Ecology—Wiley Online Library. (n.d.). Retrieved February 6, 2026, from https://onlinelibrary.wiley.com/doi/full/10.1111/rec.14337?casa_token=iE-8izFpilMAAAAA%3AJ-CcpCIStVP9Qs_gREfOq36KyjR1P5I6i212iGeImlfxnQI4RiSp-xTRtAmCdJL6Ee92V0O6ChOldINm

Toumbourou, T. D., Winarno, B., Yuwati, T. W., Lestari, S., Rachmanadi, D., Budiningsih, K., Sakuntaladewi, N., Idrus, N. I., Grover, S. P. P., Treby, S., & Rawluk, A. (2025). Collaboration for social-ecological restoration: Reflections from literature and practice. *Restoration Ecology*, *33*(3), e14355. https://doi.org/10.1111/rec.14355

Turk, T. G., Okin, G. S., & Faist, A. M. (2024). Connectivity measures across scales differentially influence dryland sediment and seed movement. *Restoration Ecology*, *32*(6), e14173. https://doi.org/10.1111/rec.14173

Yang, B., Balazs, K. R., Butterfield, B. J., Laushman, K. M., Munson, S. M., Gornish, E. S., & Barberán, A. (2022a). Does restoration of plant diversity trigger concomitant soil microbiome changes in dryland ecosystems? *Journal of Applied Ecology*, *59*(2), 560–573. https://doi.org/10.1111/1365-2664.14074

Yang, B., Balazs, K. R., Butterfield, B. J., Laushman, K. M., Munson, S. M., Gornish, E. S., & Barberán, A. (2022b). Does restoration of plant diversity trigger concomitant soil microbiome

changes in dryland ecosystems? *Journal of Applied Ecology*, *59*(2), 560–573. https://doi.org/10.1111/1365-2664.14074

Young, K. E., Edwards, B. L., Duniway, M. C., & Webb, N. (2025). Optimizing the effectiveness of connectivity modifiers to reduce dryland degradation. *Restoration Ecology*, *33*(6), e70055. https://doi.org/10.1111/rec.70055

Yu, J., Shi, J. G., Ma, X., Dang, P. F., Yan, Y. L., Mamedov, A. I., Shainberg, I., & Levy, G. J. (2017). Superabsorbent Polymer Properties and Concentration Effects on Water Retention under Drying Conditions. *Soil Science Society of America Journal*, *81*(4), 889–901. https://doi.org/10.2136/sssaj2016.07.0231

CHAPTER 5 - THE SEEDS OF GRIEF: PRINCIPLES FOR AN EMBODIED APPROACH TO ECOLOGICAL RESTORATION PRACTICE

5.1 INTRODUCTION

To plant a seed is an act of hope. Each year, with head bowed to the rich, cool spring soil, I press my fingertips into the dark clay and silt, leaving a circular imprint of myself that will become a mother for the seed I rest in there before pushing the Earth back over it, tamping the dirt down to blanket the hope of a new life. I dream of the lushness of summer, of the hummingbirds whirring overhead while the butterflies quietly bloom into dances from flower to flower, the smell of coming rain pressing in on the rippling heat. The dead sleep of winter shakes off, seed dreams come to pass in abundance. Listening to the land sing, something is healed within me. My hope in the spring is that by summer I will once again kneel to greet vibrant green leaves that have emerged like old friends, each leaf a lesson in dreaming of a loving, flourishing world.

Yet, for all the beauty that the land holds, there is also immense pain. The ceaseless, meaningless death of beings whose lives become transmuted through the psyche of capital extraction into objects for the taking leave deep grief in their wake. The consequence of this extractive logic is the climate crisis, with global surface temperatures rising approximately 2.0 ℃ since before industrialization of extraction from land and labor began in the 1900s (Rohde, 2026). This warming has led to an increased frequency and extremity of natural disasters that manifest in a myriad of other difficult realities. Activities like the clear-cutting of 70% of forests in North America by the 1920's (MacCleery, 1992), the drilling of four million oil and gas wells (Boston University Institute for Global Sustainability, 2023), and the subsequent adding of 2,000 billion metric tons of carbon dioxide (primarily from the burning of fossil fuels) into the atmosphere since mass industrialization (NOAA, 2016) have created these realities. Such statistics reveal a system of destruction, where plants, animals, water, minerals, soil, and people experience a pernicious extractivism[2] in a continuous onslaught of harm and degradation for capital. As all products and all wealth ultimately comes from the land, the industrialization of production has meant the systematic extraction of this wealth from living beings in ways that curtails their flourishing (Acosta, 2013; Gbobo, 2020; Mies, 1989).

[2] Extravictivism is defined as "a particular set of natural resource appropriations characterized by large volumes removed and/or [at] high intensity, where half or more are exported as raw materials, with no or limited industrial processing" (Gudynas, 2015, pg. 15) and "organizational logic of capital's enclosure and commodification of nature, making sacrifice zones out of communities' lands and the earthly commons on which all life depends" (Isla, 2025).

Economic systems, or the structures that dictate the flow of wealth and materials, systematize who gets wealth, where wealth comes from, and whose labor and what labor creates wealth, these structures are created by and to enforce systematized hierarchies (Inikori, 2020; Koshy et al., 2022; Mies, 2022). Take for example, oil drilling, where oil is the product that creates wealth through its sale. The soil, water, and plants that are disturbed and polluted by drilling are justified as necessary casualties (meaning, less valuable than the oil); the people who work at drilling sites are exposed to chemicals and have high rates of chronic health conditions, and are paid a maximum of $115,000 a year (National Institute of Health, 2026) while the CEOs of oil companies often make over $25 million annually (*DEF 14A*, 2025). Embedded here is the logic of hierarchy through which extractive economic systems operate. Nature (plants, animals, water, minerals) is treated as though it has less beinghood than people, and some people are treated as though they have less beinghood than those with power through constructed social categories of race, gender, class, ability, and sexuality. The logic of the capital production system justifies the extraction and objectification of the bodies on land, human and more-than-human alike, along with their labor (Ball University Center for Peace and Conflict Studies, 2013).

The roots of this kind of logic, as well as the subsequent industrialization process it engendered, are steeped in colonialism and settler colonialism. Colonialism is the process of violent assertion of power of one group of people over another with the "logic of domination" (Goff-Yates, 2000), while settler colonialism holds the "logic of elimination" (Wolfe, 2006) and is motivated by not

only the violent dispossession of land and subjugation of people, but of the settlement of Indigenous land and erasure of Indigenous peoples by settler groups (Rowe & Tuck, 2017). Further, settler colonialism is predicated on a violent hierarchy in which land is dispossessed from Indigenous peoples then extracted from through the forced and free labor of enslaved people (Inikori, 2020; Tuck & Yang, 2012). The settler colonial process often justifies itself through connection with religious ordination (such as in the case of Manifest Destiny), militarization, science, or other powerful institutions (Avalos, 2023; Morgensen, 2012). These institutional structures are then leveraged to systematize white supremacy culture, cis-heteropatriarchy, and division of humans and nature (Arvin et al., 2013; DiTomaso, 2024; Letiecq, 2024; Okun & Jones, 2001). By systematically dividing people and nature along socially constructed lines of race, gender, class, and human or not-human, the colonial project works to undermine interconnectedness and justify extraction of land and labor (Kitossa, 2000; Speed, 2017; Sze, 2018). It is this systematization that has led to the global climate crisis and a myriad of other horrific institutional harms to people's bodies and the land.

However, this logic of extraction and objectification is at odds with the hopes and dreams of our collective flourishing. We kneel to plant seeds in the Earth, tenderly tucking them into the soil, because we hope that the life contained within the seed will be so nurtured that it is inevitable that they will grow, stretching out from their shell, into something alive and beautiful that joins and connects with all the other beautiful living things. It is this hope of creating, flourishing, and healing that keeps us dipping our hands into the soil again and again. Mariame Kaba writes that , "hope is a

discipline." In keeping with Kaba's logic, I contend that it is also a lifeway, not an emotion but a practice that brings into fruition a world where beings are not placed into hierarchies but where beinghood itself is honored and the survival of one being does not mean the complete destruction of another (Kaba et al., 2021).

The practice of ecological restoration is rooted in this type of hope. To restore an ecosystem is to contribute to actions–planting seeds, adding soil nutrients, and changing water dynamics– which support an ecosystems' capacity to regain functioning of ecological processes and networks after degradation and disruption (Wickham et al., 2022). When ecosystems are damaged—whether by extreme weather linked to climate change, industrial extraction, overuse, or anything else that reduces their ability to support biodiversity, active human intervention can become necessary to help them recover within a timeframe that matters to/for people (Andel & Aronson, 2012). Restoration practitioners often try to guide ecosystems towards how they functioned historically with the goal of restoring to altered ecological processes so they resemble their states prior to degradation (Lamothe et al., 2019). More recently, however, practitioners have recognized that ecological restoration might involve a new kind of process, one where the functions are restored but perhaps the various beings that assemble that ecosystem may be different than those that were present prior to degradation (Clement et al., 2023).

To understand why large-scale land degradation happens through extractive systems as well as the varied ways that supporting the healing of land can be conceptualized, it becomes imperative to

address epistemology[3]. The belief and assumptions rooted in seemingly inviolable truths that shape how we know and interpret the world influence not just our ideas about land but also how those ideas turn into real-world practices. These underlying logics become embodied as material practice (ontology) and play a major role in how individuals, communities, and entire cultures see their relationship to land (Anderson, 1995).

As the practice of ecological restoration is fundamentally dedicated to supporting the healing of land, the epistemology from which this practice extends must disentangle itself from the colonial epistemology of domination, and separation, and erasure of beings that asserts hierarchies of beinghood. Various scholars have shown that mainstream U.S. culture is deeply shaped by colonial and settler colonial ways of thinking (Anderson, 1995; Rowe & Tuck, 2017; Whyte, 2018). This extractive worldview underlies many of the problems I have described, especially how industrial, extractive economies and their cultural logics create a particular and often harmful relationship to nature and land.

Here, I introduce the idea of embodied ecology by outlining key embodied principles of what Anibal Quijano calls "epistemic revolution," (Quijano, 2002). I suggest that applying these principles to ecological restoration can support both the envisioning and practice of ecosystem healing and the dismantling of systems of oppression that produce the damage . I contend that since the colonial and

[3] Epistemology is not a frequently used term within ecology, but rather here is called in from feminist thinkers and practitioners who insist that knowledge frameworks and creation need to be interrogated because knowledge is situated and contextualized (Haraway, 1988; Sprague, 2005).

settler colonial epistemologies embedded in ecological restoration and its cultural logics work to sever ties between land and people, a healing practice for the land and people cannot emerge from this epistemology. Rather, ecological restoration necessitates the assertion that plants, animals, minerals, water, and all organisms that make up ecosystems, including humans, deserve to be honored as fully existing beings in their own right. Ecological restoration that is motivated by a logic of domination loses its meaning. Restoring ecosystems just to enable more extraction once the "services" are completed merely facilitates further extraction and continues the cycle of exploitation and extractivism (Barra & Jessee, 2024; Whyte, 2017). For ecological restoration to be truly meaningful, it needs to be rooted in an epistemology of care for the well-being of all beings, not just humans, and must reject the extraction and objectification that comes from dominant, colonial and capitalist thinking.

Guided by the Cuerpo Territorio framework, I propose five principles by which ecological restoration practitioners can and do incorporate the material embodiment of revolutionary epistemologies into their practice towards a loving visioning of relationship to and the healing of land. I call this framework embodied ecology because though these principles begin in epistemology, they are realized in the bodies of people and land through healing and relationship.

5.2 CUERPO TERRITORIO FRAMEWORK

There are many epistemic and ontological frameworks that ecological restoration practice may incorporate. Cuerpo Territorio (or Territorio Cuerpo-Tierra, territory body-land) is one that is a

powerful articulation about the connection between degradation, devastation, and extraction from land and bodies along with the role of loving, feeling and resilience toward healing. Cuerpo Territorio is a movement and feeling that contains several assertions. First, in order to care for the land, for the territory, we must also care for women and girls. Second, that the body is the first territory (Cabnal, 2019). Lastly, cuerpo territorio asserts that "there is no ontological difference between territory and the body. Hence, what is done to the body is done to the territory and vice versa," (Zaragocin and Caretta, 2020). Born from community feminisms of Maya-Xinka Indigenous women from Abya Yala (Latin America), cuerpo territorio understands that all beings are intertwined and, therefore, that rights are not individual but collective. While the individual is a critical part of the collective, community feminists practicing cuerpo territorio show that structural forms of oppression create "disharmonization of the network of life." Harm done in one part of the network of life, such as sexual violence or the industrial extraction of minerals, is done to all parts of the network (Martínez and Agüero, 2023). The foundations of cuerpo territorio propose that land and bodies form the interconnectedness of life.

Cuerpo territorio has been formulated by the experiences with sexualized violence against Indigenous women in Abya Yala (Latin America). One important proponent of the cuerpo territorio framework, Maya-Xinka feminist Lorena Cabnal, explains that her thinking around the conceptualization came from her own and her community's fight against sexual violence perpetuated by the Guatamalan counterinsurgency agents. During this civil conflict over the theft and control of

Indigenous lands that included mass rapes of Indigenous women and girls, she asked a simple question: "if we defend the ancestral land, the land of all the struggle we have waged against colonialism, but also against the landowners...then we asked, 'why aren't women's bodies also defended as territory?' We are so protective over our land, but what about the bodies of girls and women?" (Cabnal, translated from CISCSA, 2019) . Cabnal and other community feminists in Abya Yala are also clear that although a different, powerful, and horrific wave of patriarchy was ushered in with colonialism starting in 1492, patriarchy existed and continues to exist in Indigenous societies (i.e. machismo) prior to colonization. Cuerpo territorio therefore exists as a proposal which is historically and politically contextualized by the ancestral and colonial violence that systems of oppression inflict on the bodies of people across lines of race, gender, and class as well as the body of the land and is aimed directly at healing both the people and the land.

Cuerpo territorio, though contextualized by harm, is at its core a proposition about healing through sentipensar (feeling-thinking), memory, epistemological and ontological shifting, and embodiment towards healing. In describing sentipensar and embodied feeling in cuerpo territorio, Martínez and Agüero suggest that "feeling constitutes a vital act of epistemic recovery in the body. To feel is to put the body into experience" (Martínez & Agüero, 2023). Cuerpo territorio proposes feeling and remembering both the experience of harm and the ancestral and current refusal against harm as well as the strength and wisdom of people that came before those who work to heal the ruptures in the network of life. Part of this refusal is to epistemologically and methodologically revolt from paradigms

outlined by patriarchy, which are mirrored even in organizations dedicated to the healing of land (Rodriguez Castro, 2021), toward feminist epistemologies and methodologies that are based in sentipensar and community repair.

A key technique of coloniality is forced disembodiment, or the fracturing of people from themselves and from the land in order to dispossess people of their land and extract labor from them (Mies, 1989; Favella, 2013.). Therefore, knowing through feeling (sentipensar) is a guiding knowledge of the remembering of the connection between land and bodies as is an epistemic revolt against colonial paradigms. Sentipensar calls in the spiritual, emotional, corporeal, and logical, embodying knowledge that is often overwritten by colonial logics that push for the extraction of land even as the feeling of witnessing the decimation of land is horrific. Sentipensar was popularized in academic literature by Orlando Fals Borda, a Columbian sociologist. Borda was taught about the experience of sentipensante by a Momposina fisherman in the Colombian San Jorge River in the 1980's (Fals Borda & Moncayo, 2009) but sentipensar has been known by peoples Indigenous to Abya Yala long before Borda's writing (López Intzín & Hernández, pg. 107-110). Sentipensar calls knowledge back to the body because it asserts that knowledge can be felt as much as it can be thought, and in fact, feeling and thinking are connected processes instead of separate ones.

Mapping feelings and land relations onto the body is one way that the cuerpo territorio movement methodologically engages with sentipensar . Body-mapping is a method outlined by Nohely Guzman et. al in their work with the Santa Ana de Museruna community in the Bolivian

Amazon in which women literally trace their bodies onto paper, then draw happinesses, violences, and different parts of the territories onto the silhouette of their bodies where they feel-think and remember them (Guzman, 2025). This mapping is not static, but rather a way to make explicit and to honor the connections between body and territory. In her piece, Guzman writes about Carmela's experience, a Momvina Indigenous woman whose community was being fractured by the building of a highway through her community's territory (Guzman, 2025b). Carmela describes how the extractive activities were violent both to the land and her body:

> "Loud and thunderous noises of machinery pounding the ground into the late hours of the night; seemingly endless clouds of dust raised by the constant truck traffic; odor emanating from stagnant waters in the long excavation areas associated with the construction work; and the increasing presence of foam in the river were all noted by Carmela. These, however, were not mere things happening in her community. On the contrary, they were felt in her constantly irritated eyes agitated by the dust; in frequent stomach aches; in tingling skin in fear and uncertainty about what the road might bring; and in an asphyxiating pressure in the chest out of sadness and concern for the increasing death of animals."

Carmela's knowing that the highway was violent was an embodied knowledge. She felt in the experiences of her body, her eyes burning and stomach aching, that the highway's construction was violent as much as she knew logically and spiritually that the ecological changes like the increasing presence of foam and the death of animals were extremely harmful. This is why sentipensar and cuerpo territorio are so critical, because to feel without separation of individual and community, human and ecological, is to know that the violence of extractivism is not the way towards healing. Instead, cuerpo

territorio moves towards a feeling-knowing that ontologically and methodologically implements intimacy, love, and a depth of listening that logics of domination aim to sterilize and dismiss, but which are critical for the true thriving of people and land.

5.3 MIGRATING CUERPO TERRITORIO

Cuerpo territorio was conceptualized in the specific context of communitarian feminism in Abya Yala and therefore the ways that the principles of practicing senti-pensar (feeling-thinking) of understanding and metabolizing the entangled experiences between bodies and land may arise and be practiced differently in a different context. My understandings as an author and practitioner are rooted in the North American context and are more particularly situated in the North American West alongside my practice as an advocate for survivors of sexual and domestic violence and a restoration ecologist. Cuerpo territorio cannot be responsibly applied by the North American context without first understanding the ways that the exploitation of the bodies of women, girls, and queer people have been violated and extracted from along with violation of and extraction from this land. In both what is now referred to as North and South America colonization, violence, and extraction have deeply scarred the land and people, yet the mechanisms and histories for each differ between these two land areas.

Colonial contact with the Abya Yala began with Columbus' invasion of Indigenous lands in 1492 after which the Spanish and Portuguese quickly began their horrific campaigns of violence and

extraction towards the land and people (Correia & Galeana, 2025). In Turtle Island (North America) colonists were primarily from England, France, Spain, and the Netherlands, and therefore the specific forms and legacies of settler colonialism between the two land masses were different based on the methods and logics of domination that different colonial societies embodied and imposed upon Indigenous peoples (Walker, 2012). In Abya Yala, Spanish and Portuguese colonizers aimed to violently enforce the labor of Indigenous peoples for extractive processes to produce gold, silver, and sugar, and forcibly assimilated Indigenous peoples into the Catholic church (Barreto & Lamport, 2025). Settlers in Abya Yala acted in many horrific ways, including using rape and femicide of Indigenous women as an tool for asserting control over reproduction and attempting to split people's souls from their bodies in order to dominate bodies and land (Temoney, 2021). While on Turtle Island, the English, French, Spanish, and Dutch wanted to transfigure the ancestral homelands of Indigenous peoples into new settler states, they also nefariously aimed to erase and replace Indigenous peoples through genocide, displacement, and brutality which the settlers used for claiming stolen territory as their new home (Rowe & Tuck, 2017). Both colonial contexts then kidnapped and enslaved African people to transform the land by forced labor to produce capital for the settler states to continue to assert and grow power with (Inikori, 2020).

These horrific acts like sexual violence, genital mutalation, forced sterilization, power-based physical, emotional, and financial abuse, slavery, human trafficking, femicide, and genocide all create a tremendous wounding of body and soul (Menakem, 2017; Messina-Dysert, 2012; Radford & Russel,

Diana E. H, 1992). The justification of perpetrating such an immensely devastating act against another person stems from logics of domination created by colonial institutions that categorize people's bodies by race, sex, gender, sexuality, class, and ability. It also creates false hierarchies by these categorizations that assert power of the pyramidal hierarchies' "elite" identities like white/European, cis, male, straight, rich, and able-bodied (Crenshaw, 1989.; Jagose, 1996; Mies, 1989). The systems that colonialism create like cis-heteropatriarchy (the oppression of women and queer people, (Arvin et al., 2013; Jagose, 1996) and white supremacy culture (the oppression of everyone this system considers to be "not white" such as Black, Latine, Indigenous, and Asian people along varying lines of race and colorism, (Amaya, 2024; DiTomaso, 2024)) are now seeped into many social and political institutions across the Americas and globally. These institutions enforce systematic oppressions, burrowing them into the bodies and minds of people through enacting violences which aim to assert their power and transmute the bodies of all beings into objects through victimization (Marya & Patel, 2021).

Colonial epistemologies and ontologies that perpetuate logics of domination in both Abya Yala and Turtle Island, weaponize these hierarchical systems to separate people from each other, themselves, and the land in order to extract wealth. These systems act to categorize people but they also assert that plants, animals, minerals, soil, water, and all other beings that are more-than-human are not beings but objects useful in the creation of capital (Mies, 1989; Whyte, 2018). As Marx states in Capital I, capital comes into this world "dripping from head to foot, from every pore, with blood and dirt", by which he means that capital is created in the economic structure of colonialism, which is

namely capitalism, through violent extraction from land and bodies (Marx et al., 1981). Colonialism first dispossesses land from Indigenous peoples, taking their territory, renaming and claiming the plants, animals, water, soil, and minerals as their own, then transforms land through forced or highly exploitative labor from workers, then consolidates capital at the top of the hierarchical system for the benefit of the wealthy few (Koshy et al., 2022). These systems are predicated on land degradation, and therefore have everything to do with healing of the land and people because these systems are the wounding.

Cuerpo territorio was created by Indigenous communitarian feminists who understand how the entanglements between land and body along with the link between land degradation and sexual violence occur in emotional, spiritual, and embodied ways. These systems of oppression, colonialism, cis-hetropatriarchy, and white supremacy culture, have not subsided but rather crash like waves, repeating themselves in different forms across scales and times as their perpetrators continue to embody them. The specific temporal context that cuerpo territorio was created within is post-colonial Latin America where the coupling of counterinsurgencies attempting to repress the people's rights (Granovsky-Larsen, 2023), and organized crime still are backed by colonial institutions and mentalities (Espinosa-Miñoso et al., 2022). These structures oppress communities like peasant farmers and Afro-descended and Indigenous peoples with institutional militarized violence and surveillance (Contreras, 2025). Women, queer people, and children's bodies have been at the center of victimization by this violence, with rates of femicide in places across Abya Yala like Honduras, El Salvador, and Guatemala

being some of the highest globally (G. M. Joseph & Grandin, 2010). At the same time, land degradation and economic extraction in Abya Yala is also perpetuated on a massive scale, with almost 60% of land across the continent being converted for agriculture, mining, or other economic activity and land grabs of Indigenous and peasant land from massive industry being all too common (Mollett, 2016; Zalles et al., 2021). As Katherine Esponda Contreras describes, "feminicidal violence [in Abya Yala] is neither accidental nor individual; it is a manifestation of the historical and structural denial of women's rights, particularly the rights of Indigenous, Afrodescendant, and women in conditions of poverty, within a Eurocentric economic-political system imposed in Latin America" (Contreras, 2025). Communitarian feminists practicing cuerpo territorio understand this connection between violence against women and violence against land and powerfully resist by working to create accountability, support networks, and economic systems to heal from coloniality.

Across Turtle Island, the perpetuation and institutionalization of colonialism and subsequent cis-heteropatriarchy and white supremacy culture have also created pernicious snarls between sexual violence against women, queer people, and children's bodies and land degradation. In her book, *The Beginning and End of Rape*, Sarah Deer, an Indigenous Rights activist, lawyer, and scholar, works through this entanglement as she writes about the ways that extractive industry like oil fracking is connected with the large-scale rape and trafficking of Indigenous women, a crisis that makes clear the lasting harms of coloniality, cis-heteropatriarchy, and capitalism. Deer describes that the oil fracking model relies on labor from non-Native (mostly white) men who are leaving their family for temporary

work in remote areas to live in "man camps" that are formed to provide the nonstop labor required to conduct fracking and that this work pays large sums of money (Deer, 2016). In the Bakken region of Montana and North Dakota, an area that has been extensively fracked and borders several Indigenous nations, the rise in fracking has led to a crisis of rape, assault, and violence on the bodies of Indigenous women. A 2019 study by the Journal of Justice Statistics found that since the 2006 oil boom in the Bakken region, "women experienced a 54% increase in the rate of unlawful sexual contact, which was due to a rise in reports of statutory rape," and another that "violent crimes in the area rose 121% (Horwitz, 2014), leading to rates of violence and sexual assault against Indigenous women tripling (Deer & Nagle, 2017; Grisafi, 2019)," (*Violence from Extractive Industry "Man Camps" Endangers Indigenous Women and Children | First Peoples Worldwide | University of Colorado Boulder*, n.d.; *Violent Victimization Known to Law Enforcement in the Bakken Oil-Producing Region of Montana and North Dakota, 2006-2012 | Office of Justice Programs*, n.d.). As Deer so poignantly says, "the crime that Native women are experiencing as a result of the exploding fracking business has parallels with harm being done to the planet – the land and water are being poisoned as the hearts and spirits of Native women break" (Deer, 2016).

Deer's articulation is at its center aligned with cuerpo territorio, as she demonstrates that objectification and extraction from the land comes from the same episteme as the objectification and assault of Indigenous women's bodies. To create and run a fracking operation is to strip a 5 acre area of any vegetation, to bring in hundreds of trucks, drills, and other machinery, to pump 4-million gallons

of water into the Earth per well, contaminating the water with the chemicals, sand, and waste of the fracking and be left inside the Earth's crust. Workers labor for 24/7 for months until as much of the oil that is reachable inside of the shale is extracted, and this system demands that workers somehow justify these harms (Hirsch et al., 2018; Meng, 2017). The companies extracting oil from the shale beds that are millions of years old promote the message that they are entitled to it and need it, and subsequently that the men working to do this extraction are entitled to use the bodies of women and queer people as things, not beings, even though the increase in sexual violence around fracking camps and the Missing and Murdered Indigenous Women crisis is widely known (Chase & Johnson, 2024; A. S. Joseph, 2021). Intertwined systems of harm like white supremacy and cis-heteropatriarchy train the men doing this work to justify the devastation and extraction of the land, and subsequently and concurrently, to justify the abuse and rape of Indigenous women and other marginalized peoples.

The ecology and land of what is now North America was completely altered by this violence. As Dr. Suzanne Pierre said, the "colonizers stole people, put those people to work on plantations, and completely transformed landscapes, completely transformed nutrient cycles because of that forced labor," (Alie Ward, 2022). Industrial agriculture is one of the main drivers of the climate crisis, and industrial agriculture in the U.S. started as plantation agriculture, which was a mechanism to brutalize and force labor, violence, and domination on enslaved Black people (Inikori, 2020; Lin et al., 2011). Plantation agriculture was established by white settlers after the forced removal and genocide campaign against Indigenous peoples who had stewarded and been in relationship with the land for

30,000 years before colonization (Arnaiz-Villena et al., 2010; Tuck & Yang, 2012; Whyte, 2018). White settlers then forced African people that they had brutally kidnapped to care for the land and make it produce as much as possible. As Omolade writes, Black women were also forced to have as many children as possible and appallingly objectified to "produce in excess" like the body of the land:

> "Black women's bodies were a primary means of accumulating the surplus...the fecundity of black women was key to the slave owner's goal. Gutman documents that one planter said, 'An owner's labor force doubled through natural increase every 15 years,'. 'Natural increase' meant that the black woman was encouraged and sometimes forced to have sex frequently in order to have babies" (Omolade,, 1995, p. 362-378).

The colonial epistemology and methodologies that American white men victimized Black women with mirrored those that Spanish and Portuguese settlers in Abya Yala victimized Native and Black women with, both with the aim of "accumulating in surplus" a labor force and capital. Tracing these histories makes it clear that though cuerpo territorio was conceptualized in the specific context of communitarian Indigenous feminists in Abya Yala, where they understand that territory and body are entangled through legacies and experiences of violence as much as they are in legacies and experiences of healing, connection, and love, which echoes through Turtle Island and globally. These legacies have shaped ecosystems and social structures, have both epistemologically and materially shifted the experience of being, and they therefore cannot be turned away from.

Scholars and practitioners Indigenous to Turtle Island have traced parallel legacies of violence to land and bodies to both identify the continued assault of coloniality that has led to crises of

gendered and sexualized harm and ecological degradation as well as to emphasize that Indigenous sovereignty and deconstruction of colonial paradigms are critical for healing. Potawatomi scholar Dr. Kyle Whyte verbalizes that "gender and sexual violence are ecological issues," because of the parallel roots of the two crises (Whyte, 2018). Dr. Robin Wall Kimmerer proposes that healing from these dual crises requires a shifting from the colonial economy of extraction towards an economy of gift, gratitude, and abundance, in which naming the world and relationships with other beings as a gift ripples into every exchange and interaction (R. W. Kimmerer & Burgoyne, 2024). By systematically uprooting the objectifying lens of extraction, both ecological healing and relational healing are possible.

However, current stastics make clear that crisis and ubiquity of sexual violence is a consequence of the long and entrenched histories of logics of domination throughout the establishment and upkeep of the colonial nation-state in both the United States and Latin America. In the United States, 81% of women, 78% of trans and non-binary people, and 43% of men experience sexual harassment or sexual assault in their lifetimes, and one in three women who experience rape were perpetrated against between the ages of 11-17 (Kearl, 2018; Middle, 2021). Across Latin America, rates of gender-based violence, rape, and femicide are similarly high, with as high as 42% of women experiencing physical or sexual abuse from their partners, and 1 in 4 women being married before the age of 18 (Casabonne et al., 2022).

Like Kimmerer and other scholars Indigenous to Turtle Island, the Indigenous women who conceptualize cuerpo territorio outline the wounding not only to make visible what colonial systems attempt to hide, but also to build constellations towards healing. For practitioners of ecological restoration, who work to support the healing of the land, who hope and dream planting seeds into the soil, these constellations which build out epistemologies that revolt against logics of domination are crucial to hold so close that they become embodied. Cuerpo territorio, Indigenous epistemologies, and histories of the connection between violence to bodies and violence to land, all outline that too often violence is normalized by systems of oppression which have forcibly rooted themselves into the bodies and soil of these lands. Therefore, supporting the healing of the land must actively and intentionally refuse colonial epistemologies and methodologies and instead honor the beinghood of all people as well as plants, animals, minerals, and water.

5.4 EMBODIED ECOLOGY

To heal after such harms as I have traced here requires an immense and loving hope, which flows between individuals and communities, reminding us of the depth of our intertwinement with all beings and the responsibility we have to love well. As cuerpo territorio asserts, there is no separation between the territory and the body, there is no separation between the individual and the network of life. Therefore, healing the land is intertwined with healing the community, and the epistemologies and ontologies that someone holds ripple from them into the network of life. My motivation for

articulating what it means to practice ecological restoration that embodies healing from land degradation is fundamentally tied to my hope for healing from systematic oppression, and ecological restoration is an epistemic revolt that supports how healing the land must include healing our communities, our bodies, and ourselves.

Here, I have asserted that the connection between crises of sexual and domestic violence and the crisis of anthropogenic climate change is a result of the colonial onslaught on love, intimacy, and relation. Sexual assault and domestic violence require that the perpetrator of these harms disregards the beinghood of the victim, as extractivism require that the perpetrators disregard the beinghood of plants, animals, and water. This objectification is predicated on a refusal of intimacy. Consensual sex and healthy relationships require both partners to honor each other through reading each other's bodies, talking through emotions, and uplifting spiritual connection. I contend that ecological healing requires a similar intimacy with the body of the land. A depth of noticing the responses to touch and action, a communicative and adaptive awareness of needs, and a spiritual honoring of importance and entanglement of all beings, is what embodied healing is predicated upon. Regaining intimacy and true love, the kind of love that bell hooks describes as "the will to nurture one's own and another's spiritual growth, through respect, responsibility, compassion, trust and truth-telling", is the path towards healing our collective wounding that has led to these pervasive cruelties (hooks, 2018).

I came to the work of ecological restoration and survivor advocacy through a feeling-thinking remembering of true love for the land and people I was surrounded by. Beginning when I was a little

girl in a white rural context in the Western United States, I watched as the body of the land and the bodies of the women, queer people, and girls around me were extracted from, harmed, and exploited for the capital and personal gain of men, boys, and industry. I felt and remembered, when my friends would weep in my lap, their hair in my hands, as they described the sexual violence that had been perpetrated on their bodies at such a young age, that this was a depth of wrong much older and more insidious than our time. I felt and remembered, watching the ditches burn, and the soil blow off the tops of the fields, and the horses with cracked hooves and matted hair be sold at the auction for glue and dog food, and the piglets that I bottle-fed be led to slaughter, that the entitlement the people around me thought that they had to the bodies of other beings was extreme violence. It was not until later, more woman than girl, that I understood the hot burning feeling in my stomach, the ragged ache of my lungs, and the tight plunging pain in my chest during these moments were connected through the experience of living under logics of domination. I feel, thought, and remember that these things are synonymous with disharmony of the network of living things.

Now, through my PhD work in dryland restoration ecology as well as 10-years of experience working in safehouses and on crisis lines for survivors of sexual and domestic violence, I have seen in my context and more broadly the epistemological guiding lights that bring healing closer as well as those which continue the cycle of violence. It is from these experiences, as well as my depth of familiarity and guidance from the frameworks and histories that I have discussed, that I offer five Embodied Ecology Principles. Guided by my learning about cuerpo territorio and other forms of

Indigenous, Black, and survivor-led environmental justice practice along with my practice as a survivor advocate and restoration ecologists, I have seen these principles as crucial to the practice of embodied ecological restoration. These are by no means fully comprehensive, nor did I come to this articulation alone but instead have been gently guided and taught. These principles are spirituality, abolition, relationality, accompaniment, and reflexivity.

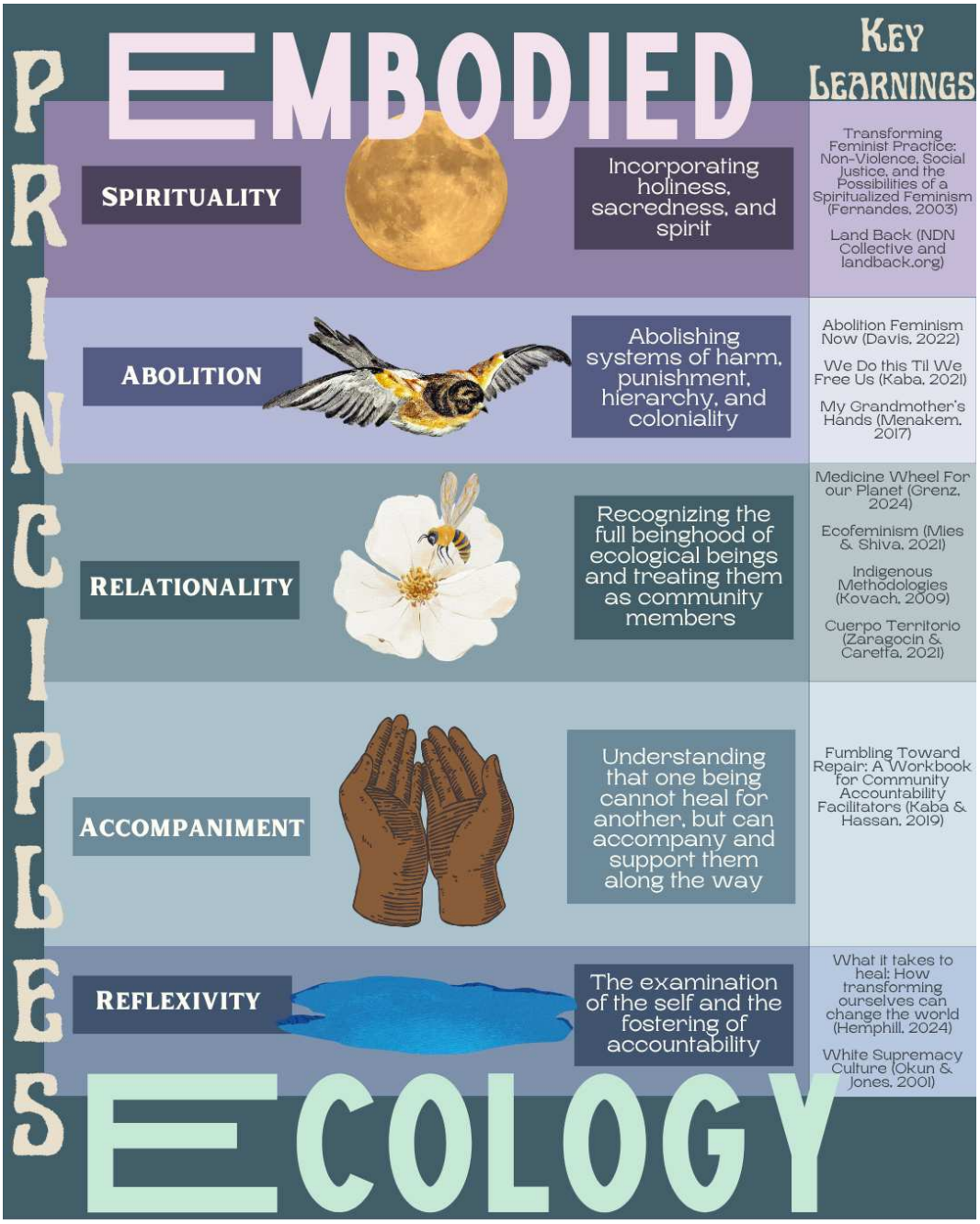


Figure 1. Conceptual framework of embodied ecology including the principle name, description, and key resources.

5.4.1 Spirituality

The connection between bodies and land is one of material, emotional, and spiritual entanglement. Through processes of colonialism and systems of oppression, all three of these things are targeted and fractured. Therefore, rebuilding and tending to spiritual connection to the land is a key pathway towards embodied healing. Writings on spiritual ecology have built out frameworks that can be learned from to embody this principle. Spiritual ecology is an assertion of intimacy with the land that is beyond material. Dr. Bayo Akomolafe has written extensively in this space, and contends that a way towards "sanctuary", or the building of coalition and new homes, from the disembodied anthropocene is to treat the "world as imbued with god" (*Making Sanctuary*, 2020). Akomolafe writes:

> "What would it look like to co-generate a politics that revisits the ordinary as if it were enchanted and surprising? What would it feel like to find god in the dirt under the fingernails of our playing children, or in the thick folds of the mundane? What would it take to come to the edges of the water, to the dense bodies of inhospitality that cannot be wished away with language and will, to the fields of hopelessness we often try to cover up with positive attitudes? What if rank cynicism were holy ground, and grief a sacrament of the mundane?" (Akomolafe, 2019)

Here, Akomolafe outlines that spirituality is not only intimacy in beauty, like in the hope and light of playing children, but in accepting the invitation to grieve for the death and destruction that has been wrought by coloniality and systems of harm. To accept that as Francis Weller writes, grief is a gateway towards loving more deeply, and towards honoring the entanglement that we as individuals have with every other being, is critical to the spiritual work of healing ecosystems (Weller, 2025). We must as restoration practitioners let the depth of grief that the land holds into our hearts and souls because to

grieve for another being is a practice of love. To touch the soil knowing that the land remembers the blood soaked into the soil, the injustices of centuries of murder, the bones of animals reclaimed by mycelial networks after fires and starvation, and to honor those lost to us with new life, hope, and love, that is the spiritual work of ecological restoration.

However, in naming spirituality, I must also acknowledge the way that colonialism has leveraged religion to cleave people from the land and each other. Colonial nations like the Spanish, English, and American used Catholicism and Christianity in particular to oppress and dismantle Indigenous and African peoples' religious and spiritual systems which were sources of connection and resistance (Paye, 2025). In North America, colonial nation-states stole Indigenous children and forced them into Federal Boarding Schools, these boarding schools were the site of atrocities and genocidal acts on children, and were often sponsored by Christian organizations to try to force assimilation of Indigenous peoples through "christianizing" them (Mann, 2016). Religion was and is frequently leveraged for colonial entities to justify colonialism, white supremacy, and cis-heteropatriarchy, even as religion's spiritual core can contain multitudes of beauty, through arguing that those privileged by these systems are divinely ordained or deserve these privileges because of God, and that all other people and nature are extractable or have less soul (Jones, 2021; Rowe & Tuck, 2017; Whitehead & Perry, 2019). However, in treating the "world as imbued with god", the spiritual must be an honoring of all beings and the entanglements between them, not preferentially along lines of systematic privilege.

Western science has historically aimed to be objective through removing emotional and spiritual elements of knowledge creation, while frequently also creating claims that support logics of domination. As ecological restoration practice is often informed by knowledge created by scientific fields like biology, ecology, and botany, the dismantling of epistemes that reinforce false hierarchies. Dr. Banu Subramaniam and colleagues sum this poignantly in saying; "colonial science was central to the shaping of human social differences– the hierarchies of gender, race, class, caste, sexuality, and nation. We must always challenge the naturalization and biologization of human differences," which is to say that these social hierarchies are not biological fact but socially constructed, and should be treated as such (Subramaniam, 2024). For example, during the early 1800s "phrenology" or using quantitative measures of skull shape as predictive of personality traits like intelligence was used to argue for the racial supremacy of Europeans and the enslavement of African peoples (Branson, 2017). For many scholars and activists who understand the entanglements between science and colonialism historicization and situating knowledges is imperative, as being clear about the context, perspective, and emotional connection of research instead of claiming objectivity is critical to making visible the powerful underpinnings of work (Jaggar, 2016; Sprague, 2005).

As the epistemologies, theoretical underpinnings, and methodologies of a practice are shaped by spiritual, emotional, and intellectual understandings, what we hold sacred is inherent to how we move through the world. As Dr. Leela Fernandes explains,"movements for social justice are sacred endeavors. Furthermore…if movements for social justice are to be fully transformative, they must be

based on an understanding of the connections between the spiritual and material realms," (Fernandes, 2003). Ecological restoration is a movement towards healing, and therefore is a movement towards justice. Planting seeds and interacting with the land is a sacred practice, and acknowledging and integrating that rather than pushing it away or separating it from the work is necessary to embodying healing ecologies. This work will look different depending on the particular individual and community context a practitioner or team is situated within. For Indigenous peoples, tending to spiritual connection may mean integrating practices of Traditional Ecological Knowledges, ceremonies, speaking Native languages, and practicing Indigenous epistemologies and methodologies into ecological restoration practice (R. Kimmerer, 2011; Robinson et al., 2021). For people with colonial heritage (e.g. white people), spirituality with the land may mean building a personal and community connection to land that does not appropriate from other cultures, but is open to being new or drawing from peoples Indigenous to Europe. Asking permissions from the land, making offerings that are personal, and utilizing methods which honor the full beinghood of more-than-human beings are good places to start. Further, spiritualizing ecological restoration and reaffirming land-based knowledges like those which Indigenous peoples have stewarded for centuries means reconnecting Indigenous peoples to their land through Land Back (landback.org).

Spiritual ecology, historicization of religion and science, and integration of the sacred, personal land connection practices, and decolonization are all critical to incorporating spirituality into ecological restoration practice. This work is heartfelt, hopeful, and sacred, and treating it with that

honor, letting this knowing seep into the way we practice, the way we are with each other, and what we fight for is a way to embody the connection between land and body. The spiritual is the constant link between cuerpo and territorio that through our grief and love, guides us back to ourselves and the land over and over again. This is why spirituality is the first principle of embodied ecology.

5.4.2 Abolition

Ecological restoration practices that work towards healing of land and people must believe in a future where colonialism and its logics of domination are abolished, composted, and made into fertile beginnings for logics of flourishing, intimacy, and community. Abolition of systematic structures which enforce coloniality and logics of domination is critical for this flourishing of all beings. Abolition ecology and the scholarship within it provides guidance towards this composting of harmful structures in relationship with land (Henyen & Ybarra, 2021). This scholarship denotes the linkages between colonialism and racial capitalism to unravel the ways that land dispossession and land extraction are connected by ownership, labor, and profit. Coloniality created racial capitalism, or the economic structure by which white supremacy and cis-heteropatriarchy dictate the flow of wealth towards those privileged by these systems (e.g. White, cis-heterosexual, male) and away from the land and labor of Black, Indigenous, Latine, and Asian people (Leong, 2013). This system reinforces coloniality and therefore, healing the land and decolonization are intertwined with the abolition of racial capitalism (Koshy et al., 2022).

Abolitionist scholar and practitioner Ruth Wilson Gillmore beautifully sums that "radical consciousness in action resolves into liberated lifeways," and therefore, that building and living revolutionary epistemes is the foundation for healing practice (Gilmore, 2017). In naming abolition as a key principle of embodied restoration ecology, my meaning is that learning about, believing in, and fighting for the deconstruction of systems of harm is critical to a liberatory restoration practice. As scholars Dr. Monica Patrice Barra and Dr. Nathan Jessee write, when restoration ecology does not move from revolutionary epistemes, there is a likelihood of reproducing systems of oppression instead of dismantling them:

> "When restoration is undertaken within institutional contexts that prioritize economic considerations—such as the preservation of corporate or private property interests above cultural survival—and when there is an over-reliance on- or privileging of western science over Indigenous sciences for environmental conservation and protection, the justification for ecological restoration and climate change adaptation gives rise to familiar forms of oppression, what Kyle Whyte (2016) referred to as a 'colonial deja vu'." (Barra & Jessee, 2024).

Therefore, restoration ecologies which reinforce racial capitalism, coloniality, and other forms of oppression through the privileging of these economic and knowledge structures only further the deepening of harms to the land and people. This is why restoration ecology which aims to be healing must move from a place that embodies abolition of systems of harm.

The abolition movement began during the fight to abolish slavery in the United States, but because the systems that created the mass enslavement of African peoples like white supremacy culture and racial capitalism are still perpetuating themselves, the movement has rippled outward into one

which works towards different worlds in which these systems are composted into abolitionist futures (Kaba et al., 2021). A key lesson from abolition work and scholarships for the practice of embodied restoration ecology is the concept of Transformative Justice, which Mia Mingus defines as "political framework and approach for responding to violence, harm and abuse. At its most basic, it seeks to respond to violence without creating more violence and/or engaging in harm reduction to lessen the violence," and that divests from institutionalized harm like those inflicted by widespread sexual and domestic violence and land degradation (Kaba & Hassan, 2019). As restoration ecology is often a responsive practice, which works to address harm after it has been done, we must consider what responding to this harm without replicating violence on the land or other people looks like.

Untangling what rooting in abolition and transformational justice may mean for ecological restoration practice is nuanced. For example, in my context working as a restoration practitioner in the U.S. West removal and restoration from large monoculture stands of the introduced grass *Bromus tectorum* (cheatgrass) is a key question tangled in layers of history and harm. This grass is native to Eurasia, and was brought to the rangelands of the western U.S. in grain and feed during the period of Westward Expansion, when colonists began their violent project of settling the western part of what is now the nation (Monsen, 1994). Now, cheatgrass has spread over millions of acres, and both increases risk of wildfire and lessens forage availability for livestock and wildlife as compared to native grasses (Alba et al., 2024a). However, herbicide and heavy machinery are often the most commonly prescribed methods of cheatgrass removal, and both of these mechanisms have complicated

entrenchments in corporate profit creation, land degradation, and secondary effects (Alba et al., 2024b; Bradbury et al., 2024; Lehnhoff et al., 2019). Simultaneously, these methods also create space for native species to thrive, and may lead to lessened harmful effects of cheatgrass. This is just one of the knotted and difficult problems that practitioners of ecological restoration face, and also speaks for the need to let embodied revolutionary epistemes be our guides towards healing practice.

These kinds of nuanced issues are not easy or clear questions, but rather contextualized by histories, structures of oppression, and emotional and spiritual connections. Fields of abolition, feminisms, and decoloniality all have confronted these kinds of knots for so long, moving through questions of working inside and outside of systems towards the sacred hope of thriving for all beings. It is not my intention to offer up universal solutions, but rather to reveal that ecological restoration cannot afford to look away from the difficult and must instead humbly ask for guidance and seek complicated and uncomfortable truths. For example, spraying herbicide to remove cheatgrass at one site is not just a singular action, but rather is contextualized by histories like the dispossession of Indigenous lands, the degradation of land through extraction, and the fueling of racial capitalism through economic structures. This does not mean that herbicide is always the wrong choice, but that honoring the depth of meaning and the connection between land and bodies embedded within ecological restoration requires a commitment to hoping for different ways and an active moving towards a world in which systems of oppression are dismantled by restorative actions instead of supported by them. This is what it means to embody abolition in ecological restoration.

5.4.3 Relationality

Relationality is a key principle in building from spiritual and emotional connection with more-than-human beings into practice. Relationality calls for a conceptualization of plants, soil, animals, and water as loved ones much like mothers, friends, and partners may be. Indigenous knowledge systems have practiced and embodied this conceptualization for millennia, and the articulation of relationality has flowed from Indigenous ontologies, cosmologies, and lifeways which teach that to be in relation with is to have responsibility to (Gould et al., 2023). Therefore, relationality is embodied by living out responsibilities and care to relations like animals, plants, minerals, and water, which may encompass ecological restoration, as if a loved one is hurt, it is the responsibility of their community to help them heal. The spiritual and the relational are braided, as the spiritual understanding of the full beinghood and sacredness of more-than-human beings ripples into the love of them and the responsibilities we have to them.

The deep and longstanding work of Indigenous ecologists, scholars, and practitioners have rippled into a "relational turn" in ecology and sustainability sciences (Gould et al., 2023; West et al., 2020). As coloniality has permeated western sciences, the assertion that animals, plants, and soil are loved ones deconstructs the sterility and objectification that can be embedded in ecological sciences. This deconstruction is referred to as the "relational turn", and is notably led by Indigenous and decolonial scholars who breathe a lovingly revolutionary episteme into their work and lives. As Nlaka'pamux scholar Dr. Jennifer Grenz writes, Indigenous ecology is relationality in practice:

> "Our ecology is not separate from acts of stewardship, but it is in fact, lived stewardship. Respect for the land and acts of reciprocity are not for the greater good, but a fulfillment of one's responsibilities within our role as balancers of our Earth Mother. Our stewardship is an act of love between relations for all relations, and it is not bound to definitive concepts of belongingness of species, nor to aesthetic concepts of nature. It is practical and it is respectful." - (Grenz, 2024)

This understanding of Indigenous ecology demonstrates that the relational turn in the practice of ecological restoration means a calling to love, intimacy, and spirit into practice.

Sentipensar and cuerpo territorio are also at their core relational ways of understanding the connection between land and bodies. Dr. Arturo Escobar, a Colombian-American anthropologist, poignantly identifies that "all entities that make up the world are so deeply interrelated that they have no intrinsic, separate existence by themselves," and that the epistemes of coloniality logic separations that are not there (Escobar, 2019). This connectedness is felt-thought in the body, as cuerpo-territorio understands. Beings are in relationship by their very existence, as the air humans breathe is the exhale of plant life and our own exhale is the inhale of the plants we are in relation with (Barber, 2008). Land degradation can be felt in our bodies because we are porous, relational beings, and so when extraction is happening within the spheres of our lives, our eyes and lungs are agitated by the dust and exhaust just as we may also grieve the loss of our loved trees, animals, and other relations (Guzmán, 2025b). This is the meaning of relationality within cuerpo territorio, which is understood through the thought-sense of sentipensar.

Learning from the generously shared knowledges of cuerpo territorio and other Indigenous conceptualizations, ecological restoration practice can incorporate relational epistemology and methodology. A relational and spiritual center motivates and guides abolitionist and responsible stewardship. For example, recent work in mixed methods restoration ecology research integrates qualitative and quantitative data to understand the socio-ecological connections of restoration sites before and throughout restoration (Land & Spencer, 2025; Talal & Santelmann, 2020). In mixed methods work by Land & Spencer in western Montana, interviews with community members who lived near a creek they were quantitatively studying, "specific knowledge of ephemeral springs, subtle long-term changes in the water table, and a sense of complex seasonal dynamics, like the creek drying up in 'August, or early September'" were understood only through integrating this qualitative dimension and added critical information to the process of restoration (Land & Spencer, 2025). Adding this contextual and relational knowledge created a deeper contextualization of the restorative practice, demonstrating that the relational is imperative in intimate restoration.

Other work has acknowledged that "weed" or introduced species management often uses terminology that is war-like, enforcing ideas of separation between "good" plants and "bad" plants, where relationality calls to a more nuanced understanding (Subramaniam, 2024). For example, Dr. Crystal Arnold's work with Aboriginal elders in Gundungurra (south-eastern New South Wales, Australia) describes the presence of weeds as "something worth noticing, be it disturbance, resilience, memory, or an unmet need for care," and describes that "they do not arrive alone; they carry stories of

colonisation, of survival, of scarred soils and interrupted cycles" (Arnold, 2026). When the mental framework around management is shifted to be relational, it is also contextual, spiritual, and historical, Arnold continues to describe this when they describe weed management as "not as a task of control, but as an opportunity to listen to Country, observing signs, patterns, and changes, and co-design actions that are context-specific and culturally informed," (Arnold, 2026). In this way, when ecological restoration honors and uplifts the relational, both in holding the beinghood of more-than-humans close in methods, and in taking the time to understand the relationships and knowledges that those who have relationships with a restoration site hold, there is much less room for restoration practice to reinforce systems of harm and instead space for regained flourishing and intimacy. As Indigenous ecologist Robin Wall Kimmerer writes, "action on behalf of life transforms. Because the relationship between self and the world is reciprocal, it is not a question of first getting enlightened or saved and then acting. As we work to heal the earth, the earth heals us," this is why ecological restoration is relational (Kimmerer, 2019).

5.4.4 Accompaniment

With these principles in mind, I propose that the role of the ecological restoration practitioner is one of accompaniment. Mariame Kaba, an abolitionist and community accountability facilitator, defines accompaniment as creating a space where survivors can be "held, believed, seen, cared for, and strengthened" (Kaba & Hassan, 2019). To accompany someone through a healing process is to witness the hurt, contribute healing practices, and to give the space and safety for the healing to occur. In my

practice supporting survivors of sexual and domestic violence, this may look like providing advocacy where survivors name the hurt, bearing witness to their stories, responding with care and affirmation, and finding resources like emergency shelter or financial support that might create time and space for healing. When we come to degraded ecosystems, the process may be similar, in that we identify the hurt and the histories and contexts of that hurt, contribute to tangible actions that might lead to repair like planting native seedlings and tending to them while they grow, and working towards the time and space for healing like excluding extractive activities from the restoration area. To accompany is to know that one being cannot heal for another, but rather to act in ways that create conditions for healing.

Because of this ethic, to accompany is to act like a loved one, not asserting domination or forcing one perceived "right" way of healing, but to instead be witness and steward. This takes a depth of listening and adjusting that if not followed, can have consequences that reinscribe harm. In the Southwest, where I work, a prime example of this is Tamarisk (*Tamarix sp.*) invasion. Tamarisk was introduced from Eurasia to control erosion of streambanks and stop sediment overload in the late 1800's (*Tamarisk | Rivrlab.Msi.Ucsb.Edu*, n.d.). However, the erosion was happening because all of the other vegetation was removed by industrial agriculture and other industrial ecosystem-based profit structures (Wheaton et al., 2019; Lin et al., 2011). Because the context was not considered and instead an assertion of what the ecosystem "should" be was enforced (agricultural fields with neat, contained soils along the streambank), tamarisk now covers 3.3 million acres in the Western U.S., where it

toxifies soil with salt exudates and pushes out native plant species (Shafroth et al., 2005). Instead of accompaniment, the settler land managers that introduced tamarisk employed arrogant logics of domination which resulted in more land degradation and loss.

Dr. Paul Farmer, a doctor who advocated for and practiced just and accessible healthcare, describes accompaniment as "to break bread together, to be present on a journey with a beginning and an end. There's an element of mystery, of openness, of trust," in which the lines between healer and patient, scientist and studied, are broken apart as colonial falsities and the beinghood of both participants is affirmed (Farmer, 2013, p.234). Accompaniment is solidarity and relationality in practice, because it affirms that the suffering of another being is your suffering, that the grief held in the soil from centuries of harm is not an abstract conceptualization of historical harm, but it is ours to attend to. It is allowing the reality of entanglement of all living beings to guide our practice, because the healing of an ecosystem is the healing of oneself, of one's community, and of repair towards a different way.

In ecological time, healing may be slow, and true accompaniment may mean responding to and honoring that slowness and staying the course. Where my family lives in western Montana, scars of a forest fire which blazed over 20 years ago still require careful attention by encouraging mycorrhizal growth through trimming dead branches and laying them across the forest floor, lessening the channeling of the river by adding rocks and logs to spread the water's braids, and the re-planting of native shrubs, grasses, and forbs. The accompaniment of this land through supporting the

revegetation and restoration of habitat for the bear, deer, and foxes that live on the same land as my family and our horses and dogs, is one of my life's greatest honors and purposes, my dearest teacher and most sacred place. It is this slowness that has unfurled a depth of intimacy which can often be precluded by the urgency of funding and project deadlines, but it is precisely this depth of intimacy that facilitates relationship and spiritual connection. Robin Wall Kimmerer writes "listening, standing witness, creates an openness to the world in which the boundaries between us can dissolve in a raindrop," (Kimmerer, 2019). This approach of slow, open, listening before responding to ecological restoration is what it means to accompany.

5.4.5 Reflexivity

As ecosystems respond to our actions, and our actions respond to ecosystems, it is critical within restorative practices to assess, respond, and adapt approaches as plants, animals, water, and soil change. This process is to be reflexive in one's practice, building an awareness of the ever changing topographies of emotional, spiritual, and material unfoldings through time. Reflexivity means to understand and respond to contexts, such as the specific ways that historical harm to an ecosystem was done by logics of domination, and the specific ways one's own social positioning, preconceived notions, educations, and emotions relate to that history. If we are to accompany ecosystems through a long journey of healing, supporting them while embodying our inseparability and that "them" is also "us", dreaming and practicing ways out of colonial legacies, and intertwining our very hearts and spirits with this work, there is a need for a critical awareness of context and response.

Drawing from feminist conceptualizations, scholars Federica Ravera, Maria Fernandez-Gimenez, and Elisa Oteros-Rozas propose that reflexivity in ecology research may be strengthened by understanding the subjectivity and relational positionality of the researcher/practitioner (Ravera et al., 2023). In describing their participation in and writing about reflexivity in community-based rangeland research, they describe that "subjectivity opens up the intimate relations of the researcher with the research, recognizing emotions, expectations, and desires about what and how to research. Positionality refers to our self-examination as researchers on how our social positions...may influence knowledge production" (Ravera et al., 2023). In the practice of restoration ecology, these themes of examining subjectivity and relational positioning also strengthen reflexivity and deepen the attunement one can have to other beings and the land.

Donna Haraway explains the importance of reflexivity and laying bare subjectivity and relational positioning through elucidating "situated knowledges", which demonstrates that a person understands and interprets the world through the lenses of themselves. Haraway notes, "vision is always a question of the power to see – and perhaps of the violence implicit in our visualizing practices. With whose blood were my eyes crafted?" (Haraway, 1988, pg. 584). As socially constructed structures like white supremacy culture and cis-heteropatriarchy inhabit institutions, epistemes, and ontologies, locating ourselves in relation to these structures, the way we are privileged or marginalized by them makes clear the ways they may inhabit our ways of thinking and being. Situating ourselves

over and over again in our web of relationships, internal and external responses, and changes creates clarity and a comfort in the unknown and ever unfolding that is critical to accompaniment of healing.

Ecologists and practitioners have outlined what reflexivity might look like in the context of ecological practice. Jasper Montana and co-authors summarize these attributes of reflexivity in ecological science, including developing a "mindset that is inquisitive, humble, brave, and open to uncertainty", writing a "journal to build self-awareness and engage in learning, providing space to think about one's assumptions, ways of acting and ways of being", and "being willing to ask difficult questions of [oneself] and others and sit with tension, disagreement, and discomfort when necessary" (Montana et al., 2020). By practicing reflexivity that is critical of systems of power and logics of domination as much as it is responsive to the ways that plants are growing, how water dynamics are changing over a landscape, and which animals have returned or gone, and the way our hearts, souls, and minds are moved by these things, the development of a truly responsive ecological restoration practice is developed. This is why reflexivity is a core principle of embodied ecological restoration.

5.5 CONCLUSION

Logics of domination systematically permeate the United States, Latin America, and globally to transmute beings into objects for the extraction and exploitation of land and bodies. This results in the dual crises of ecological degradation and sexual and gender-based violence as well as many other institutionalized harms. Practitioners and scholars of ecological restoration work towards the healing

of land, but healing the land necessitates an epistemic and ontological revolt from colonial epistemes. Here, guided by frameworks of cuerpo territorio which demonstrate the connection between bodies and land, as well as substantiating histories of entanglements of violence in Turtle Island and Abya Yala, I propose five principles which may inform embodied approaches to ecological healing. Through fostering epistemic, ontological, and methodological spirituality, abolition, relationality, accompaniment, and reflexivity into the practice of ecological restoration, practitioners may open pathways towards true healing instead of continuing rupture. These principles are not all encompassing, but rather an invitation towards intimacy, love, and relationship that is barred by extractive and objectifying frameworks. To love the land and each other well is the greatest and most powerful gift, and it is my hope that in this writing, those who love can feel seen, and those who want to love can feel called into the beautiful unfurling of closeness with themselves, plants, animals, water, minerals, human communities, and the land.

5.6 REFERENCES

Alba, C., DePrenger-Levin, M., & Hufft, R. (2024a). Incorporation of Indaziflam into Natural Areas Management of Cheatgrass and Other Short-Lived Invasive Species: Post-Fire Assessment in a

Semi-Arid Colorado Grassland. *Natural Areas Journal*, *44*(1), 9–20. https://doi.org/10.3375/2162-4399-44.1.9

Alba, C., DePrenger-Levin, M., & Hufft, R. (2024b). Incorporation of Indaziflam into Natural Areas Management of Cheatgrass and Other Short-Lived Invasive Species: Post-Fire Assessment in a Semi-Arid Colorado Grassland. *Natural Areas Journal*, *44*(1), 9–20. https://doi.org/10.3375/2162-4399-44.1.9

Amaya, H. (2024). White supremacy, settler angst, and Latine immigration to the US. *Latin American and Caribbean Ethnic Studies*, *19*(4), 441–458. https://doi.org/10.1080/17442222.2024.2309863

Andel, J. van, & Aronson, J. (2012). *Restoration Ecology: The New Frontier*. John Wiley & Sons.

Anderson, E. (1995). Feminist Epistemology: An Interpretation and a Defense. *Hypatia*, *10*(3), 50–84. https://doi.org/10.1111/j.1527-2001.1995.tb00737.x

Arnold, C. (2026). From invasive to opportunity: Indigenous insights in balance, soil health and weed management. *Ambio*, *55*(6), 1372–1384. https://doi.org/10.1007/s13280-025-02308-4

Arvin, M., Tuck, E., & Morrill, A. (2013). Decolonizing Feminism: Challenging Connections between Settler Colonialism and Heteropatriarchy. *Feminist Formations*, *25*(1), 8–34. https://doi.org/10.1353/ff.2013.0006

Avalos, N. (2023). Indigenous Stewardship: Religious Praxis and "Unsettling" Settler Ecologies. *Political Theology*, *24*(7), 614–631. https://doi.org/10.1080/1462317X.2023.2212473

Ball University Center for Peace and Conflict Studies. (2013, November 15). Logic of Domination. *The Olive Branch*. https://www.bsu.edu/-/media/www/departmentalcontent/peacecenter/newsletters-2013-to-2014/newsletter2013-november-15november-21.pdf

Barber, J. (2008). Photosynthetic generation of oxygen. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1504), 2665–2674. https://doi.org/10.1098/rstb.2008.0047

Barra, M. P., & Jessee, N. (2024). Restoration as Transformative Reparative Practice: Traditional Knowledges, Indigenous and Black Land Stewardship, and Solidarity. *Environment and Society*, *15*(1), 212–233. https://doi.org/10.3167/ares.2024.150111

Barreto, R., & Lamport, M. A. (2025). *Engaging Coloniality: The Liberative Story of Christianity in Latin America*. Wipf and Stock Publishers.

Bradbury, E. S., Holland-Moritz, H., Gill, A., & Havrilla, C. A. (2024). Plant and soil microbial composition legacies following indaziflam herbicide treatment. *Frontiers in Microbiology*, *15*, 1450633. https://doi.org/10.3389/fmicb.2024.1450633

Chase, M., & Johnson, A. (2024). Oil extraction and Indigenous women: Examining the necropolitics of the settler state in the Bakken region. *Human Geography*, *17*(1), 28–42. https://doi.org/10.1177/19427786231190426

Clement, S., Standish, R. J., & Kennedy, P. L. (2023). Expert preferences on options for biodiversity conservation under climate change. *Global Environmental Change*, *83*, 102759. https://doi.org/10.1016/j.gloenvcha.2023.102759

Crenshaw, K. (n.d.). *Demarginalizing the Intersection of Race and Sex: A Black Feminist Critique of Antidiscrimination Doctrine, Feminist Theory and Antiracist Politics*.

DEF 14A. (n.d.). Retrieved April 27, 2026, from https://www.sec.gov/Archives/edgar/data/93410/000119312522098301/d292137ddef14a.htm#toc292137_50

DiTomaso, N. (2024). The invention of race and the persistence of racial hierarchy: White privilege, White supremacy, and White colorblindness. *Social and Personality Psychology Compass*, *18*(4), e12953. https://doi.org/10.1111/spc3.12953

Escobar, A. (2019). Thinking-Feeling with the Earth: Territorial Struggles and the Ontological Dimension of the Epistemologies of the South. In *Knowledges Born in the Struggle*. Routledge.

Espinosa-Miñoso, Y., Lugones, M., & Maldonado-Torres, N. (2022). *Decolonial Feminism in Abya Yala: Caribbean, Meso, and South American Contributions and Challenges*. Bloomsbury Publishing USA.

Fals Borda, O., & Moncayo, V. M. (2009). *Una sociología sentipensante para América Latina*. Siglo del hombre ed. Clacso.

Fernandes, L. (2003). *Transforming feminist practice: Non-violence, social justice, and the possibilities of a spiritualized feminism* (1st ed). Aunt Lute Books.

Full article: Anti-colonial environmental justice in, of, and from Abya Yala: An introduction. (n.d.). Retrieved May 15, 2026, from https://www.tandfonline.com/doi/full/10.1080/17442222.2025.2518709#d1e358

Gbobo, P. (2020). *Women and the environment in Nigeria: The experience of women of the Niger Delta* (pp. 185–197). https://doi.org/10.18820/9781928480570/13

Goff-Yates, A. L. (2000). Karen Warren and the Logic of Domination: A Defense. *Environmental Ethics*, *22*(2), 169–181. https://doi.org/10.5840/enviroethics200022233

Gould, R. K., Martinez, D. E., & Hoelting, K. R. (2023). Exploring Indigenous relationality to inform the relational turn in sustainability science. *Ecosystems and People*, *19*(1), 2229452. https://doi.org/10.1080/26395916.2023.2229452

Granovsky-Larsen, S. (2023). "The Situation Will Most Likely Turn Ugly": Corporate Counter-Insurgency and Sexual Violence at a Canadian-Owned Mine in Guatemala. *Norteamérica*, *18*(1), 319–354. https://doi.org/10.22201/cisan.24487228e.2023.1.621

Grenz, J. (2024). *Medicine wheel for the planet: A journey toward personal and ecological healing* (First University of Minnesota Press edition). University of Minnesota Press.

Guzmán, N. (2025a). Cuerpo-Territorio and Indigenous Geographies Otherwise. In *The Wiley Blackwell Companion to Cultural and Social Geography* (pp. 217–232). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119634294.ch18

Guzmán, N. (2025b). 'Esta carretera nos atraviesa': Roadbuilding and mapping the cuerpo-territorio of Amazonian Indigenous girls in Bolivia. *Gender, Place & Culture*, *32*(3), 389–412. https://doi.org/10.1080/0966369X.2024.2338391

Haraway, D. (1988). Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective. *Feminist Studies*, *14*(3), 575. https://doi.org/10.2307/3178066

hooks, bell. (2018). *All about love: New visions* (First William Morrow paperback edition). William Morrow.

Hydraulic Fracturing and Health. (n.d.). National Institute of Environmental Health Sciences. Retrieved April 27, 2026, from https://www.niehs.nih.gov/health/topics/agents/fracking

Inikori, J. E. (2020). Atlantic Slavery and the Rise of the Capitalist Global Economy. *Current Anthropology*, *61*(S22), S159–S171. https://doi.org/10.1086/709818

Jaggar, A. M. (Ed.). (2016). *Just methods: An interdisciplinary feminist reader* (Second edition). Routledge. https://doi.org/10.4324/9781315636344

Jagose, A. (1996). *Queer Theory: An Introduction*. NYU Press.

Johnson, G. T., & Lubin, A. (Eds.). (2017). *Futures of Black radicalism*. Verso.

Jones, R. P. (2021). *White Too Long: The Legacy of White Supremacy in American Christianity*. Simon and Schuster.

Joseph, A. S. (2021). A Modern Trail of Tears: The Missing and Murdered Indigenous Women (MMIW) Crisis in the US. *Journal of Forensic and Legal Medicine*, *79*, 102136. https://doi.org/10.1016/j.jflm.2021.102136

Joseph, G. M., & Grandin, G. (2010). *A Century of Revolution: Insurgent and Counterinsurgent Violence during Latin America's Long Cold War*. Duke University Press.

Kaba, M., & Hassan, S. (2019). *Fumbling towards repair: A workbook for community accountability facilitators*. Project NIA : Just Practice.

Kaba, M., Nopper, T. K., & Murakawa, N. (2021). *We do this 'til we free us: Abolitionist organizing and transforming justice*. Haymarket Books.

Kimmerer, R. (2011). Restoration and Reciprocity: The Contributions of Traditional Ecological Knowledge. In D. Egan, E. E. Hjerpe, & J. Abrams (Eds.), *Human Dimensions of Ecological Restoration: Integrating Science, Nature, and Culture* (pp. 257–276). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-039-2_18

Kimmerer, R. W., & Burgoyne, J. (2024). *The serviceberry: Abundance and reciprocity in the natural world* (First Scribner hardcover edition). Scribner.

Kitossa, T. (2000). *Same difference: Biocentric imperialism and the assault on indigenous culture and hunting*. *28*, 23–36.

Koshy, S., Cacho, L. M., Byrd, J. A., & Jefferson, B. J. (2022). *Colonial Racial Capitalism*. Duke University Press.

Lamothe, K. A., Somers, K. M., & Jackson, D. A. (2019). Linking the ball-and-cup analogy and ordination trajectories to describe ecosystem stability, resistance, and resilience. *Ecosphere*, *10*(3), e02629. https://doi.org/10.1002/ecs2.2629

Land, S. R., & Spencer, D. T. (2025). Re-storying Grant Creek: Relational restoration on a degraded Montana Stream. *Ecosystems and People*, *21*(1), 2502472. https://doi.org/10.1080/26395916.2025.2502472

Lehnhoff, E. A., Rew, L. J., Mangold, J. M., Seipel, T., & Ragen, D. (2019). Integrated Management of Cheatgrass (Bromus tectorum) with Sheep Grazing and Herbicide. *Agronomy*, *9*(6), 315. https://doi.org/10.3390/agronomy9060315

Leong, N. (2013, June 20). Racial Capitalism. *Harvard Law Review*. https://harvardlawreview.org/print/vol-126/racial-capitalism/

Letiecq, B. L. (2024). Theorizing White heteropatriarchal supremacy, marriage fundamentalism, and the mechanisms that maintain family inequality. *Journal of Marriage and Family*, *86*(5), 1184–1204. https://doi.org/10.1111/jomf.12971

Making Sanctuary: Hope, Companionship, Race and Emergence in the Anthropocene • Writings – Bayo Akomolafe. (n.d.). Retrieved May 26, 2026, from

https://www.bayoakomolafe.net/post/making-sanctuary-hope-companionship-race-and-emergence-in-the-anthropocene

Mann, B. A. (2016). Native Americans, Christian Missionaries, and the Politics of the Forced School Movement. In *The Wiley Blackwell Companion to Religion and Politics in the U.S.* (pp. 139–148). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118528631.ch12

Martínez, S., & Agüero, J. (2023). Cartography of Southern Feminisms: Contributions of decolonial feminisms and community feminisms. *International Social Work*, *66*(3), 842–854. https://doi.org/10.1177/00208728211001417

Marx, K., Fowkes, B., & Fernbach, D. (1981). *Capital: A critique of political economy*. Penguin Books in association with New Left Review.

Marya, R., & Patel, R. (2021). *Inflamed + deep medicine and the anatomy of injustice* (First edition). Farrar, Straus and Giroux.

Menakem, R. (2017). *My grandmother's hands: Racialized trauma and the pathway to mending our hearts and bodies*. Central Recovery Press.

Messina-Dysert, G. (2012). Rape and Spiritual Death. *Feminist Theology*, *20*(2), 120–132. https://doi.org/10.1177/0966735011425305

Mies, M. (1989). *Patriarchy and accumulation on a world scale: Women in the international division of labour* (3. imp). Zed Books.

Mies, M. (2022). *Patriarchy and accumulation on a world scale: Women in the international division of labour*. Bloomsbury Academic.

Mollett, S. (2016). The Power to Plunder: Rethinking Land Grabbing in Latin America. *Antipode*, *48*(2), 412–432. https://doi.org/10.1111/anti.12190

Monsen, S. B. (1994). *Proceedings—Ecology and Management of Annual Rangelands*. United States Department of Agriculture, Forest Service, Intermountain Research Station.

Montana, J., Elliott, L., Ryan, M., & Wyborn, C. (2020). The need for improved reflexivity in conservation science. *Environmental Conservation*, *47*(4), 217–219. https://doi.org/10.1017/S0376892920000326

Morgensen, S. L. (2012). Theorising Gender, Sexuality and Settler Colonialism: An Introduction. *Settler Colonial Studies*, *2*(2), 2–22. https://doi.org/10.1080/2201473X.2012.10648839

Okun, T., & Jones, K. (2001). *White Supremacy Culture*. Minnesota Historical Society.

On Abolition Ecologies and Making "Freedom as a Place." (n.d.). https://doi.org/10.1111/anti.12666

Paye, A. (2025). Colonial Legacies: Slavery, Christianity, and the Transformation of Indigenous Liberian Religious-Cultural Identities. *International Journal of Research and Innovation in Applied Science*, *X*(VII), 1148–1158. https://doi.org/10.51584/IJRIAS.2025.100700104

Quijano, A. (n.d.). *Coloniality of Power, Eurocentrism, and Latin America*.

Radford, J. & Russel, Diana E. H (Eds.). (1992). *Femicide: The politics of woman killing*. Twayne Publ. [u.a.].

Ravera, F., Fernández-Giménez, M. E., & Oteros-Rozas, E. (2023). Reflexivity, embodiment, and ethics of care in rangeland political ecology: Reflections of three feminist researchers on the experience of transdisciplinary knowledge co-production. *Frontiers in Human Dynamics*, *5*. https://doi.org/10.3389/fhumd.2023.1144668

Robinson, J. M., Gellie, N., MacCarthy, D., Mills, J. G., O'Donnell, K., & Redvers, N. (2021). Traditional ecological knowledge in restoration ecology: A call to listen deeply, to engage with, and respect Indigenous voices. *Restoration Ecology*, *29*(4), e13381. https://doi.org/10.1111/rec.13381

Rodriguez Castro, L. (2021). 'We are not poor things': Territorio cuerpo-tierra and Colombian women's organised struggles. *Feminist Theory*, *22*(3), 339–359. https://doi.org/10.1177/1464700120909508

Rohde, R. (2026, January 14). Global Temperature Report for 2025. *Berkeley Earth*. https://berkeleyearth.org/global-temperature-report-for-2025/

Rowe, A. C., & Tuck, E. (2017). Settler Colonialism and Cultural Studies: Ongoing Settlement, Cultural Production, and Resistance. *Cultural Studies ↔ Critical Methodologies*, *17*(1), 3–13. https://doi.org/10.1177/1532708616653693

Speed, S. (2017). Structures of Settler Capitalism in Abya Yala. *American Quarterly*, *69*(4), 783–790.

Sprague, J. (2005). *Feminist methodologies for critical researchers: Bridging differences*. Rowman & Littlefield.

Subramaniam, B. (2024). *Botany of empire: Plant worlds and the scientific legacies of colonialism*. University of Washington Press.

Sze, J. (2018). *Sustainability: Approaches to Environmental Justice and Social Power*. NYU Press.

Talal, M. L., & Santelmann, M. V. (2020). Vegetation management for urban park visitors: A mixed methods approach in Portland, Oregon. *Ecological Applications*, *30*(4). https://doi.org/10.1002/eap.2079

Taylor, E. por M. S. y D. (n.d.). *Ich'el ta muk': La trama en la construcción del lekil kuxlejal. Hacia una visibilización de saberes "otros" desde la matricialidad del sentipensar-sentisaber tseltal – Resistant Strategies*. Retrieved May 11, 2026, from https://resistantstrategies.hemi.press/translation-of-ichel-ta-muk-insights-from-the-construction-of-lekil-kuxlejal-towards-a-visibilization-of-other-knowledges-from-the-matrix-of-the-tseltal-feel-thin/?lang=es

Temoney, K. E. (2021). The War Came Alive Inside of Them. *Journal of Religious Ethics*, *49*(3), 479–494. https://doi.org/10.1111/jore.12366

Tuck, E., & Yang, K. W. (2012). Decolonization is not a metaphor. *Decolonization: Indigeneity, Education & Society*, *1*(1), Article 1. https://jps.library.utoronto.ca/index.php/des/article/view/18630

visualizingenergy. (2023, September 4). Four million wells and counting: The history of oil and gas drilling in the U.S. *Visualizing Energy*. https://visualizingenergy.org/four-million-wells-and-counting-the-history-of-oil-and-gas-drilling-in-the-u-s/

Walker, T. (2012). European Ambitions and Early Contacts: Diverse Styles of Colonization, 1492–1700. In *Converging Worlds*. Routledge.

Weller, F. (2025). *The wild edge of sorrow: Rituals of renewal and the sacred work of grief*. North Atlantic Books.

West, S., Haider, L. J., Stålhammar, S., & Woroniecki, S. (2020). A relational turn for sustainability science? Relational thinking, leverage points and transformations. *Ecosystems and People*, *16*(1), 304–325. https://doi.org/10.1080/26395916.2020.1814417

Which emits more carbon dioxide: Volcanoes or human activities? | NOAA Climate.gov. (2016, June 15). https://www.climate.gov/news-features/climate-qa/which-emits-more-carbon-dioxide-volcanoes-or-human-activities

Whitehead, A. L., & Perry, S. L. (2019). Is a "Christian America" a More Patriarchal America? Religion, Politics, and Traditionalist Gender Ideology. *Canadian Review of Sociology/Revue Canadienne de Sociologie*, *56*(2), 151–177. https://doi.org/10.1111/cars.12241

Whyte, K. (2017). Indigenous Climate Change Studies: Indigenizing Futures, Decolonizing the Anthropocene. *English Language Notes*, *55*(1–2), 153–162. https://doi.org/10.1215/00138282-55.1-2.153

Whyte, K. (2018). Settler Colonialism, Ecology, and Environmental Injustice. *Environment and Society*, *9*(1), 125–144. https://doi.org/10.3167/ares.2018.090109

Wickham, S. B., Augustine, S., Forney, A., Mathews, D. L., Shackelford, N., Walkus, J., & Trant, A. J. (2022). Incorporating place-based values into ecological restoration—Ecology & Society. *Ecology and Society*, *27*(3). https://doi.org/10.5751/ES-13370-270332

Wolfe, P. (2006). Settler colonialism and the elimination of the native. *Journal of Genocide Research*, *8*(4), 387–409. https://doi.org/10.1080/14623520601056240

Zalles, V., Hansen, M. C., Potapov, P. V., Parker, D., Stehman, S. V., Pickens, A. H., Parente, L. L., Ferreira, L. G., Song, X.-P., Hernandez-Serna, A., & Kommareddy, I. (2021). Rapid expansion of human impact on natural land in South America since 1985. *Science Advances*, *7*(14), eabg1620. https://doi.org/10.1126/sciadv.abg1620

CHAPTER 6 - CONCLUSION

Ecological restoration is a practice and body of knowledge motivated by supporting ecosystem health. Through this work, which spans qualitative and quantitative approaches to restoration ecology provides context and support for the social, political, historic, and ecological dynamics to provide care to ecosystems and people. My work is particularly situated in the arid American West, and speaks to my relationship with the land and people in this span of land. Conducting this work has been a great honor of my life and through it I developed relationships with people, places, plants, and animals that have changed me. It is this care that motivated my work throughout my dissertation studies that carefully consider the dynamics of relationships between ecological processes and organisms, land and people, and people with each other. This concluding work will be written utilizing the lens of embodied ecology that I discuss in Chapter 5. As I stated in the introduction, restoration ecology often fails to historicize, contextualize, and center community, and often denies or looks away from its

colonial origins. It is my aim in discussing each of my chapters through the embodied ecology lens to demonstrate how my work has reached towards deconstructing these norms in the field.

Chapter 5 in particular is a manifestation of my love and dedication to the land, as it came out of a need to articulate something I had been experiencing and trying to talk about for years, that systematized power-based violence and systematized land degradation are connected and from the same source. In Chapter 5, I poured through the work of mentors, activists, scholars, and practitioners who had articulated the connection between coloniality and its subsequent manifestations of white supremacy culture and cis-heteropatriarchy and land degradation. From their work, I put together the calls towards healing that were proposed to substantiate a framework for embodied ecology. My primary contribution was the synthesis of these principles for restoration ecology, but the people who came before me and whose work I learned so much from were the originators of the knowledge. For their work I am so grateful, as it patiently taught me how to articulate things that had been swirling in my life for years.

In Chapter 5, I outline five principles for embodied ecology: relationality, accompaniment, abolition, reflexivity, and spirituality. Each of these principles represent a wider literature and body of knowledge, but are particularly important to center and incorporate in restoration ecology. In my own dissertation work, I have tried to hold on to these principles to guide my epistemology and ontology, even as most of my other chapters are quantitative restoration ecology studies. I am grateful that through my dissertation I have been gifted knowledge of so many different techniques and ways of

knowing the world, even as they sometimes present tensions and swirling questions. Again and again, I have been presented with reconciling holding more embodied epistemologies and ontologies with conducting academic quantitative ecological research, which can often subscribe to notions of objectivism that have been leveraged as mechanisms of harm (Sprague, 2016).

In Chapter 2, I explored how indaziflam, an herbicide developed to remove cheatgrass (*Bromus tectorum*) impacted the soil microbiome and plant community. Indaziflam is a herbicide marketed by the company Bayer (formerly Monsanto) which has committed serious and large-scale atrocities. I did this work in the first year of my PhD because my advisor was approached by Boulder County Parks and Opens Space, as they had questions about how indaziflam use to kill off the cheatgrass that has monopolized the foothills could impact other organisms like the soil microbiome. Because this herbicide is created by a highly capitalist and harmful company, I had mixed feelings about the project, which I describe later, in Chapter 5. To reconcile some of these feelings, I worked through a case study of this work by historicizing cheatgrass (*Bromus tectorum*) introduction in the U.S. and talking through management practices through an Embodied Ecology lens. My chapter 2 study was in close collaboration with community organizations like Boulder County Parks and Open Space and was created to help them inform their management practices. My findings that there were tradeoffs between plant and soil dynamics with indaziflam application were highly applicable to communities I live close to. I found that indaziflam application reduced cheatgrass (Bromus tectorum) presence and native plants re-established relatively quickly, but that the soil microbiome also showed

signs of both positive and negative effects from the herbicide. This work was somewhat relational in that it supports my community and the native plants who I love within it in some ways, and did accompany the people who are land managers by not asserting my own judgement, and rather quantitatively answering questions they had. On one hand, herbicide use is intensely harmful in that it supports systems of harm economically and is a mechanism to kill beings, and on the other, cheatgrass is a part of coloniality itself, killing off native plants and creating only stands of itself. Throughout this work and still, I approach this work highly reflexively, acknowledging and holding both the healing and harm, while also trying to see where I am implicated within it.

The other study that I did early on in my PhD, was a greenhouse study related to mechanics of using different seed pellet creation mechanisms and watering treatments for the emergence of plant species native to my study system in the Colorado Plateau (Chapter 3). I found that pellets that were made with a "seed ball bike" which creates more heterogenous shaped and less compact pellets were much more effective at supporting seed emergence of the native seedlings than broadcast seeding or making larger, more compact pellets by hand. I showed that in the greenhouse setting bikemade pellets were more effective at supporting seedling emergence under heavier less frequent watering events. This result supports dryland restoration efforts by providing baseline mechanism information about pellet seeding, a technique which can protect seeds from harsh conditions and promote emergence. This study had much less ethical tension and more spiritual resonance for me. Because seed pellets are so

low-input, low-tech, and easily made by anyone, it felt good to show that seeds really like to germinate within them.

By conducting this greenhouse study during the first year of my PhD, I also felt like I gained a depth of relationship with the plants in my seed mix and supported the implementation of lower-input supportive methods. Throughout the experiment, I watered, measured, and checked on every other day the plants that were growing in the mesocosms. Through this process, I became intimately familiar with the young plants in the mix, which I had often seen the adult forms of in the field. By watering them, watching them sprout and form, and spending so much time with them, it cultivated a depth of relationship that I didn't have before. I often talked and sand to the little seedlings, alone in the greenhouse for an untold amount of hours, and I felt that I was honoring their spirits by noticing how beautiful they were each day, being so delicate with them and careful to be accurate about their height and identity. I loved this project because I do think seed pellets could be incredibly useful without having to be centralized by one producer (like indaziflam is by Bayer). Community members and people caring for land can easily create their own seed pellets, and hopefully deepen relationships with the plants in their mix while doing it. Further, seed pellets have been used by activists in "guerilla gardening", where seed pellets are thrown over walls and fences of private areas to grow native plants in places that have been destroyed for industrial use (*Native Seed Balls – Dispersing Seeds with Guerilla Action*, n.d.). Contributing to the body of knowledge around this work was highly satisfying because it

was more in epistemological and ontological alignment, which was good information for directing me towards future research.

My final project also felt more aligned with embodied ecology epistemologies because it was highly community-led and allowed me to build relationships and connection with the land of the desert southwest. Chapter 4 worked through dryland restoration techniques in the field in collaboration with the Southwest Colorado Research Center and the Ute Mountain Ute Tribe, and explored techniques from the RestoreNet framework as well as those the local land steward was interested in. Like many dryland restoration studies, this work found that recruitment of native plant seedlings in degraded dryland systems is very difficult. However, it also found that compost, soil pitting, and mulching could all be practices that increase native plant establishment from seed in these systems. Further, the treatments shifted the plant community composition, demonstrating that restoration action can change the community assembly in these ecosystems. Through conducting this work, I always had in mind to be highly respectful to the land I was working on, and emphasized noticing and praising the beauty of the plants that grew there. This deepened my relationship with the land and plants, both emotionally and spiritually.

The community-led aspect of the RestoreNet project felt highly deconstructive of systems that propose ecologists and the academy as the knowers, and everyone else and the land as the known. It was incredibly important for my learning of how to facilitate community-led ecology, in which the people living closest to the land are making the decisions, and I am simply the one monitoring and

providing the information back to them about the decisions, to conduct this project. We would have annual report-outs to the Ute Mountain Ute Tribe and SWCRC community about the current trends we were seeing, which in turn would inform their land management and other decisions they were making. Further, I grew very close with many community members initially through this project, having dinners and getting land tours, which only deepened my relationships and connections to the people and land. Now, I am incredibly sad that there is a potential I won't be working in the area anymore, and I am trying to continue building my practice there since I do have such a deep context and relational abundance. It was a great honor to be trusted in these contexts, and I believe the project mirrored a lot of epistemological and ontological resonance.

My work as a whole speaks to the practice of restoration ecology in the U.S. West. I have studied on multiple scales, from as small as the emerging cotyledon to as large as global geopolitics. This work has helped me clarify my intentions as a restoration ecologist and gave me space to practice those intentions. Through this process I have come to understand the core of restoration ecology research is being taught by the land, it is building relationships with land through making detailed observations, talking to people who are the closest to it in a specific place, and trying techniques that support land while also disinvesting in systems of harm. I will carry this ethic of work with me always.

APPENDICES

APPENDIX 1: SUPPLEMENTARY MATERIALS FOR CHAPTER 2 - PLANT AND SOIL MICROBIAL COMPOSITION LEGACIES FOLLOWING INDAZIFLAM HERBICIDE TREATMENT

A1.1 FULL DESCRIPTION OF MICROBIAL SEQUENCING AND STATISTICAL ANALYSIS METHODOLOGY

A.1.1.1 Soil DNA extraction, PCR, and gene amplicon sequencing

First, DNA was extracted from 0.25 grams of the 37 soil samples using the Qiagen DNeasy PowerSoil Pro Kit (Qiagen, Hilden, Germany). Next, we used 515F/806R primers to amplify the V4 region of the 16S rRNA gene for bacteria and archaea (Apprill et al., 2015; Caporaso et al., 2011; Parada et al., 2016), and ITS1-F/ITS2 primers for the ITS gene region for fungi (Bellemain et al., 2010; Smith & Peay, 2014). Each sample was assigned a 12-bp barcode, homogenized, and then randomly assigned a location on a 96-well plate. Four blank samples were included as negative controls. Two samples with known microbial composition were included as positive controls (from Kimmel, et. al, in review). Duplicated PCR reactions were run for all samples using Invitrogen's Platinum II Hot-Start PCR Master Mix (Invitrogen, Waltham, MA). After confirming amplification and length via gel electrophoresis, amplicons were then normalized using the ThermoFisher Scientific SequalPrep

Normalization plates (Thermo Fisher Scientific Inc. USA). Both libraries were then sequenced with the Illumina MiSeq platform. The 16S library was sequenced using a 300-cycle v2 paired end kit and the ITS was sequenced using a 500-cycle v2 paired end kit. Both runs included a 15% phiX spike.After sequencing, reads were demultiplexed with idemp (idemp; https://github.com/yhwu/idemp) and adaptors were trimmed using cutadapt (Martin, 2011).

We then used the dada2 package in R (Callahan et al., 2016) to characterize the microbial communities in each sample. First, we used the filterAndTrim() function (settings: 16S truncLen = c(150,150), ITS truncLen = c(200,220), maxEE = (2,2), truncQ = 2, rm.phix = T) to trim all sequences to the same length by filtering based on the number of ambiguous bases, a minimum quality score, and the expected number of errors in the read. Next we learned error rates from 1x10^8 bp chosen from a random subset of the samples. Then we used the derepFastq() function to depreplicate the sequences, which output a list of unique sequences and their abundances, where identical sequences were grouped together. We next applied a denoising algorithm using the dada() function. This involved partitioning the sequences where the most abundant sequence was made the center of the partition, and then all sequences were compared to the center. Sequences were first compared based on kmer distance and banded alignment. Then an error rate was calculated based on differences in bases between sequences, cross-referenced with quality scores. These error rates then allowed for the calculation of abundance p-values, where low values indicate that a certain sequence is too abundant

to be considered an error in sequencing, and will then get partitioned out of the algorithm as a new taxonomic unit (here we used amplicon sequence variants, or ASVs). After the partitioning algorithm was run, we used the isBimeraDenovo() function to identify and remove bimeras (two-parent chimeric sequences), and the mergePairs() function to merge paired forward and reverse reads. Finally, we used a Bayesian taxonomic identifier as implemented in the dada2 package to assign a taxonomy based on UNITE (Oct. 2021 release for ITS) and Silva (v 138.1 for 16S).

A1.1.2 Statistical Analyses

The microbiome data was filtered and rarified prior to statistical analysis. The 16S data was first filtered to exclude ASV's where the phylum was not able to be identified, as well as samples that had below a 4000 read count, and ASV's that were chloroplasts or mitochondria. Chloroplasts and mitochondria were removed because these organelles are only found in plants and animals, and their presence indicates contamination from a species outside of the microbial community. Further, ASV's that were highly abundant in negative control samples were filtered out after verifying that these ASV's were not highly abundant in the sample data. The data was then rarified to 22,385 reads, which was the lowest read count in the 16S dataset. The same process (without chloroplast and mitochondria exclusion) was followed with the ITS dataset.

All statistical analyses were performed in R version 4.2.2 (R Core Team, 2023). To evaluate the effects of indaziflam treatment on native and exotic plant cover and biomass and soil physical characteristics relative to untreated control plots, we used generalized linear mixed effects models (GLMMs). We built these predictive GLMMs for all plant and soil response variables using the lme4 package in R (Bates et al., 2014). Separate modules were built for the following response variables: cheatgrass cover (%), cheatrass biomass (ounces per m2), cheatgrass thatch depth (cm), total native herbaceous plant cover (%), total native forb cover (%), total native shrub cover (%), native species richness, and soil mineral nutrient levels of interest (i.e., organic matter, NO3- (ppm), pH, others). In each model, indaziflam treatment (i.e., treated vs control) and time since treatment (in years; i.e., 0-5) were included as fixed effects and Site_ID was included as a random effect. The significance of individual terms ($p < 0.05$) included in final models was estimated using a Wald Type II X2 test ('ANOVA' function, car package; Fox et al., 2012). For significant variables, we used planned contrasts to explore differences in group means among levels using the 'emmeans' function (package emmeans; Lenth & Lenth, 2018).

To analyze differences in soil microbial community composition between treated and untreated plots, we used PERMANOVA (permutational analysis of variance) and PERMDISP (permutations of dispersion) tests using the using adonis2(), pairwise.adonis2(), betadisper(), and permutest() functions of the vegan, pairwiseAdonis, and smartsnp packages (Herrando-Pérez et al.,

2021; Oksanen, 2020; Polanco-Martínez, 2020). In these models, treatment (treated with indaziflam or not treated) was the predictor variable, and Bray-Curtis dissimilarity matrices of vegetation and soil variables were the response variables for both bacteria/archaea and fungi communities. PERMANOVAs were nested by site, as high variability between sites would skew results without nesting. To compare differences in diversity between treated and untreated plots within each site, we first calculated the Shannon index and species richness for each sample using the diversity() and specnumber() functions of the vegan package (Oksanen, 2020).

We then used ANOVA (analysis of variance) tests to compare the Shannon indices and species richness', first making sure the data met assumptions of normality and equality of variances using the shapiro.test() and leveneTest() functions of the car package (Fox, 2023). To parse apart if soil and ecological variables had a related effect on microbial diversity and community composition, we also conducted a multiple regression on distance matrices (MDRM) test (Goslee & Urban, 2007). To ensure that correlated variables were not included in the MDRM, the cor() function, which is in the corrplot package, was used to assess correlation between soil and plant variables (Wei & Simko, 2021). Variables correlated to a level of 0.6 or higher were not included together in the analysis. It was found that biomass plant variables (cheatgrass, native forb, native grass, and native shrub) were only weakly correlated, and therefore, these were chosen to represent plant community effect on the soil microbial community. Soil physical characteristics of soil organic matter, nitrate, and pH were chosen to be

included in the MDRM because of a priori hypotheses about these variables and the fact that they were not correlated to each other. Finally, we performed an indicator species analysis to determine taxa indicative of treated and untreated conditions. For this analysis we used the multipatt() function of the indicspecies package (De Cáceres et al., 2010).

A1.2 SUPPLEMENTAL FIGURES & TABLES

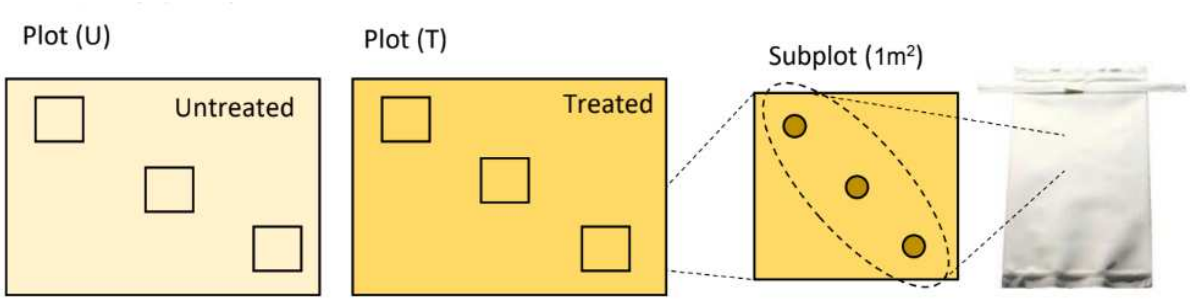


Figure S1. Subplot design of soil sampling method.

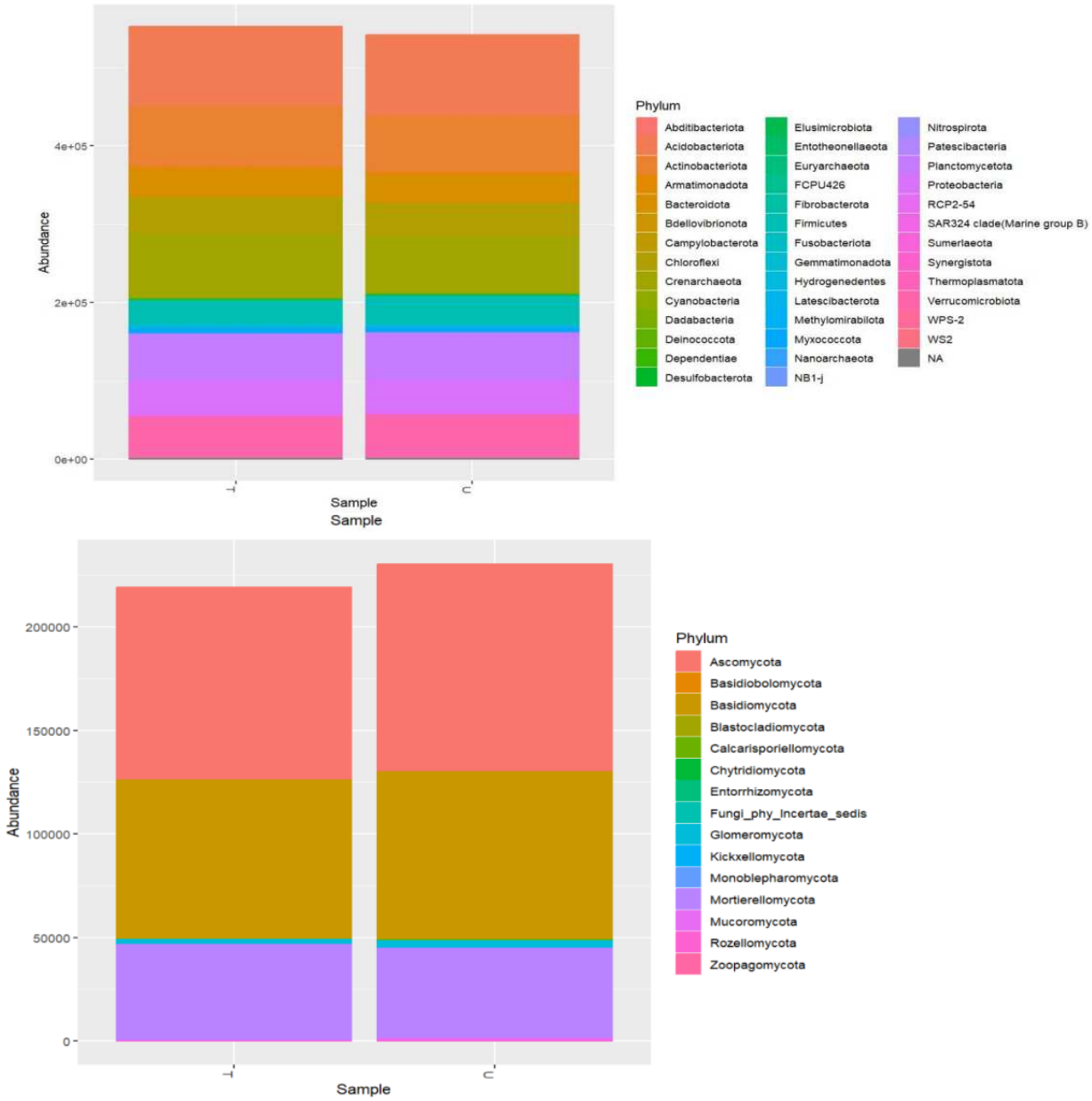


Figure S2. Bacterial and fungal community composition between treated (T) and untreated (U) sites with abundance.

Table S1. Averaged 16S and ITS Shannon index and for each site and treatment. Higher indices indicate more diversity.

	Untreated		Treated	
Site ID	**16S**	**ITS**	**16S**	**ITS**
DORO 2020	432.22	30.44	410.16	50.74
DORO 2021	432.22	59.06	364.02	39.63
RABB 2022	441.67	37.39	436.04	31.81
TREVA 2017	399.38	59.06	425.22	42.54
TREVA 2018	432.79	48.22	444.74	49.35
TREVA 2022	434.06	52.00	464.08	40.16

A)


R1_DORO_2020_T_P2.fastq.gz
R1_DORO_2020_T2.fastq.gz
R1_DORO_2021_T1.fastq.gz
R1_DORO_2021_T3.fastq.gz
R1_DORO_2021_U1.fastq.gz
R1_DORO_2021_U2.fastq.gz
R1_DORO_2021_U3.fastq.gz
R1_NTC4.fastq.gz
R1_NTC6.fastq.gz
R1_PositiveControl2b.fastq.gz
R1_RABB_2022_TM_1.fastq.gz
R1_RABB_2022_TM_2.fastq.gz
R1_RABB_2022_UJ_2.fastq.gz
R1_TREVA_2018_T2.fastq.gz
R1_TREVA_2019_U3.fastq.gz
R1_TREVA_2022_TJ_1.fastq.gz
R1_TREVA_2022_TJ_2.fastq.gz
R1_TREVA_2022_UM_1.fastq.gz
R1_TREVA_2022_UM_2.fastq.gz
R1_TRVEA_2017_U2.fastq.gz
Reads: 57822
Reads: 64565
Reads: 49266
Reads: 63852
Reads: 50940
Reads: 43058
Reads: 53454
Reads: 3271
Reads: 882
Reads: 76569
Reads: 35001
Reads: 49593
Reads: 52362
Reads: 46945
Reads: 57073
Reads: 64327
Reads: 42418
Reads: 50446
Reads: 56477
Reads: 37431
Quality Score
Cycle
100%
0%

B)


R2_DORO_2020_T_P2.fastq.gz
R2_DORO_2020_T2.fastq.gz
R2_DORO_2021_T1.fastq.gz
R2_DORO_2021_T3.fastq.gz
R2_DORO_2021_U1.fastq.gz
Reads: 57822
Reads: 64565
Reads: 49266
Reads: 63852
Reads: 50940
R2_DORO_2021_U2.fastq.gz
R2_DORO_2021_U3.fastq.gz
R2_NTC4.fastq.gz
R2_NTC6.fastq.gz
R2_PositiveControl2b.fastq.gz
Reads: 43058
Reads: 53454
Reads: 3271
Reads: 882
Reads: 76569
R2_RABB_2022_TM_1.fastq.gz
R2_RABB_2022_TM_2.fastq.gz
R2_RABB_2022_UJ_2.fastq.gz
R2_TREVA_2018_T2.fastq.gz
R2_TREVA_2019_U3.fastq.gz
Reads: 35001
Reads: 49593
Reads: 52362
Reads: 46945
Reads: 57073
R2_TREVA_2022_TJ_1.fastq.gz
R2_TREVA_2022_TJ_2.fastq.gz
R2_TREVA_2022_UM_1.fastq.gz
R2_TREVA_2022_UM_2.fastq.gz
R2_TRVEA_2017_U2.fastq.gz
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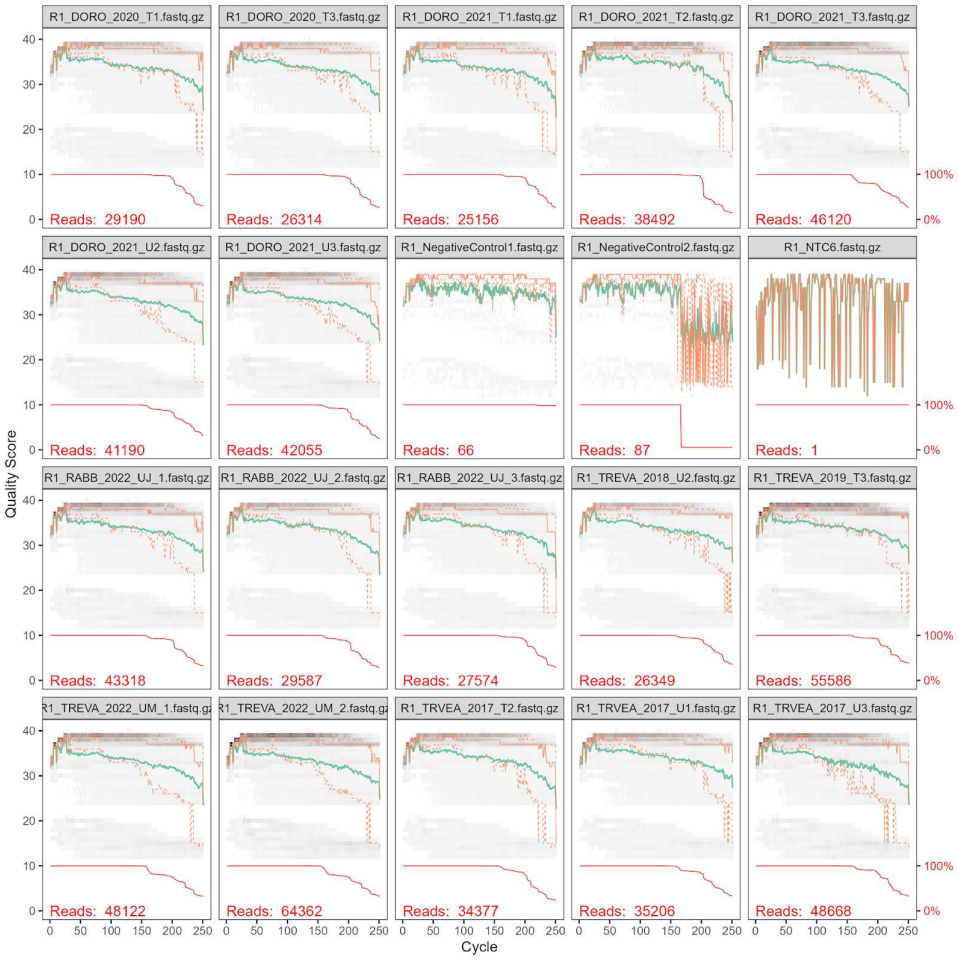
Reads: 42418
Reads: 50446
Reads: 56477
Reads: 37431
Quality Score
Cycle
100%
0%

C)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R1_DORO_2020_T3.fastq.gz
R1_DORO_2021_T1.fastq.gz
R1_DORO_2021_T2.fastq.gz
R1_DORO_2021_T3.fastq.gz
R1_DORO_2021_U2.fastq.gz
R1_DORO_2021_U3.fastq.gz
R1_NegativeControl1.fastq.gz
R1_NegativeControl2.fastq.gz
R1_NTC6.fastq.gz
R1_RABB_2022_UJ_1.fastq.gz
R1_RABB_2022_UJ_2.fastq.gz
R1_RABB_2022_UJ_3.fastq.gz
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R1_TREVA_2019_T3.fastq.gz
R1_TREVA_2022_UM_1.fastq.gz
R1_TREVA_2022_UM_2.fastq.gz
R1_TRVEA_2017_T2.fastq.gz
R1_TRVEA_2017_U1.fastq.gz
R1_TRVEA_2017_U3.fastq.gz
Reads: 29190
Reads: 26314
Reads: 25156
Reads: 38492
Reads: 46120
Reads: 41190
Reads: 42055
Reads: 66
Reads: 87
Reads: 1
Reads: 43318
Reads: 29587
Reads: 27574
Reads: 26349
Reads: 55586
Reads: 48122
Reads: 64362
Reads: 34377
Reads: 35206
Reads: 48668
Quality Score
Cycle
100%
0%

D)

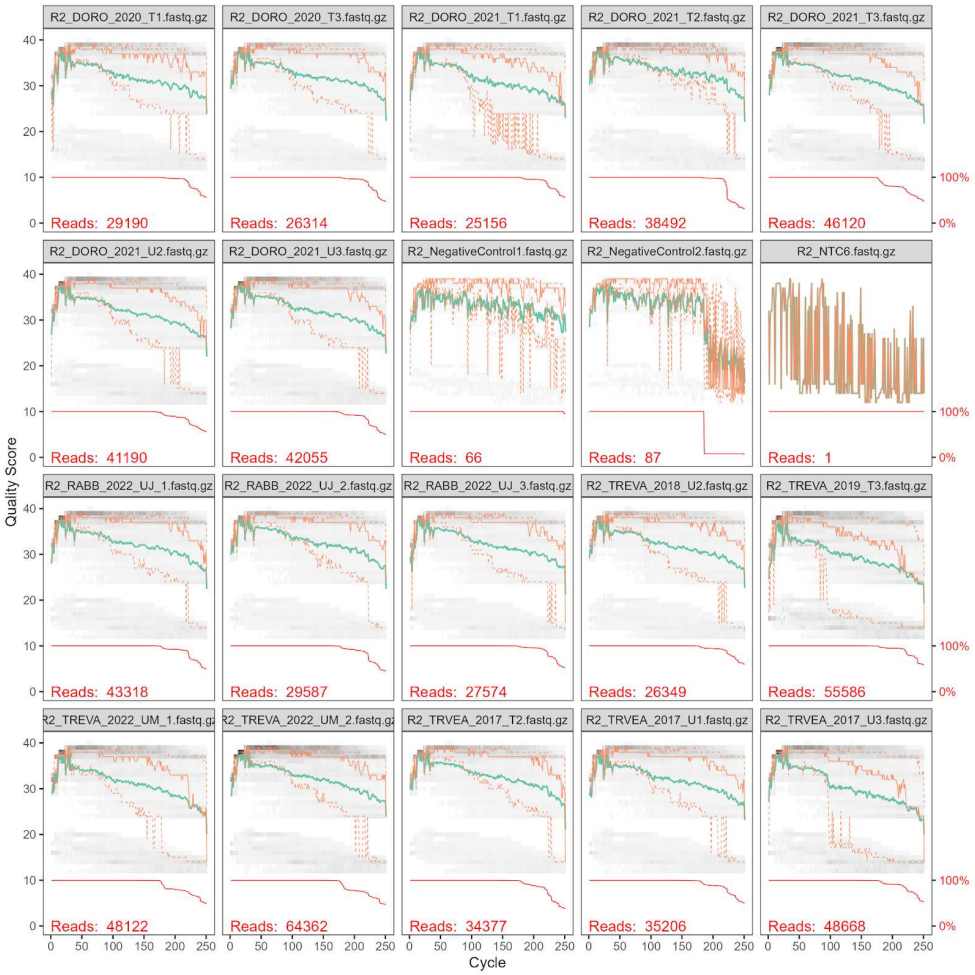


Figure S3. Quality read plots from sequencing. a) 16S forward reads, b) 16S reverse reads, c) ITS forward reads, d) ITS reverse reads.

Table S2. Linear model results for vegetation shifts with treatment. Intercept estimate comparing treated to untreated and p-value (p) are included. Significance amount marked by symbols, * = < 0.1, ** = <0.05, *** = <0.005.

Vegetation and Soil Physical Characteristic Linear Model Results

Variable	Coefficient	p	Significance
Cheatgrass Cover	0.073	0.114	
Native Herbaceous Cover	-0.046	<0.001	***
pH	0.133	0.821	
SOM	0.027	0.623	
NO3	-0.526	0.007	*

Table S3. PERMANOVA model results for differences in microbial composition, nested within each site. Correlation coefficient (R2) and p-value (p) are included. Significance amount marked by symbols, * = < 0.1, ** = <0.05, *** = <0.005

PERMANOVA Results

Gene	R2	p	Significance
16S	0.0411	0.008	**
ITS	0.0465	0.001	***

APPENDIX 2: SUPPLEMENTARY MATERIALS FOR CHAPTER 3 - COMPARING THE EFFECT OF TWO SEED PELLET CREATION METHODS UNDER DIFFERING WATERING TREATMENTS ON THE EMERGENCE OF NATIVE PLANT SPECIES

A2.1 FULL DESCRIPTION OF STATISTICAL ANALYSIS METHODOLOGY

2.2.1 Analysis methods, continued

Separate models were run for total density, forb density, and grass density, with plant density as the response variables and seeding treatment and watering treatment as fixed effects. Days since seeding was also included as a random effect to capture repeat measures. Differences among treatments were estimated using a Wald Type II X2 test ('ANOVA' function, car package ; Fox, 2023). Then, the emmeans function was utilized to conduct pairwise contrasts between variable levels (package emmeans; Lenth, 2017).

In these tests, seeding method and (multivariate)/or (univariate) watering were the predictor variables, then a Bray-Curtis dissimilarity matrix was calculated with the seedling species as the response variable. Finally, to identify plant seedlings that were most associated with specific treatment types, we conducted an indicator species analysis using the multipatt() function of the indicspec package, first by

separating by seeding method and then by watering treatment (De Cáceres et al., 2010). All data visualizations were created using the ggplot2 package (Wickham, 2016).

A2.2 SUPPLEMENTAL FIGURES & TABLES

Table S1. List of species utilized in experiment across all three seed pellet treatments and related information

Common Name	Botanical Name	Growth Form	Planting Depth	Seed per 15 qt. Tub (g)
Needle and Thread Grass	*Hesperostipa comata*	Graminoid	1.3-1.9 cm	0.0008
Sweet Vetch	*Hedysarum boreale*	Forb	0.6 to 1.9 cm	0.0022
Flax	*Linum lewisii*	Forb	3mm or less	0.0006
Common Yarrow	*Achillea millefolium*	Forb	0.6 cm	0.0001
Bottlebrush Squirreltail	*Elymus elymoides*	Graminoid	0.6 to 1.2 cm	0.0005
Blue Grama	*Bouteloua gracilis*	Graminoid	6 to 13 mm	0.0004
Galletta	*Pleuraphis jamesii*	Graminoid	0.6 to 1.3 cm	0.0011
Sand Dropseed	*Sporobolus cryptandrus*	Graminoid	3 to 6 mm	0.0002
Alkali Sacaton	*Sporabolus airoides*	Graminoid	<0.6 cm	0.0004
Winterfat	*Krascheninnikovia lanata*	Sub-Shrub	<0.6 cm	0.0006
Palmer's penstemon	*Penstemon palmeri*	Forb	0.3 to 0.6 cm	0.0002
Indian Ricegrass	*Achnatherum hymenoides*	Graminoid	1.3 to 3.8 cm	0.0009
Butterfly Weed	*Asclepias tuberosa*	Forb	0.3 to 0.6 cm	0.0008
Purple Three-Awn	*Aristida purpurea*	Graminoid	0.3 to 0.6 cm	0.0006
Big Sagebrush	*Artemisia tridentata*	Shrub (coded as forb)	< 3 mm	0.0001
Four-wing Saltbush	*Atriplex canescens*	Shrub (coded as forb)	1.2-1.9 cm	0.0001
Rubber Rabbit Brush	*Ericameria nauseosa*	Shrub (coded as forb)	0.16 cm	0.0001

Hairy False Goldenaster	*Heterotheca villosa*	Forb	0.6 cm	0.0001
Coyote Tobacco	*Nicotiana attenuata*	Forb	seed surface	0.0001

Table. S2. A) Results of linear model comparing the interaction seeding treatments, watering treatments, and the interaction between them. B) Emmeans pairwise contrasts between seeding and watering treatments. Significance denoted by p-value, * = <0.05, ** = <0.01, *** = <0.005.

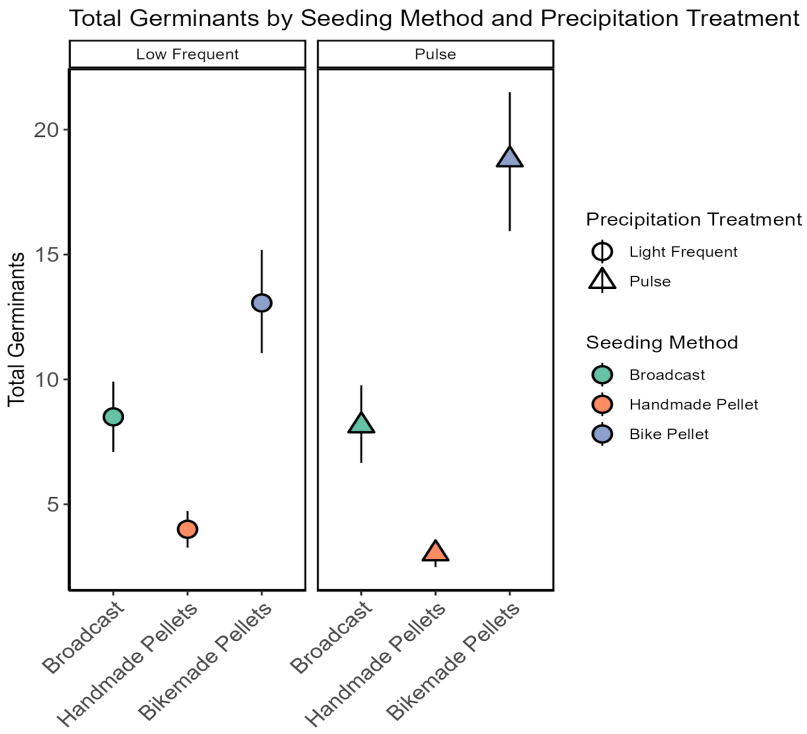
A)

Variable	**Estimate**	***z***	***p***	**Significance**
Intercept (Broadcast, Low Frequent)	1.205	2.463	0.014	*
Handmade Pellets	-0.745	-10.960	<2.0E-16	***
Bikemade Pellets	0.430	8.73	<2.0E-16	***
Pulse	-0.041	-0.745	0.456	
Handmade Pellets * Pulse	-0.250	-2.432	0.015	*
Bikemade Pellets * Pulse	0.405	5.494	2.70E-09	***

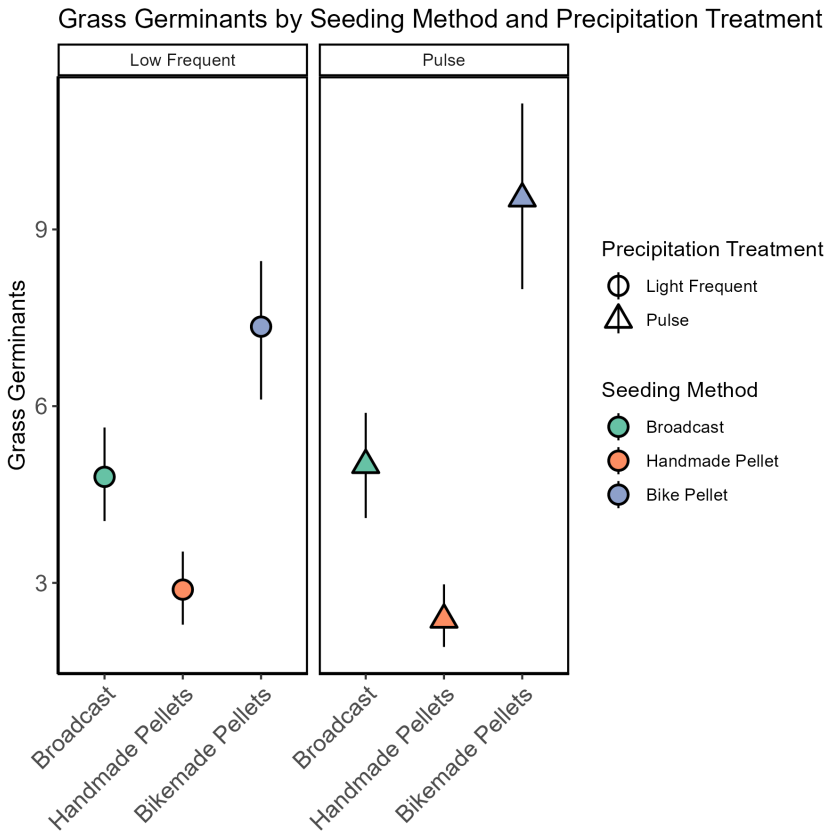
B)

Watering Treatment	**Seeding Treatment**	**Contrast**	**Estimate**	***z***	***p***	**Significance**
Low Frequent	.	Handmade Pellets - Broadcast	-0.745	-10.960	<0.0001	***
Low Frequent	.	Bikemade Pellets - Handmade Pellets	1.175	18.322	<0.0001	***
Pulse	.	Handmade Pellets - Broadcast	-0.992	-13.172	<0.0001	***
Pulse	.	Bikemade Pellets - Handmade Pellets	1.872	26.405	<0.0001	***
.	Broadcast	Pulse - Low Frequent	-0.041	-0.745	1.000	
.	Handmade Pellets	Pulse - Low Frequent	-0.288	-3.371	0.0052	*
.	Bikemade Pellets	Pulse - Low Frequent	0.364	9.051	<0.0001	***

A)


Total Germinants by Seeding Method and Precipitation Treatment
Low Frequent
Pulse
Total Germinants
20
15
10
5
Broadcast
Handmade Pellets
Bikemade Pellets
Broadcast
Handmade Pellets
Bikemade Pellets
Precipitation Treatment
Light Frequent
Pulse
Seeding Method
Broadcast
Handmade Pellet
Bike Pellet

B)


Grass Germinants by Seeding Method and Precipitation Treatment
Low Frequent
Pulse
Grass Germinants
9
6
3
Broadcast
Handmade Pellets
Bikemade Pellets
Broadcast
Handmade Pellets
Bikemade Pellets
Precipitation Treatment
Light Frequent
Pulse
Seeding Method
Broadcast
Handmade Pellet
Bike Pellet

C)

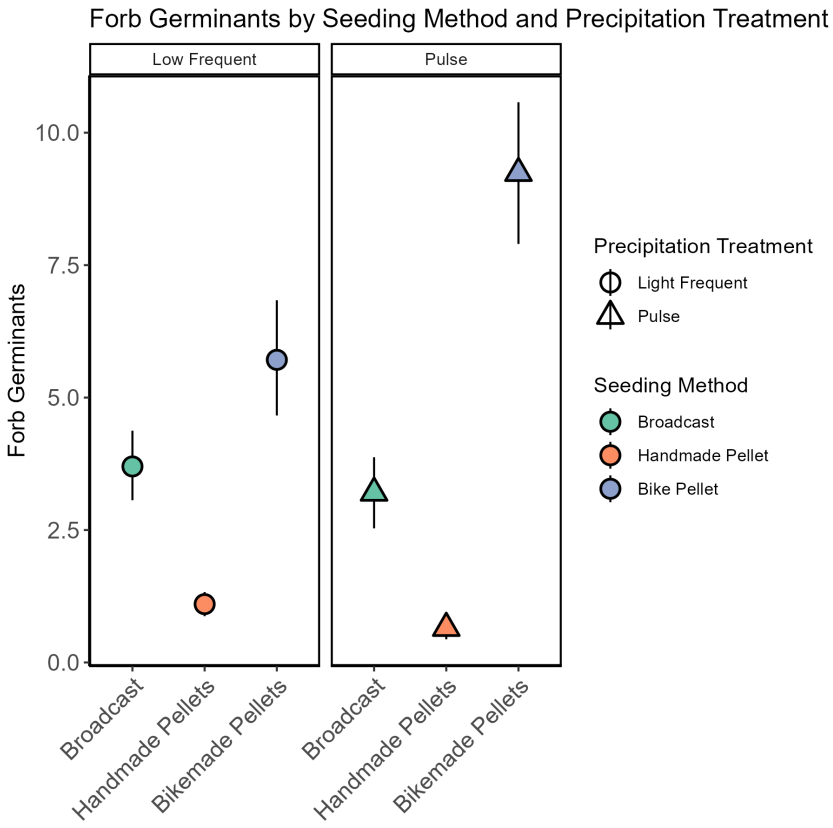
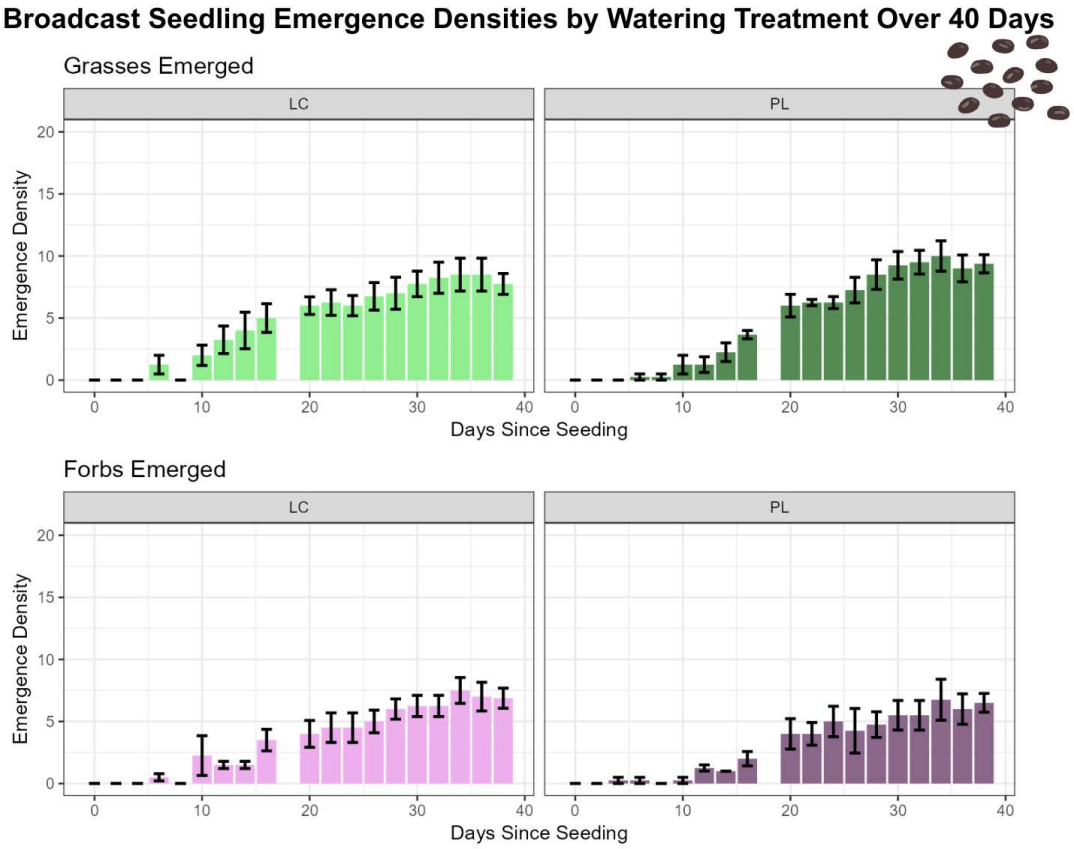


Figure S1. Average A) total, B) forb, and C) grass seedling emergence by seeding method and watering treatment.

A)


Broadcast Seedling Emergence Densities by Watering Treatment Over 40 Days
Grasses Emerged
LC
PL
Emergence Density
Days Since Seeding
Forbs Emerged
LC
PL
Emergence Density
Days Since Seeding

B)

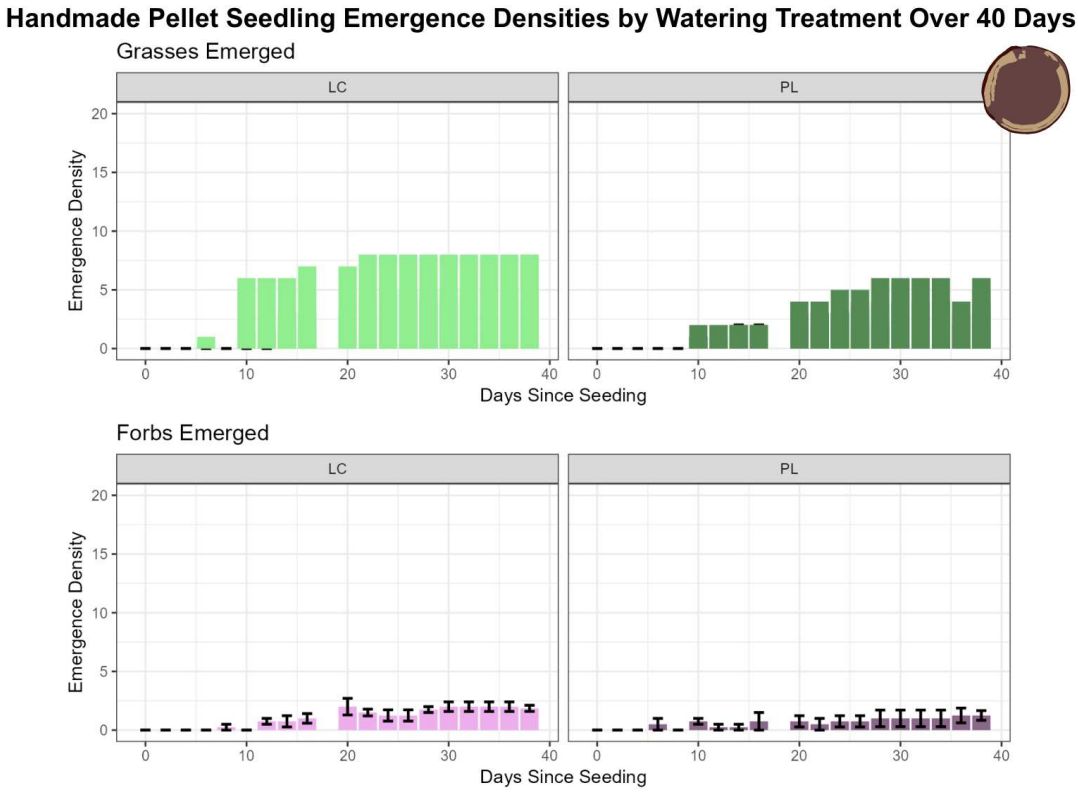


Figure S2. Differences in grass and forb seedling density between watering treatments in broadcast and handmade pellets. A) Broadcast and B) handmade pellet means with error bars representing standard deviation.

Table S3. A) Results of PERMANOVA analysis comparing the community assembly differences between seeding treatments and watering treatments. B) Emmeans pairwise contrasts between seeding and watering treatments. Significance denoted by p-value, * = <0.05, ** = <0.01, *** = <0.005.

A)

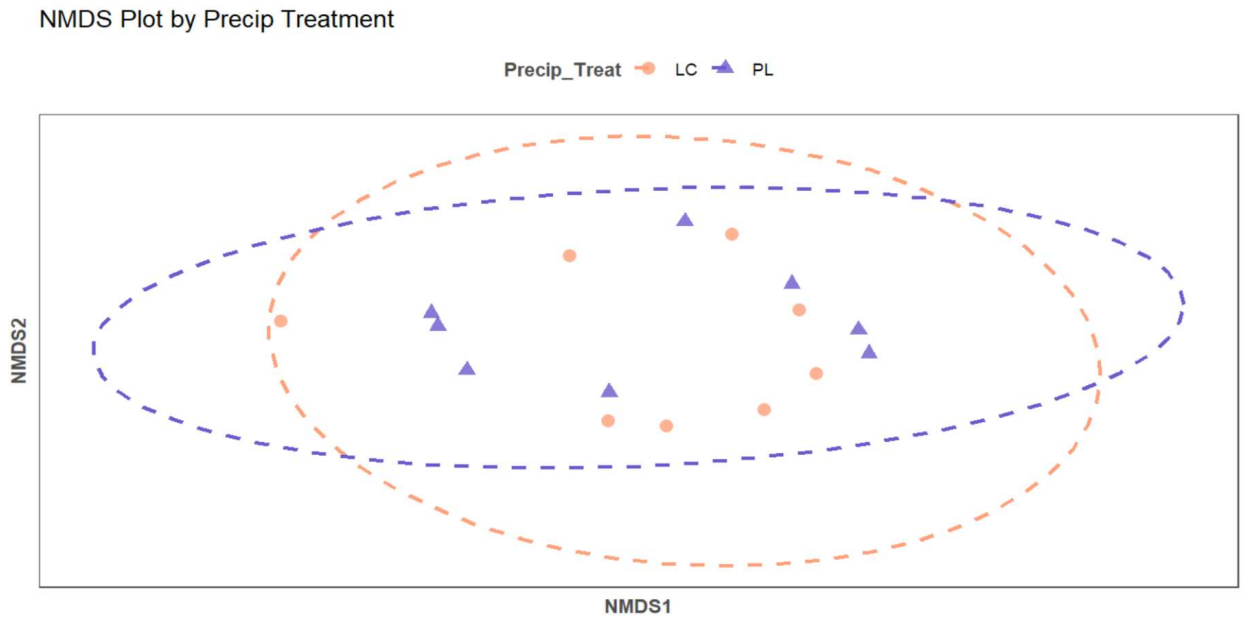
Variable	**R2**	**F**	***p***	**Significance**
Seeding Method	0.162	7.444	0.001	***
Precipitation Treatment	0.047	3.895	0.001	***

B)

A)

Contrast	**R2**	**F**	**p**	**Significance**
Broadcast - Bikemade Pellet	0.079	4.869	0.001	***
Broadcast - Handmade Pellet	0.164	9.203	0.001	***
Bikemade Pellet - Handmade Pellet	0.138	8.188	0.001	***
Low Frequent - Pulse	0.048	3.895	0.002	**

A)


NMDS Plot by Precip Treatment
Precip_Treat
LC
PL
NMDS2
NMDS1

B)

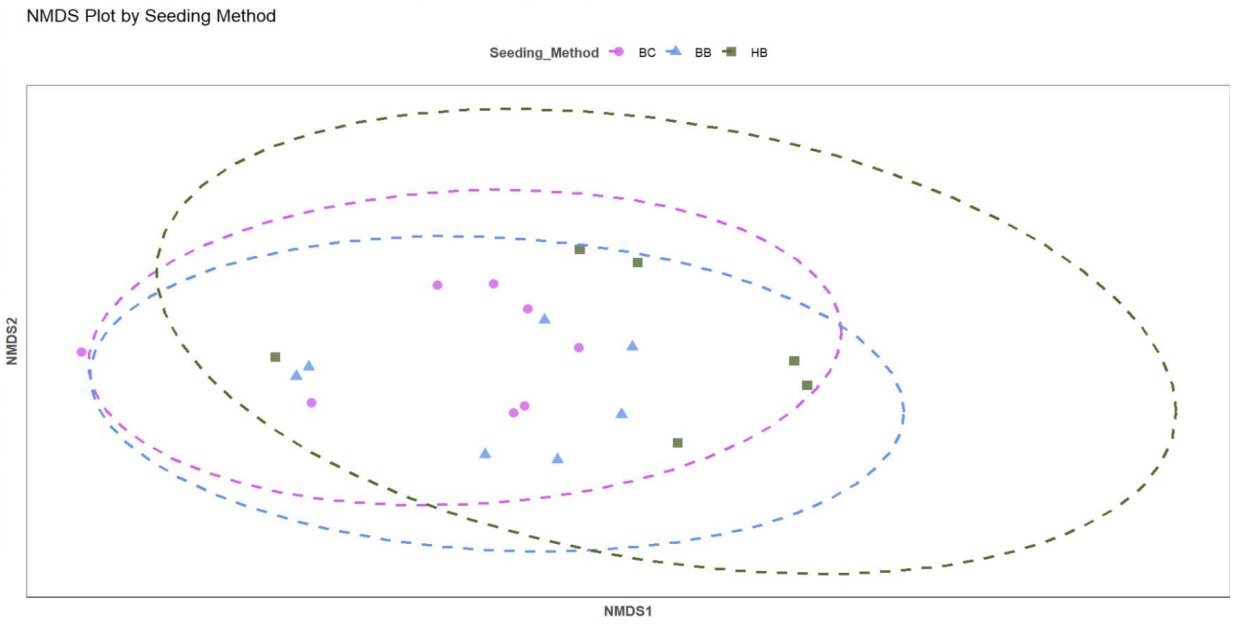


Figure S3. NMDS plots of community assembly differences by watering treatment (LC = low frequent, PL = pulse) and seeding method (BC = Broadcast, BB = bikemade pellet, HB = handmade pellet). Distance between center of centroids demonstrates the difference between communities.

Table S4. Indicator species analysis results for seeding methods and watering treatments.

Bikemade Pellets			
Species	**Statistic**	**p**	**Significance**
Linum lewisii	0.679	0.008	**

Asclepias tuberosa	0.660	0.210	*
Bikemade Pellets + Broadcast			
Species	**Statistic**	**p**	**Significance**
Aristida purpurea	0.843	0.001	***
Achillea millefolium	0.835	0.001	***
Pleuraphis jamesii	0.781	0.001	***
Artemisia tridentata	0.07	0.001	***
Atriplex canescens	0.602	0.005	**
Pulse Watering Treatment			
Species	**Statistic**	**p**	**Significance**
Achillea millefolium	0.795	0.001	***

Figure S4. Images between Day 1 and Day 42 of the same seed pellets in bikemade and handmade pellets which demonstrate differences in composition, hetero/homogeneity of pellet, and melting.

APPENDIX 3: SUPPLEMENTARY MATERIALS FOR CHAPTER 4 - PRECISION RESTORATION STRATEGIES THAT PROMOTE WATER CAPTURE AND RETENTION INCREASE SEED-BASED RESTORATION SUCCESS IN TWO SEMI-ARID AREAS IN COLORADO

A3.1 SUPPLEMENTAL FIGURES & TABLES

Table S1. Seeded species at both areas with botanical name, common name, and plant type. Rates can be found in USGS RestoreNet Installation Protocol (https://www.usgs.gov/publications/protocol-installing-and-monitoring-a-restorenet-restoration-field-trial-network-site)

Seed Mix	Botanical Name	Common Name	Plant type
Cool-Medium	Hesperostipa comata	Needle-and-Thread grass	Perennial grass
	Achillea millefolium	Common yarrow	Perennial forb
	Linum lewisii	Blue flax	Perennial forb
	Heliomeris multiflora	Showy goldeneye	Perennial forb
	Pascopyrum smithii	Western wheatgrass	Perennial grass
	Hedysarum boreale	Utah sweetvetch	Perennial forb

	Elymus elymoides	Squirrel-tail grass	Perennial grass
	Dalea candida	White prairie clover	Perennial forb
	Bouteloua gracillis	Blue gramma grass	Perennial grass
Medium-warm	Pleuraphis jamesii	James' galleta	Perennial grass
	Poa secunda	Sandberg bluegrass	Perennial grass
	Sporobolus cryptandrus	Sand dropseed	Perennial grass
	Machaeranthera tanacetifolia	Tanseyleaf aster	Perennial forb
	Bouteloua curtipendula	Black gramma	Perennial grass
	Krascheninnikovia lanata	Winterfat	Perennial shrub
	Penstemon palermi	Palmer's penstemon	Perennial forb
	Achenatherum hymenoides	Ricegrass	Perennial grass

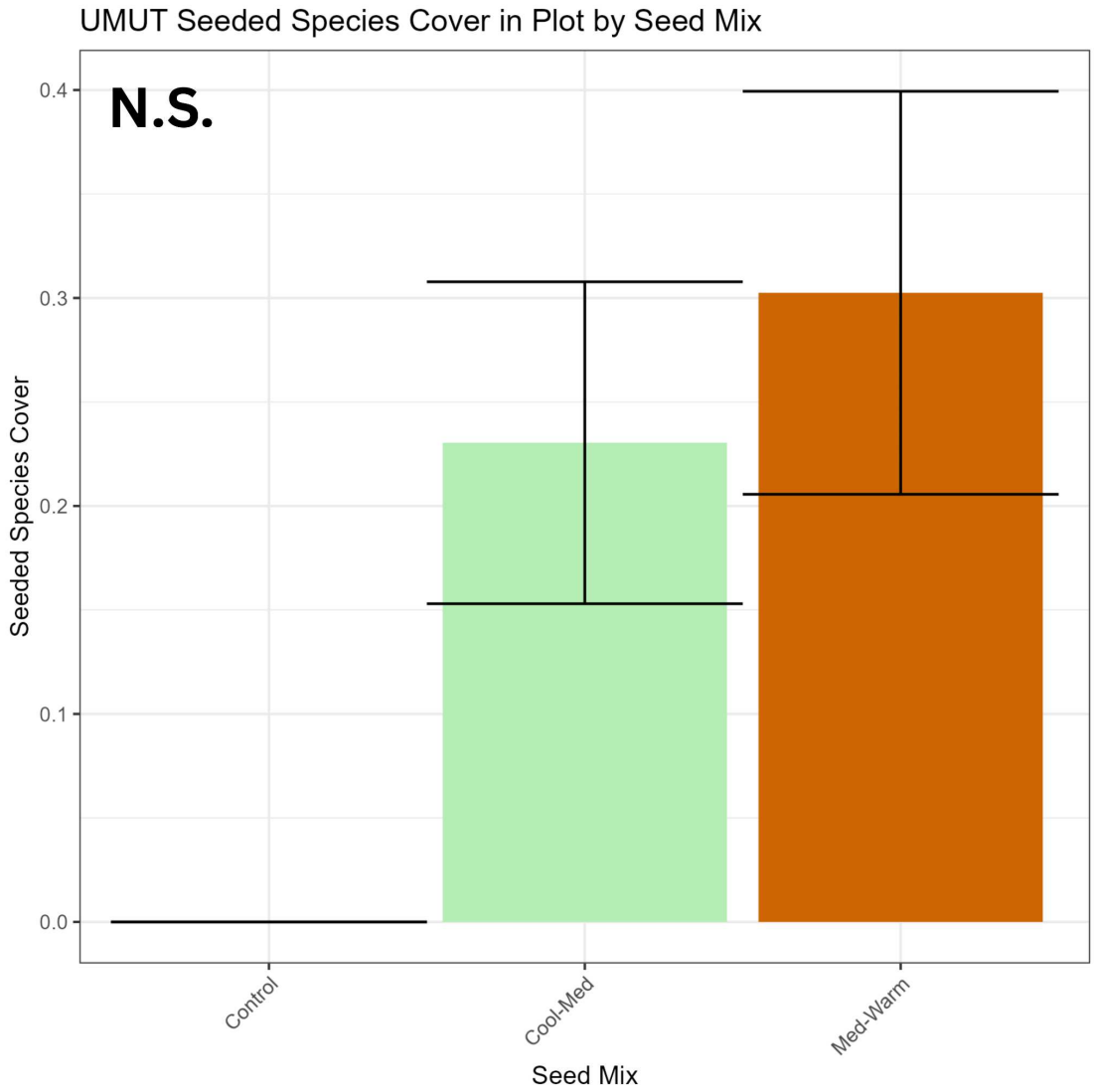


Figure S1. Seeded species cover (%) in full plot at the UMUT site by seed mix. Results only visualized, not statistically significant (N.S.).

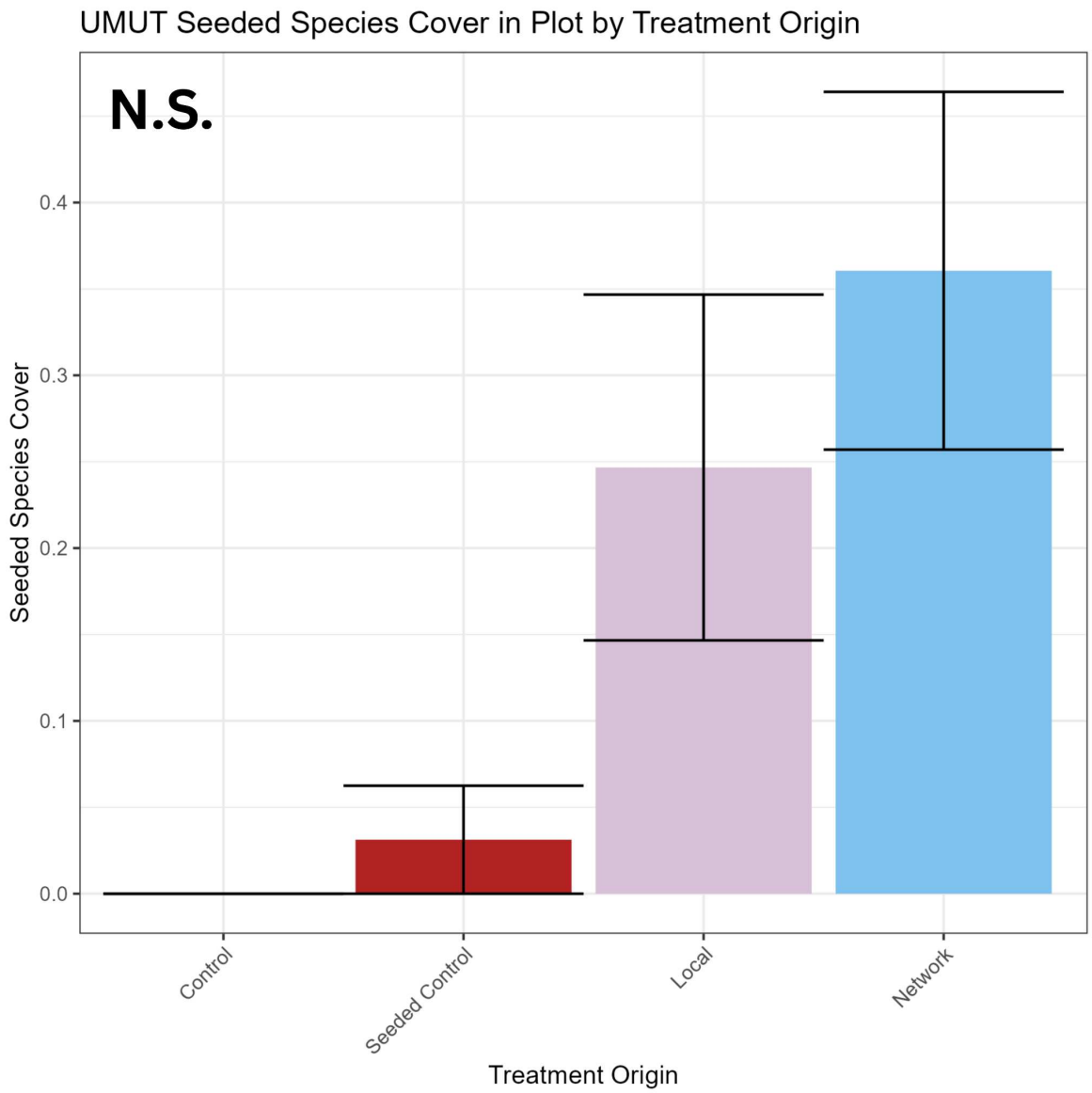


Figure S2. Seeded species cover (%) in full plot at the UMUT site by treatment provenance. Results only visualized, not statistically significant (N.S.).

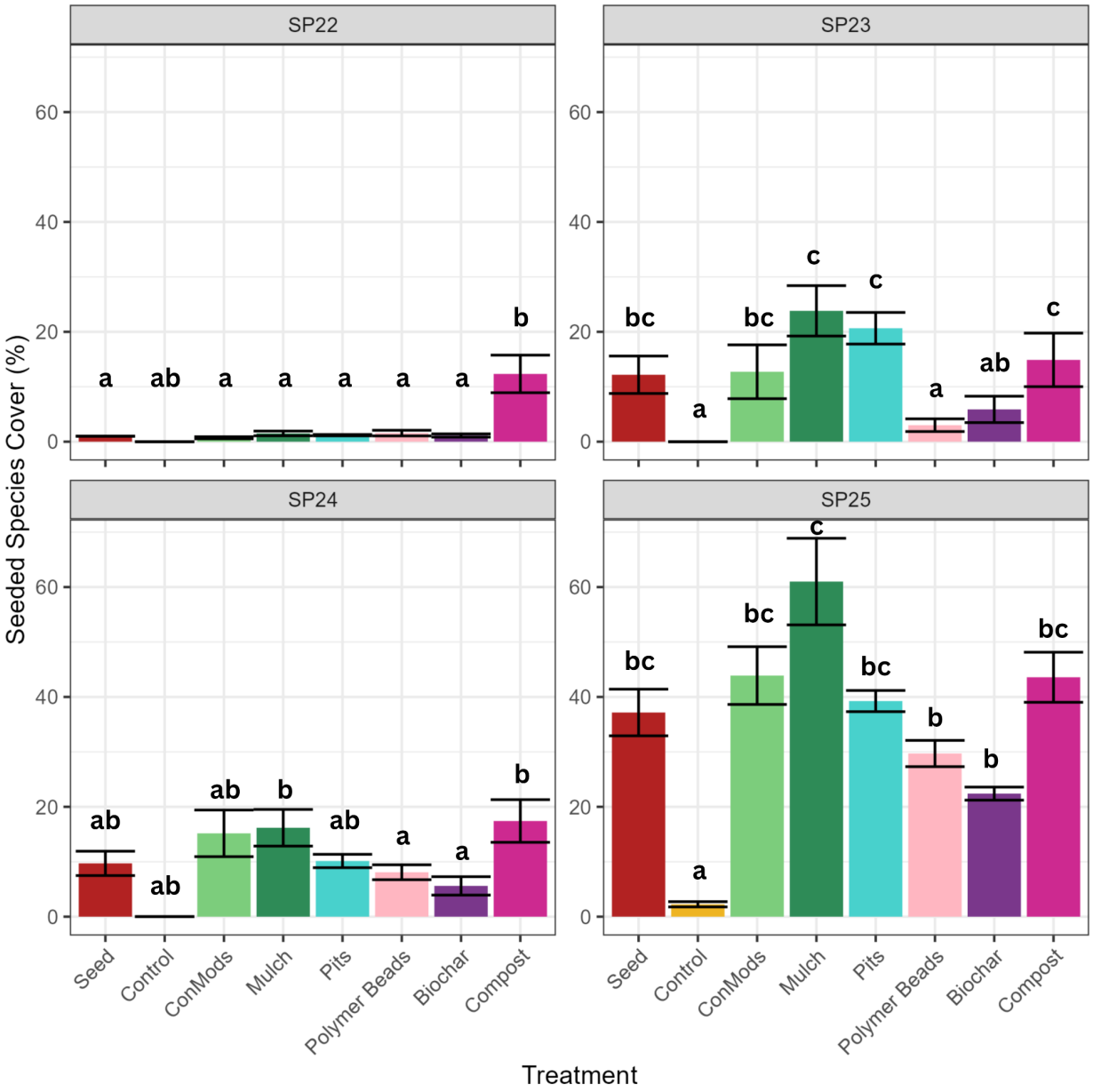


Figure S3. Seeded species cover (%) in full plot at the SWCRC site by treatment during each monitoring push.

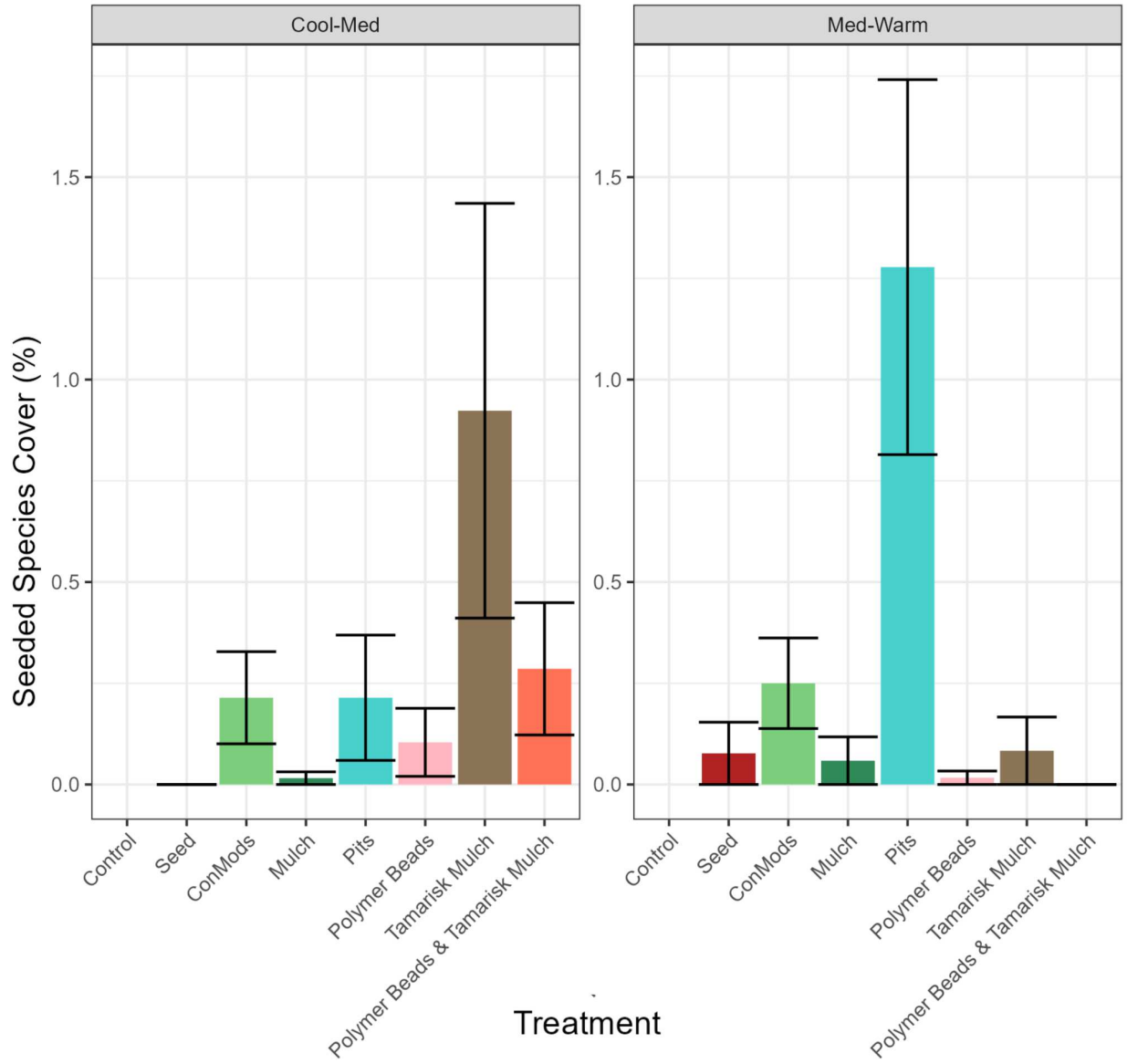


Figure S4. Seeded species cover (%) in full plot at the UMUT site by treatment. Results only visualized, not statistically significant (N.S.).

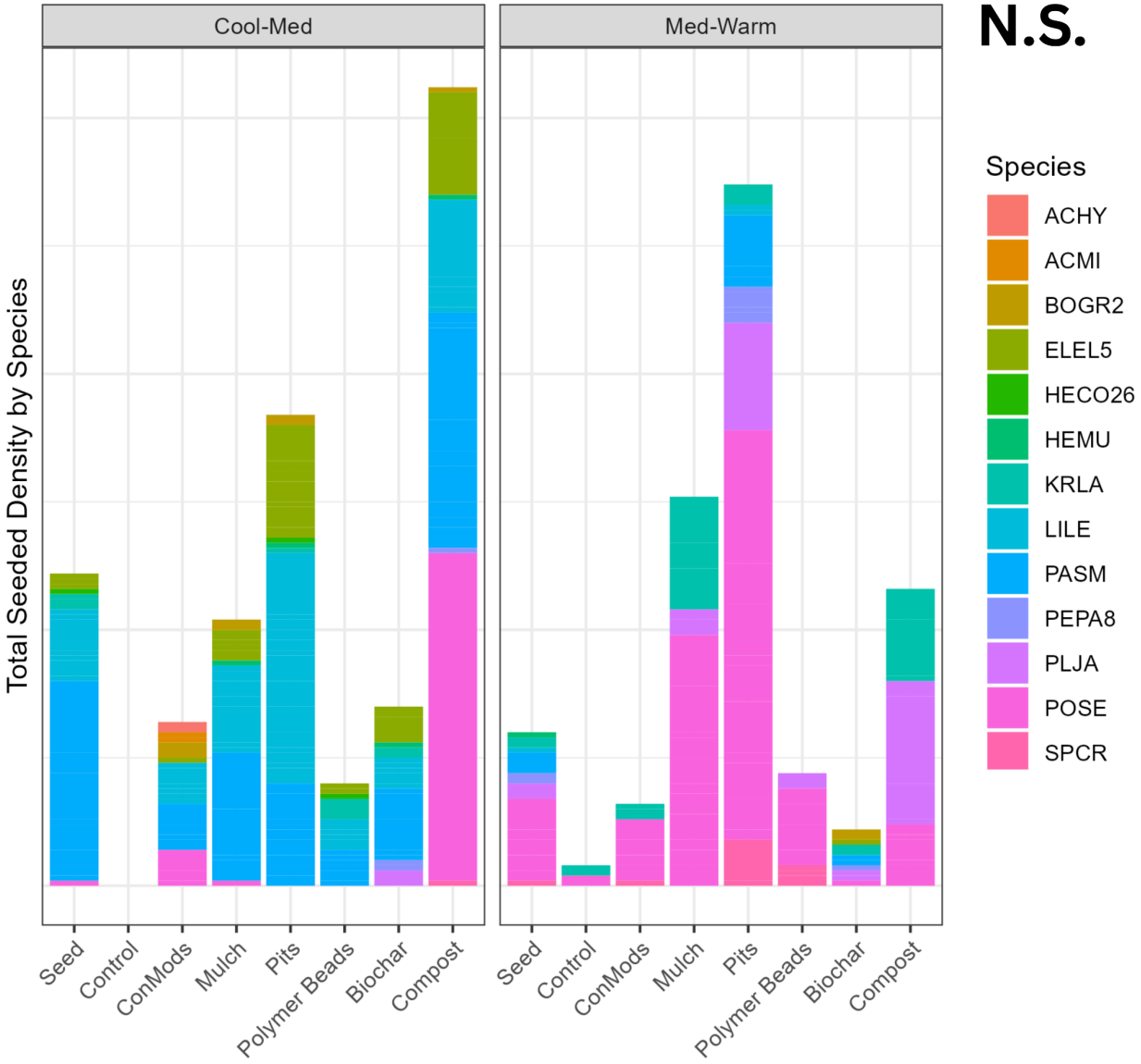


Figure S5. Density of different seeded species in the 0.25m2 subplot at the SWCRC site by treatment and average species. USDA species plant codes utilized in the legend (https://plants.sc.egov.usda.gov/) Results only visualized, not statistically significant (N.S.).