DISSERTATION

PARTNERSHIPS ON COLORADO CONSERVATION LANDS:

SOCIAL-ECOLOGICAL OUTCOMES OF COLLABORATIVE GRAZING MANAGEMENT

Submitted by

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In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2022

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ABSTRACT

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For millennia, rangelands of the Western United States, characterized by high quality forage and profuse biodiversity, have supported large herds of migrating herbivores. In turn herbivory has contributed to the maintenance of these ecosystems over time, a sort of co-evolution. Without disturbances like herbivory, they are vulnerable to soil erosion, woody encroachment, invasive species, and decreased soil quality and biodiversity. More recently, populations of native herbivores have drastically diminished on vast tracts of rangelands, including public lands. Government agency partnerships with cattle ranchers may fill this ecological gap and contribute to additional sociocultural and socioeconomic benefits. On the Colorado Front Range, the eastern flank of the Rocky Mountains, these kinds of public-private partnerships tend to be collaborative endeavors where natural resource conservation objectives intertwine with livestock production objectives. However, a debate over cattle grazing on government-owned rangelands is ongoing at local and regional scales.

Could conceptualizing cattle as *partners* in conservation be a win-win for the livestock and rangeland conservation sectors, resolving the seemingly paradoxical objectives of food production and natural resource management? To learn more about collaborative grazing management on Colorado’s rangelands, we investigated four northern Front Range partnerships between private ranchers and government agencies. Through a participatory and holistic research

model we addressed the three pillars of sustainability (ecological, social, and economic) and evaluated these landscapes as complex social-ecological systems.

Our specific objectives were: (1) to compare ecological indicators in areas managed with cattle grazing to areas that had been excluded from cattle grazing for at least ten years; (2) to evaluate how stakeholders in public-private partnerships perceive and value ecosystem services on government-owned lands, while understanding their level of consensus or discord toward management approaches and how these perceptions may influence collaborative decision-making; and (3) to develop an agent-based system dynamics model of human-environment-animal-forage dynamics that could be used as a learning and management tool in this region and potentially across global rangelands.

For the *ecological* component (1) we examined soil health measures of organic carbon, total nitrogen and water infiltration; vegetation measures of biodiversity and plant community composition; and forage nutritive quality. We learned that areas historically managed with grazing had higher percentages of soil organic carbon and nitrogen and higher forage nutritive quality compared to ungrazed areas. Water infiltration rates and plant community composition were similar in grazed and ungrazed areas, indicating that long-term grazing had not significantly altered these aspects of the landscape but rather maintained them, while supporting cattle production.

For the *socioeconomic* component (2) we studied the human dimension of rangeland ecosystems, where socioeconomic livelihoods and sociocultural values are entwined with land use. We explored values and perspectives of diverse stakeholders regarding rangeland ecosystem services. We noted patterns in how stakeholders prioritized certain ecosystem services categories over others and how this prioritization was a reflection of unique value systems. We learned stakeholders largely agree that multi-use rangeland management incorporates conflicting interests and tradeoffs, like recreation versus agricultural use. There was consensus that cooperative and collaborative management is an auspicious approach and may open doors to solutions, as stakeholder perspectives are likely rooted in overlapping values.

Knowledge gained from the ecological and socioeconomic studies was used to create an agent-based model, *ECo-Range* (Ecological Co-management of Rangelands), an applied learning tool to aid in management decision-making to meet social, ecological and economic objectives (3). As proof-of-concept, we used scenario simulation to examine relationships and interactions among ecological and socioeconomic themes. The model illustrates relationships among environmental conditions and management decision variables by generating measurable outcomes such as residual forage biomass, cattle performance, and vegetation heterogenity.

This dissertation advances the science and practice of collaborative conservation, which in this case supports sustainable food production through range-based cattle management. Through a holistic and cross-disciplinary approach to research and shared effort across multiple academic departments, local producers, and government agencies, we demonstrate that public-private partnerships in sustainability and natural resource management can nurture success in all dimensions of sustainability. Synergies between agriculture and conservation are possible, where cattle may be considered partners in the maintenance or even improvement of ecological function. Collaborative programs that provide additional grazing lands to ranchers in exchange for an ecosystem service also buffer ranching livelihoods and economic sustenance – a sustainability win-win. Sustainable rangeland management is not only about the ecological underpinnings of a place but also about supporting the people and communities who hold direct relationships with those landscapes. A social-ecological systems approach to research makes the weaving of diverse yet interconnected components possible.

ACKNOWLEDGEMENTS

"It takes a village," is a phrase we have all heard before. Until now, though, I don't believe I ever truly understood it. The completion of this dissertation was only possible because of my village, a community of people and organizations whose support was indispensable.

First, I would like to acknowledge my husband, Giovanni Taormina, for doing everything in his power to give me the physical, mental, and emotional bandwidth needed to achieve this lifelong goal. He has supported me every step of the way and made sure our family never lacked anything. Secondly, I acknowledge my parents, Malcolm and Ursula Monlezun, who from my earliest days, always believed in me and gave me new and bigger wings every time I grew out of my old ones. I credit them for teaching me responsibility, morality, integrity, and perseverance, all essential qualities for these past years of graduate school.

I am grateful for my brother, Benjamin Lee Monlezun, my closest friends, especially Wendy Loraine Colonna, my extended family, especially Uncle Charles, Aunt Sharon, and Cherie Monlezun, for strengthening me with their stories, making me laugh, and cheering me on along the way. Their words of encouragement and love were like rose petals dropped along the path, reminding me that I was heading in the right direction and had the courage within me to keep going.

I extend my sincerest gratitude for my past and present academic mentors, especially my PhD advisor, Stacy Lynn, as well as my dissertation committee, for their guidance and expertise as I waded through personally uncharted territory. I am grateful for their leadership styles buoyed by empathy, professional integrity, and a passion for teaching and guiding students to reach their fullest potential. I could not have asked for more brilliant and caring mentors through these years.

I would like to thank the people and their organizations who collaborated with us for this research endeavor. Their partnership proved to me the value of collaborative science and gave me hope that the management of our remaining “open space” and public rangelands are in the hands of people who truly care and desire to find solutions to the challenges we face today. In addition to the following list of partners, I extend special gratitude to the 40 participants of the human dimension component of my dissertation (Chapter 3), who persevered through a global pandemic for the sake of advancing science and research:

- City of Fort Collins Natural Areas Department:
  - Matthew Parker
  - Justin Fredrickson
  - Crystal Strouse
- Boulder County Parks and Open Space:
  - Robert Alexander
  - Chase Dryden
- Colorado State Land Board:
  - William Woolston
  - Lyndsay Brandt
- Ranchers:
  - William Altenburg
  - Bill Hogan
  - Quinn McElwee
  - Nick Trainor

I would like to thank the National Resource Conservation Service’s soil scientists, Kari Sever and Andy Steinert, for their time spent in the field with me to verify soil profiles at our research plots. Thank you to Colorado State University’s EcoCore lab technicians for their soil analysis services, as well as the undergraduate students from the SUPER (Skills for Undergraduate Participation in Ecological Research) Program, who each spent an entire academic year exploring our data, testing hypotheses, and creating academic reports and posters on the study. These brilliant students include, Arielle Collier, Sophia Thomas, Spencer Varga, and Gunnar Wagner. I extend a special thanks and great honor to Arielle Collier and Chiara Taormina, who served as field research technicians, and Gunnar Wagner, who served as a research assistant and coding wizard for the development of our agent-based model.

Last but not least, I am deeply grateful for the support of my scholarship donors and grant providers over the past three years, who lightened the financial burden of higher education and scientific research. My entire family benefited from this kind of community generosity and altruism. These donors and sponsors include:

USDA Western Sustainable Agriculture, Research and Education (SARE), 2020-2022
Lowry Ranch Stewardship Advisory Committee, 2020-2022
School of Global Environmental Sustainability Fellowship, 2021-2022
Office of the Vice President for Research Fellowship, 2021-2022
Oscar and Isabel Anderson Graduate Fellowship 2021-2022
James E. Ellis Humans and the Environment Scholarship, 2020-2021
Bohart Conservation Scholarship, 2020-2021
Francis Clark Soil Biology Scholarship, 2019-2020

PREFACE

The body of scientific literature is an ocean of stars, some dimmer than others, some brighter than others. I am humbled knowing that this star I am dropping into the ocean will be somewhere between bright and dim. Who may read these, my words, today, tomorrow, or years from now? I will never know…and therefore, as I write I remind myself that my deepest intention has simply been to learn and to relate. This dissertation is more than a means to another degree or scholarly accomplishment. It is an effort to form a relationship with others, humans and nonhumans, through questions and observations, theories and conclusions. In these pages, I am just telling another story of life through the lens of science.

In this scientific journey, one of the most important lessons I have learned is that there is not only one acceptable way or one effective way of communicating science, and in fact, many of the mainstream paths for communicating science never reach or "speak" to those who may benefit most from the learning. One path of communication that is both timeless and has the power to cross cultural and temporal boundaries is storytelling. The principles that have guided my work are conservationism, altruism, and stewardship, and therefore, I will use a story to convey their meaning and significance.

We called my paternal grandmother Maw-Maw. Maw-Maw was, as far as we know, 100% German and grew up in the Cajun French cultural region of south Louisiana. Her grandparents were immigrants and settled in a tight-knit German-speaking settlement there called Robert's Cove. They were master rice farmers, but that point is for a different story. Let's just say they were wholesome agrarians, through and through.

Maw-Maw knew how to do, seemingly, everything, from delivering babies (she had 10 of her own) to playing the accordion. She passed away when I was twenty-one years old. I am fortunate to have known her, my only grandparent who lived long enough to follow me into adulthood. I didn't realize how much her ways would impact me, given the all-too-brief time we shared in this life. Perhaps she runs in my veins; perhaps she runs through my neural pathways, co-created by the carvings of early life experiences. Nevertheless, I feel her presence in a very real way. I am still learning from her….

This story is about Maw-Maw, but this story is also about ecology, rather a way of living ecologically, not necessarily "green" actions, like recycling and buying organic, as these notions were hardly around in

Maw-Maw's time. What I'm talking about is a frame of mind, an eco-mentality infused with values shaped by life experiences—like being a German immigrant in racially-charged southern USA during World War II, or watching your parents "lose the farm" after the Great Depression, or surviving the loss of two of your own children in a drowning accident. Such things shape us and our relationships with other people, creating the concentric spheres of nature within which we call home. I will further my point in a trifold of anecdotes: pear preserves, alley cats, and chicken harvest.

During my childhood, I spent many weekends at Maw-Maw's house. The small pasture on the south side of the house was lined with a handful of pear trees along the fence. There were also fig, kumquat, satsuma, and other fruit trees on the land, but this story is about pears. I remember going out with her to harvest the fruit. I was encouraged to not collect that which still clung to the branches but to harvest the pears that had fallen to the ground and had not yet been discovered by birds or squirrels. Maybe this was to keep me busy, since I could only reach so many branches, but thinking back, maybe this was a greater lesson in not being wasteful—making use of only that which nature could spare. When the tree chose to let go of its own sweetly protected seed, it was fair game…for us or for the birds and squirrels…and finally, the decomposers, ants and worms. Soon after the harvest, as if by some act of magic, I would find these pears, cooked down and mixed with a bit of sugar and cinnamon, in a jar on the breakfast table. We would spread the soft preserves on toast with room-temperature butter. A delicious, nourishing treat to start the day. Only now am I conscious of the steps it took for the fruit of those trees in the pasture to make their way into my mouth. How easy it is for us today to grab a jar of jam off the shelf in the store, completely disconnected from the balancing act of sun and water and earth, and the responsibility of taking part ourselves. For Maw-Maw, being disconnected was not an option, and even if it would have been, I'm not so sure she would have chosen it. Conservationism.

Maw-Maw married a Cajun-Basque Frenchman and they raised their large family in a very small agricultural and fishing town. Paw-Paw's work was in the bulk fuel business. They say he opened a new business each time Maw-Maw was pregnant, but propane was his main gig. Big white trucks with red hand-painted letters delivered vital resources to surrounding farms and ranches. All the families outside of town also depended on topped-off propane tanks to keep their families warm and fed. Paw-Paw was never willing to let a child go cold or hungry, so he accepted barters, a freshly cleaned goose here, a sack of rice there. On handwritten ledgers, he kept track of credit on the honor system and was known to forgive that which could not be given. Maw-Maw and Paw-Paw lived "in town" with a grass alley behind their big white wooden house that allowed safe passage for children (and animals) between 2 rows of houses without having to intersect paved streets. In my day, there seemed to have always been stray cats hanging around, especially as the sun began to sink behind those sheer curtains of Spanish moss down by the lake. Maw-Maw called them "alley cats." Each evening, I can recall her preparing a small dish of milk and torn up slices of bread (a would-be delicacy at an earlier time in her life) for the alley cats. Sometimes she'd ask me to bring the dish out back through the squeaky screen door and place it at the base of the steps where purring bellies awaited. I remember it feeling so warm and sparkly inside to feed those alley cats. I also remember my grandmother often serving herself last and very little at the dinner table. Making sure everyone else had their plenty before partaking herself, she waited for all the "children" (she had many grandchildren as well) to finish eating, and then she would complete her meal with what food was left in little clumps and piles, scooted left or right by chubby hands, to satisfy her own belly. Yet, those alley cats got fresh milk and sliced bread. Putting the needs of others before one's own was as common in that big wooden house as lullabies were at bedtime. Altruism.

I never saw it with my own eyes, but my Maw-Maw was known for being able to wring a chicken's neck with a flick of her wrist. Remember, she was German, big-boned, as they say. Being a vegetarian during my teenage years, I was abhorred yet fascinated by this local legend. Little did I know, I would be a rancher myself one day, and intimately understand this relationship with my own food. Maw-Maw had a household of twelve. Think about how that translates into countless numbers of dishes to wash, shirts to iron, socks to scrub, shoes to darn, hems to stitch, boo-boos to kiss, and twenty consecutive years of hanging out cloth diapers to bleach in the sun. Meal preparation was but a daily necessity, and while no time could be spared in the act of bringing the ole bird to terms with death, I remember that cooking was an ongoing ordeal. Was there ever not a pot on the stove from when I woke up in the morning to when I brushed my teeth at night? Not that I can remember. In addition to fruit trees and chickens, Maw-Maw and Paw-Paw tended a *greenhouse, and a 15-acre potato and turnip "patch" where ecological knowledge had passed from hand-to-hand through three generations. I remember spending time in those swamp-lined rows picking potatoes and turnips, which ended up in sacks and gifted to propane customers or which earned a little credit at the local grocery store. In those days, times were never too hard to spread the wealth, I guess. The "boys" learned to hunt rabbit, duck, blackbird, and goose. All of those went in the pot. Plants and animals and our lifecycle entwined with theirs was a concept embedded in Maw-Maw's way of life. Now, being an agrarian myself, I realize how much care and tending, sweat and blood, and conscious choice that this way of life required of her—child and animal, land and home. Stewardship.*

And so, conservationism, altruism, and stewardship – These are principles rooted in the life of one woman and in the memories of her granddaughter, an ecological frame of mind, of generations passed, a way of living in relationship with our environment and each other… A path we would all do well to re-member.

And so, this dissertation is a study, but it is also a story, one which weaves the principles of conservationism, altruism, and stewardship in a tapestry of scientific inquiry.

Chapter 1 starts with the theoretical and philosophical foundations for exploring the social-ecological complexities of rangeland ecosystems. I draw from a temporally and culturally broad pool of thinkers and doers in the ecological, political, and social sciences to build a framework for the research studies that follow. I conclude with a proposition that we use intentional language and a new metaphor to imagine a kind of rangeland stewardship imbedded in relationship.

Chapter 2 presents a study of soil and plant dynamics on government-owned lands that are collaboratively managed with cattle grazing. I compare historically ungrazed portions of land to areas where cattle roam. I consider differences in soil nutrient cycling, hydrology, plant species composition, forage quality, and patterns among these variables to answer the question: *Are there significant differences in soil nutrient composition, plant community and species diversity, and forage quality between historically grazed and ungrazed areas?*

Chapter 3 describes a social science study in which I explore the values, perspectives, and opinions of various stakeholders affiliated with government-owned conservation lands. I attempt to answer the question: *What are the unique sets of values and perspectives toward ecosystem* *services among collaborative grazing management stakeholders, and how does the prioritization of these values drive dynamic decision-making?* I use both qualitative and quantitative methods to create a social narrative that helps us understand the complex human dimension of rangeland ecosystems, where socioeconomic livelihoods and sociocultural values are entwined with land use and the ecosystem services we derive from our relationship with these landscapes.

Chapter 4 presents a novel application of agent-based modeling to represent the social-ecological dynamics of grazing systems. I use a combination of geospatial information technology applications, climate data, and verified parameters to create a simulated "world" where human decision-making is directly linked to land and livestock outcomes under variable and emergent environmental conditions. Our model, *ECo-Range* (Ecological Co-management of Rangelands) is intended for use as a learning and management tool to answer the question: *How do select cattle management and land use decisions affect grazing system outcomes under various environmental conditions?*

Chapter 5 is a synthesis of learning and impacts derived from preceding parts of the dissertation. In this concluding section, I discuss the significance of collaborative conservation and contributions of this dissertation to the future management and developing story of rangelands. I close with a note of encouragement for the world's community of rangeland stewards to continue to re-imagine and re-story our relationship with these ecosystems, as the challenges of our times call for a new paradigm of attuned adaptability, creativity, knowledge and… love.

Each chapter 1-4 in this dissertation is intended for future publication as a standalone article in a peer-reviewed journal. Therefore, each chapter is intended to be read as an individual work. Each chapter is complete with its own extensive literature review for purposes of the dissertation, although this specific content will be condensed for future manuscripts. Formatting, language and tense may differ between chapters. All future articles will have at least one co-author; thus, I use the plural pronoun "we" throughout.

DEDICATION

To my son, Gavino Malcolm, who, at age four, gave me my 2nd most cherished title (after Mamma) – "Grasslands Helper." That the world we create for our children today be one of beauty, peace, and relationship, infused with a sense of reciprocity for all living things and respect for the ecological processes of which we are a part.

TABLE OF CONTENTS

CHAPTER 1: THEORETICAL FOUNDATIONS FOR RE-IMAGINING THE RANGE

RANGELANDS, A STORY

For millennia, rangelands, characterized by high quality forage and profuse biodiversity, have supported large herds of herbivores. In turn herbivory has contributed to the maintenance of those ecosystems, sustainably shaping plant communities, forage quality, wildfire patterns, and soil nutrient cycling (Bell 1971; Derner et al. 2006; Gibson 2009; Knapp et al. 1999; Porensky 2020; Teague et al. 2016). By use of the ecological term "maintenance," I also mean the timeless dance of feedback cycles, symbiotic relationships, and adaptability through interconnectedness. Rangeland is defined as "land supporting indigenous vegetation that either is grazed or that has the potential to be grazed and is managed as a natural ecosystem. Range includes grassland, grazable forestland, shrubland and pastureland" (Society for Range Management 1998).

Wedged between the towering Rocky Mountains to the west and the rolling Western Great Plains to the east, Colorado's Front Range is a rich and colorful mosaic of various land uses and land ownership patterns (Figure 1.1). In addition to defining the region's cultural heritage, open rangelands are some of its most valuable assets.[1] Rich in natural resources, fertile soils, a mild climate, and access to two major watersheds, rangelands are highly valuable to this ecoregion and to humans, yet without evolutionary disturbances like herbivory, they are vulnerable to soil erosion, invasive species, decreased soil quality and decreased biodiversity (Environment Colorado Research and Policy Center 2006; Rondeau 2001).

[1] I acknowledge that referring to aspects of nature and the non-human world as "assets" has an anthropocentric edge. To speak of nature as an *asset* or a *natural resource* is to assume that it exists for humankind's use and exploitation. I will address this further in a later section of the paper. However, in this Introduction to my work, I choose to use the words *assets* and *natural resources* for the sake of writing within the epistemic regime of my field.

Figure 1.1. Map illustrating the area called the Colorado Front Range, according to Colorado's official tourism website. https://www.colorado.com

We have long since driven out the abundant herds of wild herbivores from Earth's vast rangelands. Large migrating herbivores, like bison (*Bison bison*) of the American West and wildebeest (*Connochaetes gonu*) of eastern and southern Africa, are known to have traveled hundreds of miles, sometimes cross-continental, to fulfill their nutritional needs (Bell 1971; Boone et al. 2006). Their movements and impact across the land was adaptive to ecosystem dynamics, like drought, rainfall, fire, and predation. They also responded to influences of indigenous peoples, who played a role in shaping rangeland ecosystems through hunting, cultivation, wood collection, and strategic use of fire. In these times, there was a balance of give and take, an ebb and flow of resources and population dynamics that was necessary to maintain the ecological integrity of these systems (Ellis and Swift 1988; Illius and O'connor 2000). Yet as the historical range of migratory animals was fragmented by colonialism and growing human populations, and as some large herbivore species were nearly wiped from the map, these resilient ecosystem processes were altered.

More recently, cattle, among other livestock species, have replaced their wild brethren. In response to consumer demands for sustainably raised animal products, improved natural resource management, and climate change mitigation, both the ecological and agricultural sciences are working to demystify how cattle may contribute to the sustainability, and even regeneration, of these landscapes by mimicking the native large herbivores of the range (Cusack et al. 2021; Environment Colorado Research and Policy Center 2006; Knapp et al. 1999; Schwartz 2013).

Over the last thirty years, the Colorado Front Range region has accounted for more than half of the state's population growth (Mladinich 2006). In 2020, I conducted a land ownership-land cover analysis using geospatial data from the National Land Cover Database (Yang et al. 2018) and data made available by the Colorado National Heritage Program and Colorado State University (Colorado Natural Heritage Program and the Geospatial Centroid 2020; Yang et al. 2018). This analysis revealed that government-owned lands encompass over 65 percent, or 450,000 ha, of more than 1,300,000 ha of rangelands on the Colorado Front Range. In other words, almost two-thirds of all Front Range rangelands are government-owned.

This was not the case just two generations years ago when private family ranches defined the cultural heritage of the Western Great Plains (Environment Colorado Research and Policy Center 2006; Knapp and Fernandez-Gimenez 2009; Oberholtzer et al. 2010). Recent trends on the Front Range show that family-owned ranches are more frequently being sold for nonranching uses, commonly urban development (Environment Colorado Research and Policy Center 2006; Knapp and Fernandez-Gimenez 2009; Oberholtzer et al. 2010). The danger in this trend is not only the loss of intact rangeland habitat, but loss of local ecological and practical knowledge acquired over generations of family and social networks and direct experience with the landscape (Environment Colorado Research and Policy Center 2006; Knapp and Fernandez-Gimenez 2009).

A combination of increasing real estate values, competition for water resources, and higher labor costs associated with urbanization, is making it difficult for ranchers to maintain sustainable operations, or for a new generation of agrarians to enter the ranching lifestyle (Environment Colorado Research and Policy Center 2006; Oberholtzer et al. 2010). The material wealth of ranching is typically bound in land and livestock assets, and the only way for ranchers to realize this wealth, when necessary, is to sell these assets, particularly land. Therefore, projections of private agricultural and rangeland losses to urban-related development are formidable and underscore the impermanence of rangelands under such economic drivers of change.

Meanwhile, the future of these and global rangelands may rely on various and innovative approaches by diverse institutions, organizations, and initiatives government agencies, community cooperatives, indigenous nations, private landowners, small non-profit organizations, and large non-governmental organizations (NGOs). I believe rangeland conservation depends on two interconnected and cooperative efforts: 1) developing strategies to keep private ranches in agricultural production, and 2) adopting trans-scale and trans-sector (public and private) programs to manage and protect rangeland ecosystems that would otherwise be converted to alternative land uses. This kind of work is already being attempted and studied across the world, commonly referred to as *collaborative conservation* (Kemmis 2001; Plummer and Hashimoto 2011; Reid et al. 2021; Whyte 2016; Wilkins et al. 2021).

The challenge to modern grazing systems, specifically in the American West is three-fold: a) the availability of intact, healthy rangeland ecosystems to support cattle production, b) the sustainability of economic markets for range-based cattle production, and c) a social-ecological ethics that informs just policy and inspires moral human behavior. This dissertation presents a tapestry, rather than a road map. I will weave these ideas, supporting theories, and proposed challenges into the presentation of experimental studies and conceptual models, beginning with a thought-exercise, a proposal for the re-storying of rangelands that begins with us, our language, and our philosophical approach to stewarding these landscapes.

RE-STORYING, THE METAPHOR

Some of the oldest traces of humankind's presence on Earth is in the form of art. Cave drawings, tools, talismans, jewelry – the use of color and form that simultaneously creates and harbors meaning in its very essence is as present in human history as gathering food. We know that preliterate cultures did not even have a concept for art, as we think of it - art for art's sake. They had crafts and were crafts(wo)men, combining utility with beauty (Bookchin 1982; Morton 2018). The very essence of their community with their surroundings inspired an animism and brotherhood with non-human nature. Their use of metaphor and myth was a way of knowing, understanding, and being in the web of life (Bookchin 1982). In *Ecology of Freedom*, Murray Bookchin (1982) describes the Eskimos' use of carved ivory for tools and the Plains Indians' relationship with the horse:

> *...by assuming subjectivity in the ivory and horse, [they] establish contact with a truth about reality that mythic behavior obscures but does not negate. They correctly assume*

that there is a "way" about ivory and horses, which they must try to understand and to whose claims they must respond with insight and awareness (p 322).

The term "Way," is universal to the language of all early communities, united ethos, ritual, sensibility, duty, and lifestyle with cosmogony and with the substances that made up the world. To set one apart from the other was simply incomprehensible to the extraordinary sensibility of that remote era (p 318).

Whether in art or craft, symbols that tell stories become metaphors. They reflect centuries of rich indigenous ecological knowledge about animals, plants, geology, and water, and provide "prescriptions for sustainability" about restoring balance with nature or the consequences of taking too much (Kimmerer 2013). Examples of these prescriptions through the lens of traditional ecological knowledge can be found in Dr. Robin Wall-Kimmerer's (2013) *Braiding Sweetgrass* and her stories of, The Three Sisters, Maple Nation, and The Honorable Harvest. I believe that metaphors from early stories and myths are still found in our "collective social imaginaries" (Schulz 2017), and continue to construct and inform the mental and physical policies by which we live.

In the American West, our stories about rangelands are largely about taking and conquest. If we contemplate films and storybooks of the "wild wild west," we become aware of an intense focus on commodification of natural resources, the robbing of land from indigenous peoples, and the disadvantaged life of cattle being driven across dusty, barren landscapes. Images of an also beauty-laden, wide open prairie are juxtaposed with plot lines glorifying the exploitation of and disharmony with the natural world. How have these metaphors from popular culture framed and perpetuated our collective understanding of rangeland ecosystems?

In fact, metaphor does more than provide a platform of understanding. It also creates feeling. Why is the American West so easily romanticized? Perhaps because we crave the "rich sensual stimulation of the natural world" because we are aesthetically and archetypally bound to it (Ophuls 2011). Beauty is critical, an essential truth that is beyond logic or discourse because it is an experience, the experience of co-existing with something beyond oneself (Morton 2018; Ophuls 2011). For an idea to take effect and have power in the masses, it needs to invoke emotions. Metaphor, clothed in beauty, may have this power. For example, in his discussion of ecopsychology and indigenous traditional ecological knowledge, Johnathon Coope proposes that for people to act urgently on climate change, it has to become an "emotional issue" (Coope 2019). We are a species who yearns for emotion because it gives depth to our understanding. In *Plato's Revenge*, William Ophuls (2011) writes:

> *As obligate poets, we necessarily add feeling to understanding. The cerebral cortex simply has no way to think in isolation from the older subcortical layers of the brain that are emotionally attuned to symbolic meaning (p 79).*

The ecosystems of our planet and the way we understand them are shifting and require critical and adaptable attunement by people. Greg Marshall, who coaches climate activists, said that there is a "need for environmentalism to move from the head to the heart" (Coope 2019). Metaphor can naturalize, transform, transcend, and reconstruct our cognitive realities and identities at the urgent pace required by today's environmental crises (Schulz 2017). To find meaningful metaphors that stand for our physical realities is, I believe, the "task of science" (Ophuls 2011). Assimilating the arts within science may enlarge its practice and its receptivity by eliciting emotions. Afterall, metaphor has a much longer history of communicating truth than scientific data (Haraway 2016).

The state of Earth's rangeland ecosystems requires this critical urgency. Here, I heed Coope's advice and attempt to "re-story" our relationship with rangelands (Coope 2019). To do this I propose a three-element metaphor that speaks to the needs of rangeland stewardship today. This metaphor stems from a myth painted in the 1927 silent film, *Metropolis*, "The mediator between head and hands must be the heart" (Lang 1927). The story of *Metropolis*, written by Thea von Harbou, depicts a utopian society blind to their not-so-alternative reality, where a hidden society of workers and machines toil in subterranean darkness to make the world above run.[2] One day, an above-ground citizen discovers and falls in love with a woman machine from the underground, and there thickens a plot of awakened consciousness, revolution, love, and revenge. Woven within this work are metaphors for class division, environmental justice, exploitation, and idealism. As the primary allegorical theme in the film, the *head-hands-heart* metaphor is an offering of mediation, where the heart is the answer to an extreme disconnect between the head and the hands (Figure 1.2). It speaks to the transformative power of the heart in human-to-human and human-to-nature relationships.

I choose to ground my social-ecological theory of rangeland ecosystem stewardship in the scientific and artistic phenomenon of metaphor because I believe that it is something perhaps missing in our approach to modern wicked problems (Rittel and Webber 1973), those that

[2] This metaphor also echoes the microscopic world of the soil microbiome, of which we are just recently beginning to understand. The billions of organisms that our sense of sight cannot detect unassisted may be responsible for life as we know it. Like the underground society of Metropolis, if the soil microbiome were irreversibly disrupted (i.e., by pesticides, herbicides, and chemical fertilizers), it would initiate a cascade of devastation on Earth's above ground social-ecological systems.

reductionist, linear thinking have obscured. What if we deconstructed some of our old stories and in their stead re-imagined and reconstructed new stories (Haraway 2016)? I intend the head-hands-heart metaphor could contribute to such a re-storying.

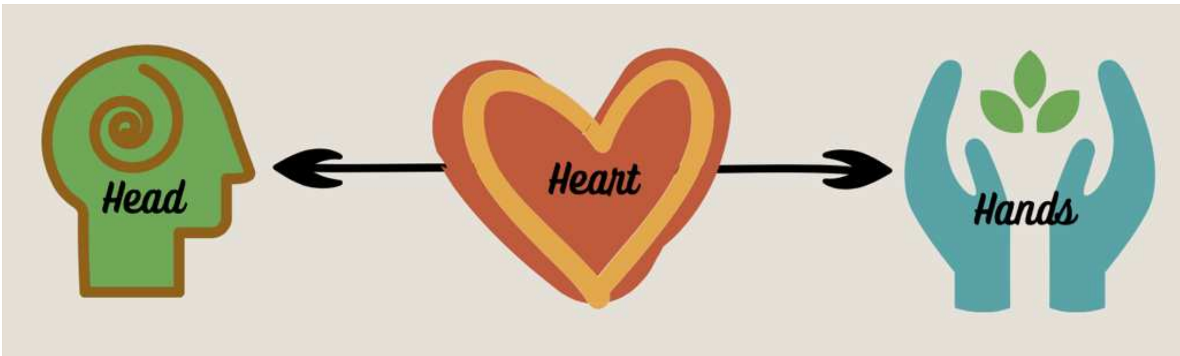


Figure 1.2. Conceptual diagram of the head-heart-hands metaphor as an approach to rangeland management and ecological stewardship.

THINKING, THE HEAD

"It matters what ideas we use to think other ideas (with); it matters what stories we tell to tell other stories with; it matters what thoughts think thoughts..." (Haraway 2016). Donna Haraway (2016) gives wings to this motif in her work, *Staying With the Trouble: Making Kin in the Chthulucene*. She calls for a new way of thinking in ecology - *sympoiesis*, defined as "collectively-producing systems that do not have self-defined spatial or temporal boundaries" (Dempster 2015; Haraway 2016). By this she refers to the undeniable interconnectedness of every animate and inanimate component of our world. People, animals, plants, rocks, and water are to be thought of as assemblages in the web of life. I believe that if we continue to turn a blind eye and act on one component while ignoring impact on another, we will be on a path to self-destruction.

The word *ecosystem* is a blend of *ecology* and *system. Ecology* comes from the Greek word, *oikos*, home and dwelling place, and signifies the study of organisms and their environments. *System* comes from the Greek, *systema,* which is an organized whole or a group of parts that operate together for a common purpose (Woodmansee et al. 2021). Therefore, an ecosystem is a home where a group of organisms live in concert with each other through a common purpose. Ophuls (2011), an ecologist and political scientist, claims that "ecology is the surest cure for modern hubris." Why? Because the ethics that result from an ecosystem-based worldview flow directly from the laws of ecology itself - symbiosis, balance, interrelationship, mutualism, and natural limits. Bookchin (1992) calls this the "naturalization of humanity," the mimicking of natural laws and ecological design.

For me, the study of ecology also means commitment to being a perpetual student with countless teachers, every flower, protozoa, hervibore, headwaters, seed, fish, fruit, insect, and bird. Ecological thinking, therefore, is about understanding the profound effect our decisions and actions have on other life forms, and how we may sustain the liveablilty of our world, not for some, but for all. In *Being Ecological,* Timothy Morton (2018) explains that ecological awareness is "equivalent to acknowledging in a deep way the existence of beings that aren't you, with whom you coexist. Once you've done that, you can't un-acknowledge it. There's no going back." It seems that few other cognitive frameworks have the capacity to reconcile the relationship between humans and nature in this way.

We may also need to expand beyond quantitative field data drawn from objective measurement. For some time now, rangeland scientists have advocated that research be conducted "in the context of complex adaptive systems in which human variables such as goal setting, experiential knowledge, and decision-making are given equal importance to biophysical variables" (Briske et al. 2011). Giving equal weight to the human dimension and ecological measurements reconciles the misconception that we are somehow outside of the natural system being studied. I turn to deep ecology, ecocentrism, systems ecology, and social ecology to further this theme.

The *deep ecology* philosophy is one which does not set humans apart from nature, but which places them in a role of symbiosis and a relationship that is complex, egalitarian, autonomous, and anti-class (Naess 1973). For deep ecology, all living things have intrinsic value, which can only be understood through an intimate connectedness and profound identification with all life. Intrinsic value has recently resurfaced as a significant socio-culture value type connected to the ecosystem services concept and the way human valuation of nature leads to patterns in decision-making (Díaz et al. 2018; Pascual et al. 2017).

Likewise, *ecocentrism,* according to Eckersley (1992), an influential theorist in environmental politics, upholds that:

> *The world is an intrinsically dynamic, interconnected web of relations in which there are no absolutely discrete entities and no absolute dividing lines between the living and the nonliving, the animate and the inanimate, or the human and nonhuman (p 49).*

This view challenges the Western status quo of anthropocentrism, where the natural world is primarily of instrumental value to humans, who are regarded as separate, superior beings and the pinnacle of evolution. Eckersley (1992) sees anthropocentrism as not only an inaccurate perspective on life but also a potentially dangerous one.

An ecocentric consciousness is an alternative approach to the anthropocentric framework for global problems of environmental sustainability. In considering the human values, attitudes, and beliefs which drive anthropocentric actions, Helen Kopnina (2012) proposes biospheric altruism as an extension of human concern toward nature, not because of its economic value, but because of its intrinsic value. We could consider an anthropocentric approach as shallow ecology, and an ecocentric approach, deep ecology. Through the union of the emotional, cognitive, and philosophical dimensions of human nature, maybe a truly ecocentric, deep ecological perspective can be expressed toward the natural world (Kopnina 2012).

Systems ecology is a mental paradigm and a way of practicing ecology rooted in this holistic view of the world, where networks of people and their environments are dynamic, adaptive, and ever-changing (Woodmansee et al. 2021). Its essential lesson is that "our fate is linked to everything else in the biosphere and that we do not and cannot exist apart from the rest of nature" (Ophuls 2011). The challenge for addressing rangeland ecosystems through the lens of systems ecology is persuading large numbers of people to adopt these new concepts, beliefs, and even values (Woodmansee et al. 2021). In fact, it has been said that the most powerful fulcrum for changing a system's behavor is its "mind", the mental map controlling its objectives, organization, and "rules" (Ophuls 2011). Systems ecologists can bridge these gaps with philosophers, sociologists and behavioral scientists. Therefore, rangeland ecosystem science should not be conceived of as a natural science alone, but also a social science. As Nathan Sayre (2017), a human geographer and author of *Politics of Scale: A History of Rangeland Science*, said, "There's a growing recognition that, in fact, our environmental problems and challenges have more to do with people than they have to do with ecosystems and the bio-physical sciences per se."

Regarding the human dimension of an ecological world view, Bookchin (1982) presents the concept, *social ecology*, an expression implying that environmental issues are really social issues. Bookchin's social ecology is founded on three principles: 1) Unity in diversity where balance and harmony are achieved through an "ever changing differentiation, an ever-expanding diversity;" 2) Natural spontaneity, where respect for nature entails giving leeway for diverse biological processes that develop varied ecologies; and 3) Non-hierarchical relations, thinking of ecosystems as webs with an interlacing nexus, rather than a stratified pyramid. Like systems ecology, social ecology proposes a web-like metaphor to describe the human-nature relationship.

Those of us who are privileged to live and work within rangeland ecosystems understand that "humanity does not stand apart from the whole system. We exist because of the system, and our continued existence requires understanding and respecting the mutual interrelationship that binds man's fate to the rest of nature, living and nonliving alike" (Ophuls 2011). We know that damage to one part of the system for the sole benefit of another is simply unsustainable. Yet as a collective society we tend to act on the contrary for the sake of short-term gains. If we employ a short-term mentality, then economic needs and lifestyle desires take precedence over potential long-term consequences or consequences to system components outside one's immediate circle. How do we engage those people who do not want to take part in the sustainability conversation, who deny the dangers of climate change, or the need for mass behavior change?

Can re-storying by the collaborative and transdisciplinary efforts of ecologists, social scientists, and economists, erode those mentalities which are leading us all down a treacherous path? Deep ecology, ecocentrism, systems ecology, and social ecology provide philosophies that seek to re-inspire our way of thinking, by endorsing the undeniable sympoiesis of the human and more-than-human realms. Like Haraway, I believe it does matter what thoughts we use to think other thoughts, and what stories we use to generate our own stories, because these ideas are what feed our actions.

ACTING, THE HANDS

In the head-hands-heart metaphor, the hands are the transcription of thoughts into action. In effective rangeland stewardship, the first action step is to ask questions, then make observations and construct ideas about how things work. This is also science. Science is a lens for viewing the world through systematic, critical inquiry. However, it is the process of "doing" science that brings us into intimacy with life beyond human beings (Kimmerer 2013). It is this intimacy that fills us with wonder and relationship, the kindling needed to spark the right kind of action.

Sustainability science is a field formally born in the 21st century and offers one of many sets of hands for taking action in a sympoietic world. It is a unique field in that it is solution-focused and addresses real-world situations that can only be studied beyond the bounds of orthodox scientific method (Boone and Galvin 2014; Boone and Lesorogol 2016). Questions of sustainability focus on interdiscplinary problems that span from hyper-local to global spatial scales in highly dynamic environments, in which impacts are often beyond the scope of political and management boundaries where the causes lie. It is precisely this mis-match of origin and impact scales and the reach of centers of power that leads to the wickedness of sustainability problems.

Sustainability science is a field that examines social-ecological systems, often those that are human-engineered, to understand challenges that threaten the integrity and future of life (Kates et al. 2001). Highly dynamic and coupled tightly with humans across the globe, rangeland ecosystems are well-suited for a sustainability science perspective. The concept of sustainability is often illustrated by a metaphor: a three-legged stool, with each leg representing a component: 1) ecology/environment, 2) people/community, and 3) economy (Basiago 1998; Purvis et al. 2019). Each of these three components must be addressed and integrated in the quest for sustainable solutions. A potential flaw of this metaphor, however, is the illusion that each component should be given equal footing. Is it ever truly sustainable if economic gains are given equal weight to ecological function? Consider the story of the Colorado River (Formisano 2022):

> *Today, the Colorado is a far cry from the historically unpredictable, silt-laden river that the region's original inhabitants and subsequent explorers would have known. Although some of the river maintains some of its former luster, it has been described as a "river no more," as thousands of ditches, dams, and headgates divert much of the Colorado's flow toward exploding urban centers and expansive agricultural areas (Fradkin)… Depending on one's point of view, these dams have brought countless economic benefits or environmental disasters to the arid west (p 1).*

It is difficult for humans to conceive of scales outside of human-scaled frameworks, at the expense of excluding other beings and processes we are not able to factor (Morton 2018). Failure to avoid so-called unintended consequences is at the root of many of our problems today. Previously, actions in favor of sustainability, were also actions that worked to optimize certain components of complex socio-ecological systems (Walker and Salt 2012). Optimization means being efficient with our natural resources, and so we may change approaches to manufacturing systems and supply chains to optimize and improve efficiencies. Unfortunately, modifications on the basis of efficiency do not necessarily result in sustainable systems, because focusing on select system components may leave other components deficient and vulnerable (Walker and Salt 2012). Examples of this can be found in industrialized agricultural, geological, and energy extraction systems. These structures are so tightly bound in the optimization of isolated components, that one upset in the system causes disturbance throughout. These so-called efficient systems lack *resilience* (Walker and Salt 2012). Without resilience, the capacity to recover from disturbance through adaptation or resistance, a system is not sustainable, ecologically, socially, or economically.

The challenge in creating action based on an ecocentric philosophy is taking into account all potential outcomes and on diverse temporal and spatial scales. Often, programs that prove successful in creating resilient and sustainable ecosystems share a common theme – *collaboration* (Walker and Salt 2012; Woodmansee et al. 2021). In addition to creating community and social accountability, collaborative action ensures that a multitude of perspectives are recognized and diverse voices are heard, even those which speak without words (Ophuls 2011). Dr. Seuss' children's book, *The Lorax*, still best describes what I believe should be a pervasive existential societal dilemma: Who will speak for the trees? (Geisel 1971).

Collaboration starts with recognizing which persons or entities need a voice at the table, and then extending a participatory role to them. David Schlosberg's (2009) theory of environmental justice emphasizes the importance of recognition and participation of all stakeholders, which broadens engagement across the public sphere. He applies his environmental justice theory to ecological justice, including non-human nature (Schlosberg 2009).

> *But almost all individual animals—human and nonhuman—need not just some others of their own species, but a full environment, including nonsentient life and ecosystem relations, as part of their capability set in order to flourish (p 148).*

Schlosberg's is a holistic framework rooted in ecological thinking. In this sense, animals, plants, and ecosystems are recognized as contributors at the table of collaboration. Schlosberg contends that we need to recognize nature as part of our shared community, and through this recognition, the natural world may "participate" in human decision-making (Schlosberg 2009). I propose that we further Schlosberg's idea of participation to incorporate shared responsibility.

Using case studies that portray successful efforts in collaborative ecological work, Kyle Whyte (2016) emphasizes the role of shared responsibilities between people and nature and between different groups of people. For Whyte (2016), responsibility is synonymous with "interdependence, caring, sharing, reciprocity, and stewardship." The idea here is that both humans and nature have mutual responsibilities toward each other. Therefore, if we imagine water, for example, as having a responsibility toward humans, animals and plants, then we can make collective decisions that respect water's role in the larger web of relationships (Whyte 2016).

Working on problems in the natural world without working on our relationship with the natural world would likely falter because we would have removed ourselves from the whole system by thinking this way. It would be an "empty exercise" (Kimmerer 2013). Therefore, relation-ing ourselves with nature in acts of reciprocity may be the real work. This is a unique way of thinking in science, and one that owes credit to indigenous cultures and their profound way of living in relationship with the natural world (Whyte 2016). Kimmerer (2013), also hinges much of her approach to ecological dilemmas on reciprocity:

> *One of our responsibilities as human people is to find ways to enter into reciprocity with the more-than-human world. We can do it through gratitude, through ceremony, through land stewardship, science, art, and in everyday acts of practical reverence (p 190).*

This echoes Haraway's (2016) concept of *response-ability.* Response-ability poetically connotes our *ability* to consider all of the social-ecological underpinnings, histories, and potential outcomes in the way we *respond* to life. In Haraway's (2016) words, "it is presence and absence, killing and nurturing, living and dying – and remembering who lives and who dies and how." Response-ability is action stemming from ecological thinking.

Response-ability calls into question not just individual choices and behavior, but also governance and the communal policies put in place as guides. In William Ophuls' discussion of the work of Jean-Jacques Rousseau, it becomes clear that individual will and desire is most often prioritized over that of the general will, the result of which is characterized by the exploitation and degradation of nature and people (Ophuls 2011). This is echoed in the "tragedy of the commons" concept in which the unmanaged self-interest of individuals, with disregard for the common good, will result in depletion of resources (Hardin 1968). Ophuls (2011) explains, "In other words, perfectly reasonable and legitimate private desires and actions aggregate into global outcomes that no reasonable person would want." A moral and ethical compass is needed. Ophuls (2011) continues, "Governments now confront the Herculean task of effecting an epochal economic, social, and political transition from the industrial age to the age of ecology."

Perhaps looking to examples of past and current ecological societies, those founded on ecocentric thought and a non-dualistic mental paradigm of humans *in* nature rather than humans *and* nature, may shed light on what collaborative initiatives and governance could look like in the age of ecology. Consider the United Nations, the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005), the Intergovernmental Panel on Climate Change (Pachauri et al. 2014), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Díaz et al. 2015) as examples of organized efforts that have created expansive riffs in this arena.

Collaborative governance is a platform that has the capacity to bring the politics of an ecological society into the re-storying of humans in nature. Like the principles of natural, ecological laws, collaborative governance fosters mutualism, connectedness, and the recognition of collective values through a consensus-driven process (McIvor 2019; Tang and Tang 2014). It is a response to a failed traditional top-down bureaucratic approach, substituting "multisectoral collaboration, stakeholder engagement, and public participation" for "command and control administration" (McIvor 2019). It is also a response to the social-ecological problems of today, which are increasingly wicked and multifaceted (McIvor 2019). Collaborative governance lends to an adaptive approach to interconnected, heterogenous systems (McIvor 2019), integrating local and diverse sources of knowledge. Because of this, collaborative governance is finding a place in the stewardship of government-owned rangelands where shared discovery and decision-making may lead to mutually beneficial outcomes for both ecosystems and societies (Reid et al. 2021).

Rangeland ecosystems are constantly evolving, and the emergence of newly discovered dynamics, challenges, and solutions is commonplace. Collaborative rangeland governance and stewardship that incorporates an inclusive, localized, participatory approach among transdisciplinary stakeholders may be key to effective management and a long-term, social-ecological ethics. In fact, studies have shown that collaborations between environmental agencies and ranchers can foster healthy ecosystems on government lands, while maintaining productive cattle operations (Sherwood 2010). Collaborations may be built upon a win-win strategy to meet the pluralistic values and objectives associated with protecting undeveloped wilderness areas, managing natural resources, producing food, and supporting community livelihoods.

Over time, collaborative rangeland stewardship may also be transformative for coupled human-natural systems through building relationship among stakeholders, integrating diverse sources of knowledge, co-producing new knowledge, social learning, networking, and implementing action (Reid et al. 2021). Case studies from unique sociocultural contexts around the globe show us that collaborative stewardship and governance of rangeland ecosystems is changing how "science gets done" (Reid et al. 2021)… as long as conservation is not used as a profiteering tool for high-level financial gain by off-site sources of power at the expense of the livelihoods of those people living close to the land. In other words, we have to be careful that political and social powers are not allowed to take precedence over distant landscapes and people in the name of conservation.

FEELING, THE HEART

But what are the head and the hands capable of in absence of the heart? Systems ecology and ecocentric philosophies provide a conceptual road map for ways of thinking, while sustainability science and collaborative governance provide methodological tools for doing. I believe we still need a driving ethos, a philosophy that can bridge the gap between the head and the hands, one, I would argue, that is rooted in love. After all, the word *philosophy* comes from the Greek, *philo* and *sophia*, meaning the *love of wisdom* (Morton 2018).

A sense of morality and near-sacred regard for nature was at the heart of the *land ethic* and conservationism according to Aldo Leopold, where one's sense of "community" also includes soils, water, plants, and animals (Leopold 1949, 2014). Leopold's land ethic incorporates an ecological conscience and emphasizes that our care should extend out from social contexts to include land and animals (Leopold 1949, 2014).

What tethers us to a dysfunctional and fragmented relationship with the natural world? Is it our inescapable dependence on nature for our own survival that drives us to be unintentional accomplices in the destruction of that upon which we depend? Is it our fear of death, fear of scarcity? This can be seen in the demise of biodiversity for the sake of productivity (Shiva 2000), the poisoning of waters downstream for the advancement of agriculture upstream (Broussard and Turner 2009), and many other examples where short term benefit is prioritized over long-term sustainability. Science has enlightened us to sometimes unanticipated consequences of our actions. So why do humans, collectively, still lack the ability to extend morality and care to these extra-human and longer-term social-ecological contexts?

The mechanism for cultivating a sense of morality and care for the natural world is *connection*. If we could truly restore an awareness of our interconnectedness with fellow nature, develop a sense of community and kinship with it, then we would not continue on the paths we've been treading. When we feel connected to another being, we naturally begin to care for that life. A heart string is tuned. Little by little, through continued relationship and mutual experiences, the greatest melody of all is born – *love*. Love is deeper than morality and reaches far beyond a social-ecological ethics.

In fact, forming a connection with other species is essential for humans, according to Gandhi (Godrej 2016). Humans need relationship with nature for self-guidance, truth, and as a beacon for social justice (Godrej 2016). The absence of this connection has been called, "species loneliness," which philosophers define as "a deep, untamed sadness stemming from estrangement from the rest of Creation, from the loss of relationship" (Kimmerer 2013). Kimmerer (2013) ponders, "I wonder if much that ails our society stems from the fact that we have allowed ourselves to be cut off from that love of, and from, the land." If only we become active witnesses to our symbiotic relationships with the processes and beings of the natural world will we be capable of love, gratitude, and reciprocity (Kimmerer 2013). This also underscores the significance of access to green spaces and nature by urban dwellers (Manigault-Bryant 2018).

Unbiased witnessing is what we do in science and perhaps why ecology is such a profound thread for entwining humans with the natural world. Conducting an ecological study is like trying to have a conversation with someone who speaks a different language (Kimmerer 2013). We may ask the questions, but plants and animals, rivers and soil will respond without words. It is our responsibility then to observe, to learn their languages. How else would we form an intimate connection with nature if not by learning how it speaks? There is no better way to describe how ecology feels like love than with the words of Kimmerer (2013):

> *I've never met an ecologist who came to the field for the love of data or for the wonder of a p-value. These are just ways we have of crossing the species boundary, of slipping off our human skin and wearing fins or feathers or foliage, trying to know others as fully as we can. Science can be a way of forming intimacy and respect with other species that*

> *is rivaled only by the observations of traditional knowledge holders. It can be a path to kinship (p 252).*

Yet, not only is love not mentioned when we write about our scientific observations or address societal concerns in ecology and sustainability science, love is discouraged and often seen as bias or advocacy toward our subjects of study. Dr. Stacy Lynn, a research scientist at Colorado State University's (CSU) Natural Resource Ecology Laboratory describes her experiences with this:

> *In science, it is often thought that becoming too connected with (human) communities where one works will bias the research and compromise its integrity. On the converse, having worked in the same community in Tanzania for twenty years, there is nothing more valuable to me in my work there than my relationships with the community and the place, being able to conduct useful community-driven research. Without these relationships – dear friendships, deep knowledge and mutual respect built over time and across what many would experience as insurmountable cultural divides – and this sense of dedication and purpose to people, why am I doing this work at all?*

This approach of discouraging love and connection with one's work can be seen as a form of censorship and "has serious consequences for public dialogue about the environment and therefore for real democracy, especially the democracy for all species" (Kimmerer 2013). Therefore, I was shocked, yet ecstatic, when my CSU department of Ecosystem Science and Sustainability, hosted a special seminar featuring Dr. Lavel Merritt Jr's, presentation "Applied

Ecology Through Love." I hung onto every word because I knew he was speaking with the language of ecology we need today. Dr. Lavel, a Legislative Affairs Specialist for the National Park Service, reminded me that in science, love is there, buried in field notes and codes, spreadsheets and academic papers. It is there, and how much more would people listen to what we had to say, if we spoke and wrote to their hearts, where plants and animals are subjects, instead of objects?

Yet, cultivating awareness of and connection with other forms of life does not have to involve great ideas or studious action (Morton 2018). Morton (2018) suggests, "How about just visiting your local garden center to smell the plants?" Art and ceremony offer yet other means of nurturing our relationship with nature (Kimmerer 2013; Morton 2018). Indigenous knowledge recognizes the power of art and ceremony and has much to share with our Western culture, since we have largely forgotten this way. Metaphor, again, has a role here, encompassing a particular aesthetic. Aesthetics foster beauty, free the imagination, and reason with the heart through feelings (Ophuls 2011). Through this invocation of feelings, we may enrich relationship.

When pastoral cultures speak of their relationship to the grasslands and the natural processes that sustain their livestock, they often use metaphor. They give nature animism as if it were a part of their family or their own being. "This is our life. We and our pastures are one body," describes a Khazakh herder in eastern Mongolia (Fernández-Giménez et al. 2017). The Potawatomi braid sweetgrass, in an act of care and loving attention, describing it as "the flowing hair of Mother Earth" (Kimmerer 2013). There is tenderness in these metaphors, and they emanate love because a reciprocal relationship is acknowledged. There is no reason why, when we address the stewardship of rangeland ecosystems in the American West, we cannot invoke the same reverence.

In rangeland ecosystem stewardship I believe we should let our hearts mediate our head and hands, like a common denominator that unites us all. In this way, we may restore connection, internalized acknowledgement of our sympoiesis with nature. Then, we may care enough to cultivate kinship, so that the only choice we have left is to love.

RE-IMAGINING, THE RANGE

The stewardship and conservation of rangelands and their unique role in global ecosystem processes, wildlife habitat, cultural heritage, and human livelihoods will rely upon innovative and collaborative approaches to long-term, social-ecological outcomes. A recent study that investigated six unique collaborative rangeland partnerships across the world concluded that the future of such work must focus on the co-development of mental models, morals and ethics, system-level transformations, and paradigm shifts (Reid et al. 2021). This finding agrees with many of the themes I have addressed.

I have presented, here, a theoretical framework. It is a theory unconventionally rooted in metaphor and the re-storying of rangeland ecosystem stewardship so that an ethos of interconnection, love, gratitude, and response-ability mediates an ecological mental model and collaborative action based in sustainability science and systems ecology. This theory is my humble contribution to the future of ecological stewardship and especially the rangelands of the Rocky Mountain west, which I call home. The word *humble* comes from the Latin, *humus*, meaning, *from the earth*. If I trace the very origin of my theory, indeed, it is from the earth.

I grew up in southwest Louisiana, a mosaic of rural and urban life linked by vast and diverse landscapes of swamp, farmland, bayous, levees, lakes, and oak groves of Spanish moss. The drive to my grandmother's house, east down state Highway 14, will be imprinted on my memory forever. Seemingly endless fields of green scrolled just beyond the backseat window.

Rice fields, rows of soybeans, and grassy pastures filled my young eyes like troves of emeralds. Later in life, my family began summer road trips cutting clear across Texas to Colorado. A different panorama sparked a familiar fire in my heart. Acres and acres of rangelands dotted with horses and cattle made me dream. These landscapes spoke to me without words. They breathed purpose into me through beauty and wonder. It was as if they tapped me on the shoulder for years asking me to pay attention. My relationship with these immense grassland ecosystems began with only a sense of admiration, and much time passed before I learned to reciprocate their languages. I am learning still.

One of their languages is a language of irony. From a distance, grasslands appear quite simplistic, where graminoid and shrub species dominate a visually uniform landscape. Rainfall is relatively low, trees are sparse, and if you're not lucky enough to catch a glimpse of a passing herd of 4-legged animals, you may not notice any animal life at all, except the occasional bird or insect traversing your line of sight. Yet, a closer look reveals a much different landscape. Stooping down to inspect the plants around your feet, you will notice a hundred different shades of green radiating from a diverse community of plants. Small forbs decorated in yellow, purple, and white flowers are there in the mid and lower canopy. Pushing aside a swath of grass, you may observe a world of arthropods, and scooping your fingertips beneath the soil will expose the dark humus of roots and invertebrates. If you placed a fistful of this soil under a microscope you would witness a tiny universe of protozoa, bacteria, and other microbial organisms living and dying in the web of life. Amidst these explorations, countless birds and pollinators, as well as mammals large and small have made witness to your presence. Witnessing them in return would reciprocate their efforts. And there would be the beginning of relationship with this place.

Grassland ecosystems comprise many voices speaking from heterogenous scales of time and space. It would be impossible for any one observer, scientist or not, to learn all of these languages proficiently, complicated yet beautified by their various metaphors and hist-stories. Who will speak for the rangelands? It will take a village.

I believe that a holistic, three-element metaphor, head-hands-heart, can ethically and sustainably steer us toward restoring and re-storying our relationship with Earth's rangelands. Such a relationship, rooted in symbiosis and ecological thinking, would be a de-coder for the social-ecological paradox in which we live today, where conservation, urban development, and food and energy production objectives seem contradictory. Collaborative approaches to science, stewardship, and governance of these landscapes are crucial and offer a transformative path, since they summon the recognition and participation of all possible voices. Short of a paradigm shift, this would require a transdisciplinary symphony between the biological and social sciences and the persuasion of others to embrace the teachings of ecological knowledge and natural law. Re-storying the range through metaphor could re-member these neglected relationships, opening our minds with our hearts. Kimmerer wrote, "Imagination is one of our most powerful tools" (Kimmerer 2013). So, let the re-imagining begin.

CHAPTER 2: TO GRAZE OR NOT TO GRAZE GOVERNMENT-OWNED LANDS: SOIL AND PLANT OUTCOMES OF COLLABORATIVE MANAGEMENT

INTRODUCTION

Could conceptualizing cattle as *partners* in conservation be a win-win for the livestock and rangeland conservation sectors, resolving the seemingly paradoxical objectives of food production and natural resource management? For millennia the ecology of western grasslands and rangelands, characterized by high quality forage and profuse biodiversity, has supported large herds of herbivores, and in turn herbivory has contributed to the preservation of those ecosystems over time, a sort of co-evolution (Bell 1971; Gibson 2009). However, a debate over the impacts of cattle grazing on government-owned rangelands is ongoing at local (Curtin et al. 2002; Derner et al. 2006; Porensky 2020; Porensky et al. 2017), national (Brunson and Huntsinger 2008; Donahue 1999), and global (Fernández-Giménez et al. 2017; Timmins 2002) scales. While some studies have found cattle grazing can improve soil health, plant biodiversity and provide quality habitat for wildlife (Abdalla et al. 2018; Augustine et al. 2017; Derner et al. 2009; Porensky 2020; Reeder and Schuman 2002; Reeder et al. 2004; Teague et al. 2016; Teague et al. 2011), others have concluded that livestock grazing particularly disrupts ecosystem function by removing significant plant matter and altering soil function (Abdalla et al. 2018; Daniel et al. 2002; Derner and Schuman 2007; Pietola et al. 2005). Still other studies have attempted to resolve the discrepancy underscoring nuances in scale of inquiry, regional climate influence, and precipitation effects (Briske et al. 2013; Derner et al. 2018; Sanderson et al. 2020).

We are learning it is not the act of grazing alone that results in land degradation but that human management of grazing on a fragmented landscape may also drive grazing outcomes. The importance of understanding the human dimension is underscored by increasingly complex social-ecological systems. Government-owned and private rangelands face uncertain futures due to the effects of climate change, development, changing policy, and economic pressures. Understanding the potential of multi-use government lands to provide wildlife habitat, biodiversity, healthy soil, and resilient ecosystems while also providing quality forage for domestic livestock that contribute to rural ranching livelihoods and local food systems will be essential to future land management and conservation strategies. It is a matter of sustainability, and addressing its three pillars – ecology, society, and economics – in decision-making (Basiago 1998; Purvis et al. 2019). Getting this management right is becoming even more important as competition for space and demands for ethical and sustainable food production increase.

We investigated landscapes managed by grazing partnerships between government land agency stakeholders and private ranchers in a western Great Plains region to answer the overarching question: *Are there significant differences in soil nutrient composition, plant community and species diversity, and forage quality between historically grazed and ungrazed areas?*

Often in scientific inquiry, we interest ourselves in cause and effect relationships. In doing so, we isolate two components, the actor and the acted-upon, and in doing so, eliminate other complexities and potentially confounding variables. In this approach, the assumption is that reductionism may lead to better understanding of the true independent effects of one variable upon the other. However, in social-ecological systems such as rangelands, we believe it is through holism and embracing complexity that we reach understanding (Briske et al. 2011; Provenza et al. 2013; Teague et al. 2013). The human-herbivore-plant-soil relationship in managed rangeland ecosystems is one that cannot be well understood through reductionistic thinking. Systems thinking, then, is the appropriate path, where we conceptualize a living web of people and their environments that is dynamic, adaptive, and ever-changing on diverse temporal and spatial scales (Berkes and Folke 1998; Woodmansee et al. 2021).

We approached our overarching question from a social-ecological systems perspective. Rangeland ecology is inherently complex due to its profuse biodiversity on all trophic levels coupled with increasingly variable weather patterns. Rangelands are abundant in sociocultural and economic benefits to humans like recreation, food production, and quality of life through access to green and wild spaces. Therefore, balancing management objectives on rangelands becomes an exercise in prioritizing human needs and values, which are tightly coupled with the natural world. There is tangible competition on government-owned lands among food production, energy production, wildlife conservation, and recreation objectives for limited rangeland space. Research and literature in the ecosystem services sector has elucidated just how critical land use and natural resource management has become, especially the intersection of agriculture and food production (Allen et al. 2018; Knight et al. 2011; Raudsepp-Hearne et al. 2010; Scherr and McNeely 2008). We emphasize that these places are living, breathing matrices of microorganisms, plants, water, and mineral cycles that require certain conditions for sustainable ecological function and resilience.

Creation of effective resource management plans on government lands is, therefore, multifaceted and incorporates social-ecological tradeoffs among needs and objectives. For example, government-owned lands managers are commonly interested in managing for soil health and plant community outcomes for natural resource conservation objectives, while ranchers are commonly interested in managing for forage quality to meet cattle nutritional needs. It is not that the interest of either group of stakeholders is unilateral, but when it comes to the negotiating table, diverse stakeholders may prioritize some objectives over others based on their individual perspectives, needs, and values (see Chapter 3). From a systems perspective, all of these management objectives are actually interrelated. Herbivore-plant-soil components co-create a thriving rangeland system that contributes to vital nutrient cycling (Figure 2.1). Evaluating forage productivity or rangeland carrying capacity alone is not enough for effective stewardship of complex and dynamic grazing lands. There is an entire network of relationships among animals, plants, soil, the microbiome, and humans to which we must attend. Our study seeks to better understand the coexistence of some of these network components.

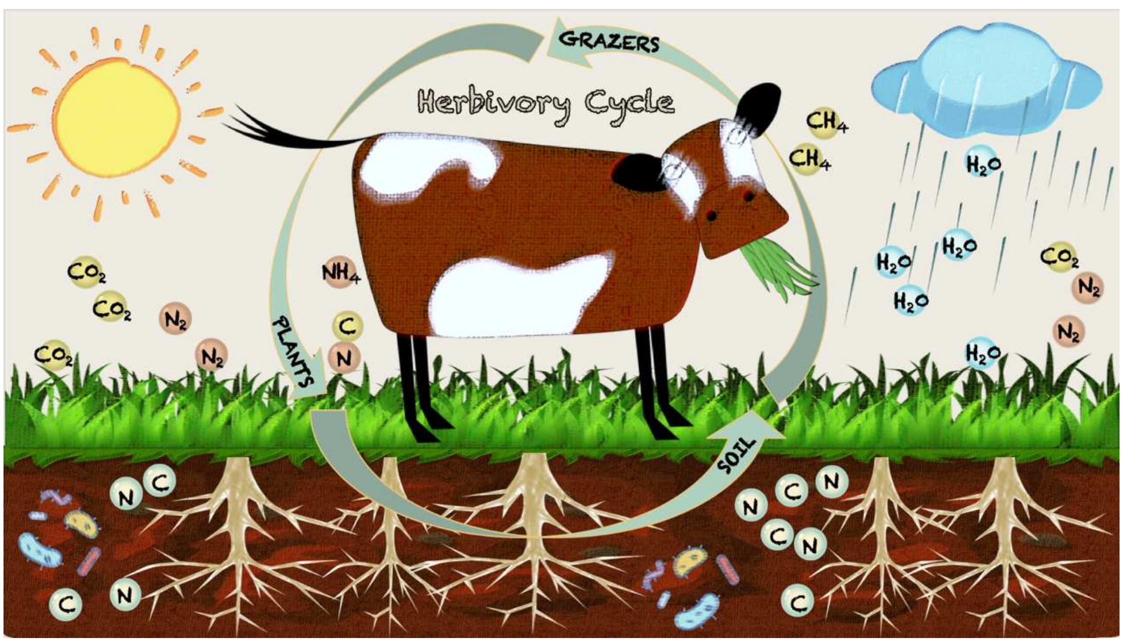


Figure 2.1. Conceptual diagram of the herbivore-plant-soil relationship, incorporating the cycling of nitrogen and carbon compounds.

We explored our question on government-owned rangelands on Colorado's Northern Front Range. These landscapes have historically been managed in part through grazing leases, where management plans and grazing strategies are co-created through collaborative efforts between ranchers and government agency workers. Assessing similarities and differences in the technicalities among grazing management approaches was not the focus of our inquiry. Instead, we understood the collaborative aspect of management as a common thread, where multiple stakeholders' perspectives, knowledge, needs, and values were integrated into stewardship plans.

Our objective, rather, was to compare areas on these landscapes that were managed with cattle grazing to areas that had been purposefully excluded from cattle grazing for at least ten years for various reasons not related to their quality. After at least a decade of adaptive collaborative grazing management versus grazing exclusion, what differences can we detect in terms of soil nutrient composition, plant species communities, and forage quality, and what are the apparent relationships among these variables? How might these outcomes guide future management decisions that aim to balance the ecological, social, and economic constituents of sustainability?

BACKGROUND & SIGNIFICANCE

Evaluating the sustainability of multiuse government-owned lands is crucial in western states like Colorado where cattle are the top agricultural commodity, the majority of which are in rangeland or pasture-based production systems (Environment Colorado Research and Policy Center 2006; United States Department of Agriculture 2017). Nearly half of Colorado's total land area is classified as agricultural land, and approximately half of this agricultural land consists of rangelands used for livestock production (Environment Colorado Research and Policy Center 2006). Regarding government-owned land, corroborated data from 1990-1998 reported that 39.86% of Colorado's total land was owned by federal (35.46%) and state (4.39%) entities (Natural Resources Council of Maine). More recently, a report from the Congressional Research Service stated that 36.2% of Colorado lands are owned by the federal government (Congressioinal Research Service 2020; Lang 2020). These reports did not include county or municipal land ownership. To fill the gap, in 2020, I conducted a land ownership-land cover analysis of the Colorado Northern Front Range using geospatial data from the National Land Cover Database (Yang et al. 2018) and data made available by the Colorado National Heritage Program and Colorado State University (Colorado Natural Heritage Program and the Geospatial Centroid 2020; Yang et al. 2018). This analysis revealed that government entities, encompassing federal, state, county, and municipal levels, owned over 65 percent, or 450,000 ha, of more than 1,300,000 ha of rangelands. In other words, almost two-thirds of all Northern Front Range rangelands were government-owned. The most recent comprehensive analysis on land and water use of government lands reported that 95 percent of total public lands in Colorado are leased for grazing (Sherwood 2010).

The Front Range, wedged between the Rocky Mountains and the Great Plains, is characterized by a semi-arid climate with mild winters, low annual precipitation, low humidity, high evaporation, and periodic drought (Mladinich 2006; Montgomery et al. 2016; Soil conservation service 1975). This high-plains region is capable of achieving an annual growing season of 140-148 days per year, due to adaptive agricultural methods including managed irrigation from mountain snowpack and crop rotation practices (Montgomery et al. 2016). The Northern Front Range was once covered in extensive grassland ecosystems, inhabited and shaped by generations of the Arapaho, Cheyenne, and Ute indigenous peoples. European settlers identified the landscape as ideal for ranching, and ever since, livestock, forage, and vegetable crops, such as wheat and corn, have been primary aspects of agricultural production here. In addition to defining the region's "Western" cultural heritage, these rangelands are considered some of Colorado's most valuable assets (Environment Colorado Research and Policy Center 2006). The continued potential of these landscapes to provide habitat rich in biodiversity and forage quality and a thriving soil biome will depend on complex social-ecological systems where livestock production and natural resource conservation are woven together in a tapestry of management, culture, and science. Our study directly addresses a trio of ecological beacons that are important to effective rangeland management: soil health, plant community, and forage quality.

Soil Health

Soil is a living, dynamic biome of microorganisms, vertebrates, and invertebrates, animated by mineral and water cycles. There are as many organisms in a teaspoon of soil as there are humans on Earth (Schwartz 2013). In systems thinking, it would be difficult to effectively study the herbivore-plant relationship in absence of soil. In our study, research collaborators chose to investigate several soil response variables: total nitrogen (TN), organic carbon (OC), and water infiltration (WI). These variables were selected due to their importance in plant growth and as indicators of nutrient cycling between biotic and abiotic ecosystem factors (Gibson 2009; Wedin 1996). Carbon is also an element of particular interest for the scientific community in light of climate change and the potential for rangeland ecosystems to sequester atmospheric carbon, providing an avenue to mitigate global warming, while supporting global food systems (Conant et al. 2001; Cusack et al. 2021; Gerber et al. 2013; Gill et al. 2010; Rojas-Downing et al. 2017).

An overview of the literature involving grazing effects on soil health demonstrates that effectively managed grazing may improve soil nutrient cycling and specifically increase soil TN and OC, especially in the upper soil depths (Beukes and Cowling 2003; Derner et al. 1997; Manley et al. 1995; Mosier et al. 2021; Niman 2014; Schuman et al. 1999; Teague et al. 2016; Teague et al. 2011; Wang et al. 2016; Xu et al. 2018). At the same time, other studies have concluded that livestock grazing may disrupt soil structure, function, and reduce nutrient cycling (Abdalla et al. 2018; Daniel et al. 2002; Derner and Schuman 2007; Pietola et al. 2005). Discrepancies across the literature may be due to nuances in scale of inquiry, regional climate influences, and precipitation effects (Briske et al. 2013; Derner et al. 2018; Sanderson et al. 2020).

In general, herbivory has been shown to aid the rate of nitrogen cycling due to its alteration of two major pathways of nitrogen loss: combustion and volatilization (Knapp et al. 1999). This conclusion is significant because nitrogen is often the most limiting nutrient for plant production (Bingham and Cotrufo 2016; Myrold 2005). It has more pathways for loss than other nutrients, and therefore, the effect of grazing on soil nitrogen content is an important factor in a sustainable system (Gerrish 2004; Knapp et al. 1999). Compared to other uses of farmable land like production of hay or silage, grazing actually removes less nitrogen from the soil (Gerrish 2004). In fact, 83%-90% of nitrogen consumed in forage (Barnes 2003; Gerrish 2004) and 60-90% of all nutrients consumed by grazing animals (Olson-Rutz 2015) is returned to the soil via manure and urine. In other studies, grazing was shown to increase nutrient cycling, specifically nitrogen availability, due to feedbacks between herbivory and plant response (Holland et al. 1992; Wang et al. 2016). Rotational grazing has especially been linked with increased soil nitrogen retention (Mosier et al. 2021).

Managing rangeland soil health through improved grazing practices has significant potential for carbon storage, a secondary effect of which reduces livestock agriculture's carbon footprint (Conant et al. 2001; Cotrufo et al. 2019; Cusack et al. 2021; Mosier et al. 2021; Rowntree et al. 2020; Schuman et al. 2002; Teague et al. 2016; Wang et al. 2016). In fact, effective management has been shown to increase soil carbon storage on existing rangelands from 0.1 to 0.3 Mg C ha^{-1} $year^{-1}$ and up to 0.6 Mg C ha^{-1} $year^{-1}$ on new grasslands (Schuman et al. 1999). More dramatically, one study claimed that after 20 years of a multispecies rotational grazing strategy, an average of 2.29 Mg C ha^{-1} $year^{-1}$ soil carbon was sequestered (Rowntree et al. 2020). Project Drawdown illustrated that improved strategies on rangelands, including managed grazing and silvopasture systems, have the greatest potential to sequester carbon compared with any other land use strategy, after tropical forest restoration (Hawken 2017). In 2001, an extensive research project synthesized the results of 115 studies of soil carbon data from 17 countries (Conant et al. 2001). It concluded that improved management of rangelands, by various means including grazing, can improve forage production, which is directly related to the sequestration of atmospheric carbon. In this case, marginal grasslands can become "carbon sinks" by improvement through effective livestock management (Conant et al. 2001).

Another equally extensive study examined soil data from 164 sites worldwide, which were used for extensive grazing (Abdalla et al. 2018). Considering variation in grazing intensity and regional climate, the authors concluded that an increase or decrease in soil OC was dependent upon both the climate and grazing intensity (Abdalla et al. 2018). For example, high grazing intensity produced an overall increase in TN and a significant increase in soil OC in areas dominated by C4 (warm season perennial) grasses compared to areas dominated by C3 (cool season perennial) grasses (Abdalla et al. 2018). Researchers also concluded that adequately adapting grazing intensity to ecoregion and local context may prevent overall soil degradation (Abdalla et al. 2018). Another meta-analysis in the Northern Great Plains, USA, concluded that grazing management had restored soil carbon and nitrogen pools to pre-Dust Bowl levels (Wang et al. 2016). A study in Texas, USA, compared rotational grazing to light and heavy continuous grazing and grazing exclosures (Teague et al. 2011). Researchers found that

OC was highest with rotational grazing, whereas TN was higher in the grazing exclosures (all of which had varying number of years without grazing and diverse management approaches otherwise), and WI was similar throughout all scenarios (Teague et al. 2011).

A secondary effect of improved soil OC may be the improvement of WI (Niman 2014). Water is arguably the most important nutrient of grassland ecosystems, and the main determinant of a productive or non-productive year in ranching. However, water is useless unless it is able to penetrate the soil surface. Reduced WI can lead to erosion, runoff, and decreased uptake by plants, which can lead to reduced productivity and vigor. Aside from human or livestock impacts, soil texture (e.g., clayey versus sandy) influences WI rates and must be taken into account when evaluating a grazing context (Duniway et al. 2010). Research has shown that grazing impacts on rangeland soil hydrology or WI varies according to timing, intensity, and frequency of land use (Döbert et al. 2021; Pietola et al. 2005). A study in Oklahoma, USA, demonstrated that high livestock densities can modify soil structure near the surface by compacting the soil, increasing the bulk density, and reducing WI (Daniel et al. 2002). In Finland a study comparing clay and sandy soils found that trampling by cattle near drinking sites severely reduced WI rates, 10-15% and 20% respectively compared to untrampled sites (Pietola et al. 2005).

On the other hand, a study in the Canadian Great Plains showed that an adaptive grazing approach, which incorporated adequate rest periods between grazing periods, improved WI (Döbert et al. 2021). Likewise, overall plant cover, preferably by graminoids, and litter mass has been tightly associated with higher infiltration rates (Chartier et al. 2011; Döbert et al. 2021). Notably, a study of silvopastures in Oregon, USA, discovered that while WI rates and soil porosity decreased with livestock grazing, those metrics returned to comparable levels of ungrazed areas after a period of rest (Sharrow 2007). Existing literature on grazing and soil WI rates leads to diverse outcomes and recommendations. It appears that geographical context and soil texture are important factors, in addition to the nuances in livestock management approaches.

Plant Community

In healthy grassland ecosystems, plant communities move toward increased heterogeneity where a diverse variety of plant species fill various ecological niches (Schwartz 2013; Symstad and Jonas 2011). This creates stability in the face of environmental fluxes and resilience in the face of disturbances, like grazing, fire, or drought (Isbell et al. 2015). In general, grazing animals work to thin out dead biomass and impact plant diversity through grazing selectivity, in turn maintaining productivity and resilience (Isbell et al., 2015). Additionally, grazing of dominant grasses by herbivores allows a “competitive release” for lesser competitive forbs to thrive (Damhoureyeh and Hartnett 1997).

Herbivory is a complex relationship between herbivores and the landscape. Large herbivores, like cattle, are known to affect plant communities in several ways: a) grazing exposes different plants in different stages of growth to sunlight and influences plant competition through selectivity, and b) trampling accelerates decomposition of organic matter and litter and drives fallen seed into the soil for germination. Hence, the secondary effects of defoliation by herbivores also contribute to measurable biological changes, which are multi-faceted (Knapp et al. 1999). To measure the effects of grazing on plant community dynamics, we decided to investigate several indicators: biodiversity, native versus exotic species abundance, and relative abundance by functional group (cool season graminoids, warm season graminoids, annual graminoids, forbs, and shrubs). These variables were selected due to their importance in overall ecosystem health, significance for study stakeholders, and because of their importance in local and national rangeland monitoring and assessment (Ahlering et al. 2021; City of Fort Collins 2007; Symstad and Jonas 2011).

An overview of the literature demonstrates that grazing effects on plant community dynamics and biodiversity is dependent upon geographical and ecological context, as well as management approach, especially stocking rate and grazing intensity. Some plants are sensitive to defoliation, while others are more tolerant (Bakker et al. 2006; Gibson 2009). One study compared long-term grazing effects on high productivity sites and low productivity sites over a 7-year period in grasslands of North America and Europe (Bakker et al. 2006). It was observed that plant diversity increased on the higher productivity sites, but decreased on the lower productivity sites (Bakker et al. 2006).

In Europe, moderate grazing intensities resulting in residual stubble heights of 8 cm for cattle or 4 cm for sheep led to the greatest improvement in species biodiversity (Milne and Osoro 1997). In Texas, USA, a multi-ranch study also found that a moderate grazing intensity increased plant species diversity, while a reduction in grazing intensity, such as in a continuous grazing scenario, led to a reduction in biodiversity (Teague et al. 2011). According to a 20-year study in Arizona USA, high-intensity grazing removed more biomass creating more niche availability and expansion of invasive species, especially in combination with periods of drought, while grazing at a moderate intensity actually increased drought resilience and resulted in high levels of native plant diversity and low levels of exotic species diversity (Souther et al. 2020).

Alternatively, a 13-year evaluation in the Chihuahuan Desert in southwest USA showed that light grazing of 26% utilization resulted in improved survival of perennial plant species by 51% with no change in standing crop after the peak growing season (Holechek et al. 2003).

Moderate grazing of 49% utilization resulted in a decrease of overall standing crop by 114 kg ha^{1} and only an 11% survival of perennial plant species (Holechek et al. 2003).

In an western USA Great Plains study, ungrazed areas encompassed a lower degree of plant biodiversity than areas grazed at moderate or varying intensities (Toombs et al. 2010). In a long-term study at the Konza Prairie Biological Station in Kansas, USA, researchers discovered that cattle grazing significantly increased native plant species richness compared to ungrazed areas (although bison (*Bison bison*) grazing had an even greater impact) (Ratajczak et al. 2022). Porensky et al. (2020) observed greater native species richness in grazed areas and greater invasive species richness in ungrazed areas in the western Great Plains. A 55-year study conducted in central Colorado, USA, which examined grazed versus ungrazed areas, demonstrated that the ungrazed exclosures actually contained the least amount of biodiversity compared to other areas of varying grazing intensities (Hart 2001). In the grasslands of Bulgaria, a study was conducted that compared abandoned land to grazed land, where comparatively, the grazed areas showed a significant increase in plant species diversity (Vassilev et al. 2011). Depending on the specific ecological context of research on biodiversity and plant community response to herbivory, results may point to different conclusions. Therefore, when interpreting the relationship between livestock grazing and plant community dynamics, it is important to consider environmental gradients, as well as biotic and abiotic factors, in addition to management approach (Souther et al. 2020).

Forage Quality

Forage nutritive quality in rangeland ecosystems hinges on the resiliency and vigor of plant and soil communities despite disturbances like drought, fire, and herbivory (Knapp et al. 1999). Management that encourages high forage nutritive quality is an important objective for both livestock production and wildlife habitat and was a significant variable of interest for stakeholders in this project. Three nutrient components were selected as response variables due to their significance in forage digestibility and ruminant performance: crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF). ADF includes cellulose and lignin, while NDF includes hemicellulose, in addition to cellulose and lignin. Together, ADF and NDF determine the amount of lower quality complex carbohydrates in forage that may occupy space in the rumen of cattle, but not contribute to energy and macro-nutrient needs. Therefore, higher forage nutritive quality is typically defined by greater CP/ADF and CP/NDF ratios (Holechek 1984; Kilcher 1981).

Graminoid, forb, and shrub species all contribute uniquely to the nutritional needs of large herbivores (Holechek 1984). In turn, the effects of cattle grazing on forage quality has long been of interest to the rangeland science community. This is especially useful to inform livestock managers of potential needs for supplemental nutrition and to better understand the biological dynamics of the forage-herbivore interface for sustainability objectives (McCuistion et al. 2014; Rouquette Jr 2016). It is known that in absence of herbivory the oxidation of dead plant material, or litter, limits further plant productivity, although a certain amount of litter is necessary to retain soil moisture and contribute to the return of organic matter to the soil microbiome (Gibson 2009). Therefore, grazing, a natural disturbance of grassland ecosystems, removes standing dead or mature plant matter, thinning a potentially thick and undesirable blanket of litter and allowing improved plant productivity. Grazing or defoliation during the growing season prevents plant maturation into the reproductive stage, which is associated with a natural decrease in nutritive quality (Gibson 2009; Kilcher 1981). Therefore, in theory, grazing may contribute to the maintenance of higher forage nutritive quality, by keeping plants in a vegetative growth stage containing more immature, nutrient-dense foliage (Kilcher 1981).

In the case of wild herbivores in the Serengeti and Yellowstone National Parks, grazed areas contained greater overall plant biomass and forage quality than ungrazed areas (Frank et al. 1998). Grazing stimulates regrowth from the base of defoliated shoots and new stems, which is more nutritious, digestible, and photosynthetically active (Frank et al. 1998). Therefore, the movement of herbivores across grazing lands actually leaves higher quality forages in their wake (Frank et al. 1998). Furthermore, by the deposition of urine, nitrogen in the form of urea can be mineralized in a matter of days (Gerrish 2004; Knapp et al. 1999). This naturally results in a measurable increase in nitrogen, a component of protein, content of plant leaves (Gerrish 2004; Knapp et al. 1999).

Research involving cattle grazing has demonstrated similar outcomes, although results are often correlated to management approach and grazing intensity. In the uplands of the Czech Republic, intensive grazing produced more desirable effects such as increased total biomass production, crude protein, and forage digestibility compared to continuous grazing (Pavlů et al. 2006). A 50-year study conducted at the Central Plains Experimental Station in Colorado, USA, used a clipping method to simulate defoliation by cattle. Researchers observed that light grazing had a more stable, long-term impact on protein and digestibility than heavy grazing or no grazing (Milchunas et al. 1995).

In another study conducted on the Texas Experimental Ranch, USA, crude protein and digestibility increased with higher cattle stocking rates and rotational grazing compared to lower stocking rates and a continuous grazing system. Standing litter was higher in the latter management approach (Heitschmidt et al. 1987). In Italy, after rotational grazing had been implemented for five consecutive years on previously continuously grazed grasslands, researchers observed an increase in forage productivity, diversity, and quality (Pittarello et al. 2019). Similarly, in a study in Oregon, USA, that investigated sheep grazing, crude protein and digestibility of fall forage was higher in areas that were grazed in the spring compared to ungrazed areas (Rhodes and Sharrow 1990). Crude protein increased by 8-12% while dry matter digestibility increased by 2-31% depending on the plant species (Rhodes and Sharrow 1990).

STUDY AREAS

Four multi-use conservation areas that include cattle grazing leases in their management plans were selected for this study: Coyote Ridge Natural Areas (CRN) and Soapstone Prairie (SSN) in Larimer County, Coalton Trailhead Open Space (CTO) in Boulder County, and Lowry Ranch (LRR) in Arapahoe County (Figure 2.2). One criterion for study site selection was access to a representative area that had been excluded from cattle grazing for a minimum of ten years. The second criterion was that these government land agencies engaged in partnerships with local rancher lessees. Ranchers typically used their grazing leases to access additional forage resources during the growing season for herds of cow-calf pairs or weaned yearling cattle as part of a growth production phase. This provided valuable rest and recovery periods for pastures on their own ranches. Collaboration was the common management thread that united all study sites. Stakeholder demographics varied. Cattle production cycles and breeds varied from site to site, and grazing schedules varied slightly by year and pasture. The consistent factor was that each of the landscapes we studied incorporated a collaborative approach to management.

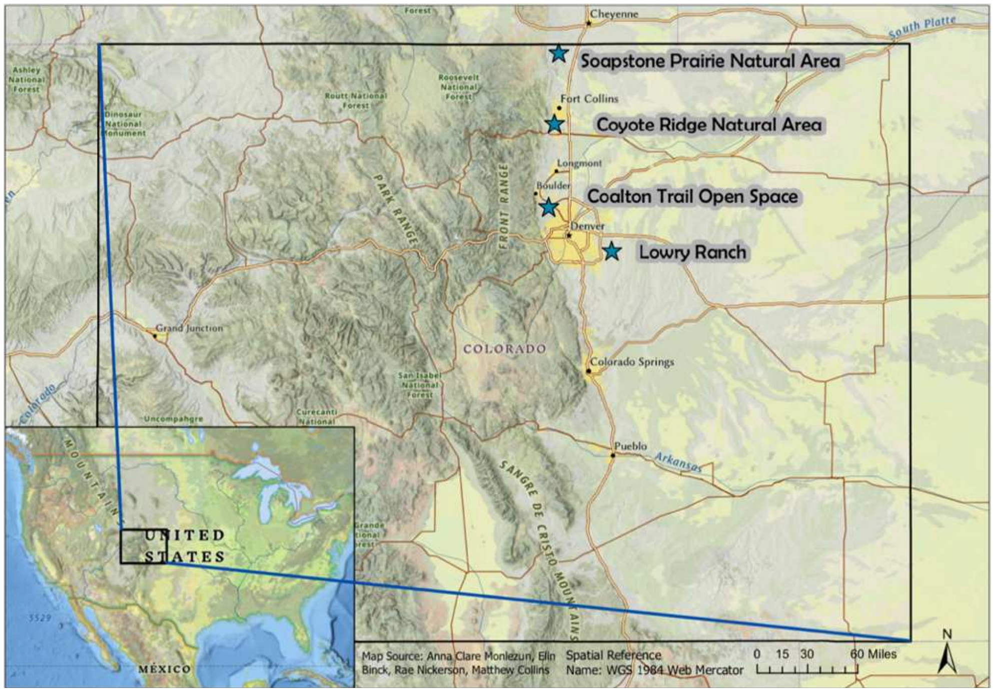


Figure 2.2. Map of four Colorado Northern Front Range study sites located in Larimer, Boulder, and Arapaho counties. Study sites were located within government agency properties and managed in part through cattle grazing leases.

CRN was a once a private ranch, homesteaded and operated by the same family since 1959. They were "pioneers" in ecologically-oriented ranch management and partnered throughout their ownership with the Natural Resource Conservation Service (formerly the Soil Conservation Service) for land health and soil improvements. The family donated the property to the City of Fort Collins Natural Areas Department in 2017, and it has been collaboratively managed with a rancher lessee since 2019. An adjacent portion of the original ranch is currently owned by Larimer County Natural Resources Department and has been excluded from cattle grazing for over twenty years.

SSN is an expansive and diverse landscape acquired by the City of Fort Collins Natural Areas Department in 2004 and has been collaboratively managed with the Folsom Grazing Association since then. The Folsom Grazing Association, formerly known as the Soapstone

Grazing Association, had actually owned and managed the territory since the 1950s, when they bought it from a private ranch.

CTO is a large contiguous property that was acquired by Boulder County Parks and Open Space in small parcels over time. It has been collaboratively managed with the same rancher lessee since 1995. CRN, SSN, and CTO are all government-owned lands located in the vicinity of populated urban areas, and are therefore popular recreation sites for hiking, biking, and horseback riding.

LRR is a property of the Colorado State Land Board acquired in three separate transactions over twenty-seven years. It has a diverse history as an experimental bombing range and an army airfield until it was converted back into ranch land. It was managed by a continuous grazing approach until 2007, when ranching ceased for seven years. In 2014 with a new sustainability initiative, LRR's management transitioned to holistic management and rotational grazing. Although LRR is a government-owned property whose revenue supports public interests, it is not open to the public for recreation.

These lands are classified within two Major Land Resource Areas (MRLA): a) 49, Southern Rocky Mountain Foothills, and b) 67B, Central High Plains (USDA 2006). Importantly, all four study sites are physically situated on the thresholds of these ecological regions and actually bridge both MLRA's within their property borders. Therefore, we acknowledge that their geophysical, soil, biological, and climatic properties are more appropriately associated with an ecotone that comprises characteristics of both MRLA's, and research results may be extrapolated across these regions. MRLA 49 is characterized as a foothills region with an annual average precipitation of 305-635 mm (12.0-25 in) but can range as high as 820 mm (32.3 in) (USDA 2006). The average annual temperature is 0.9-11.4 C (33.6-

52.5 F), and the frost-free period ranges from 75-165 days (USDA 2006). MRLA 67B is characterized as semi-arid and is within the Colorado Piedmont section of the Great Plains. Average annual precipitation is 32.0-51.0 cm (12.6-20.1 in) with high interannual fluctuations (USDA 2006). The average annual temperature is 7-13 C (44.6-55.4 F), and the frost-free period ranges from 130-180 days (USDA 2006).

The following additional descriptions characterize both MRLA 49 and 67B: rainfall events are typically intense and short-duration and occur mainly in spring and early summer, while snow makes up winter precipitation (USDA 2006). Soils have a mesic temperature regime, a ustic or aridic moisture regime, are very shallow to very deep, well drained, and loamy (USDA 2006). Nearly 50% of these land areas are grassland and pasture used for farming and ranching and support native species like blue grama (*Bouteloua gracilis*), buffalo grass (*Buchloë dactyloides*), needle-and-thread (*Hesperostipa comata*), western wheatgrass (*Pascopyrum smithii*), prairie junegrass (*Koeleria macrantha*), and threeawn (*Aristida purpurea*) (USDA 2006).

MATERIALS & METHODS

Field Sampling and Sample Analysis

A total of six, 50 m linear transects were placed on each of the four study sites. Four transects were randomly located in areas under long term grazing management (*grazed* areas), and two transects were located in areas that had been excluded from cattle grazing for a minimum of ten consecutive years (*ungrazed* areas) for various managerial reasons (Figure 2.3). The ungrazed transects on the CRN study site, were located in an adjacent property of Larimer County Natural Resources Department, who does not incorporate grazing leases on that property. Ungrazed transects on the CTO, LRR, and SSN study sites were within the same property boundaries of grazed transects but which had been excluded from cattle grazing due to long-term fence and gate infrastructure. Ungrazed transects were limited to two per study site due to the limited spatial extent of ungrazed areas and our goal of minimizing autocorrelation across transects located too closely together. All grazed and ungrazed transects were located in areas where landowners could verify long-term absence of herbicide use, mowing, or other invasive land management strategies. We use the term *area,* as in "key research area," located within various geographical portions of these study sites and often delineated for cattle management by permanent fencing (e.g. pastures, allotments, exclosures).

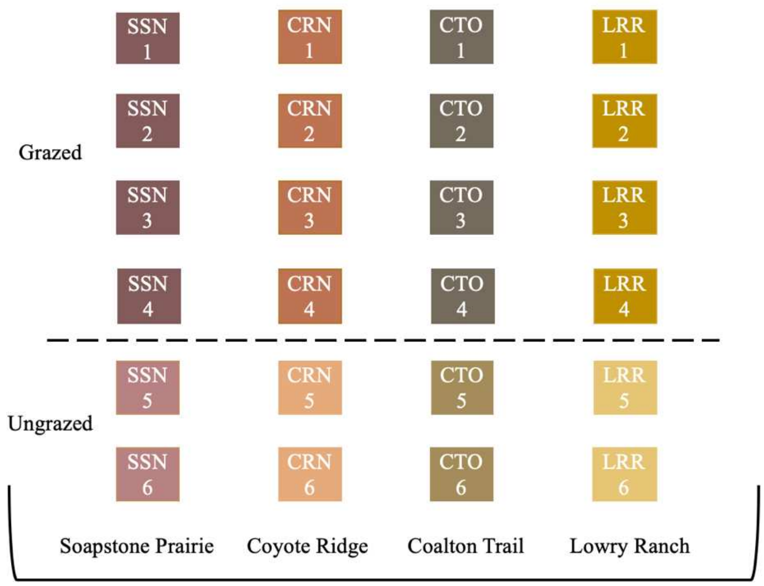


Figure 2.3. Conceptual diagram of transect design in a study comparing grazed and ungrazed areas on four government-owned conservation lands.

Transect locations were selected based on similarities of slope and soil texture across study sites and were placed with adequate distance, at least 20 m, to fence lines or water troughs to reduce the effects of heavier hoof traffic around those areas. Soil scientists from the USDA National Resource Conservation Service (NRCS) conducted expert in-depth soil profile analyses at each transect in coordination with other sampling to verify biological consistency across transect locations. Appendix A reports the soil units within which transects were located. We systematically measured specific variables along each of the twenty-four transects. These variables were associated with each of the three ecological components (Table 2.1).

Table 2.1. Categories of response variables coinciding with management goals.

Soil Health	Total nitrogen Organic carbon Water Infiltration
Plant Community	Biodiversity Species functional groups Species origin groups
Forage Quality	Crude protein Acid detergent fiber Neutral detergent fiber

We collected forage quality data during the growing season and prior to cattle grazing, May 17-June 18. We collected soil health and plant community data during peak vegetative growth July 14-August 11. All data were collected in each of two consecutive years, 2020 and 2021.

Soil Health: To test the hypothesis that collaborative grazing management improves soil health as indicated by levels of TN, OC, and WI, samples were collected to a 20 cm depth, using an 8.25 cm diameter soil auger. Soil cores were extracted from one random location within a 25 cm x 25 cm quadrat placed at 10 m intervals on alternating sides of each transect and at a 1 m minimum distance from the transect. Each core was divided into two sub-cores 0-10 cm and 10-20 cm to be processed individually for a total of ten subsamples – five shallow and five deep – per transect. Data from each set of subsamples were averaged across each transect so as to avoid spatial autocorrelation among single subsamples. This resulted in a sample size of n = 24 for each sampling depth, where each *n* was the mean of five subsamples.

Samples were stored in individual paper bags, air-dried for a minimum two weeks, then finely ground using a mechanical porcelain pestle. Samples were analyzed for percent total carbon (TC) and percent TN as determined by combustion analysis (Nelson 1982) using the Velp 802 CN analyzer (Velp Scientifica Srl, Usmate Velate, Italy) available in Colorado State University's (CSU) Natural Resources Ecology Lab (NREL) EcoCore facility. Inorganic carbon (IC) was analyzed using the Modified Pressure-Calcimeter Method (Sherrod et al. 2002). IC was subtracted from TC to determine percent OC.

Soil WI was calculated using the single-ring infiltrometer method to test the hypothesis that collaborative grazing management improves hydrologic function (Currell 2016; Johnson 1991) measured through water infiltration time. In accordance with this method, a 15.24 cm diameter ring (standard 6-inch factory dimensions) was placed along each transect at 10 m intervals, within each soil sampling quadrat, for a total of five subsamples per transect. Using a graduated cylinder, 444 mL of water was poured into the ring to create a 2.54 cm (1-inch) depth. Infiltration rates were measured as the unit of time for water to completely penetrate the soil surface. We treated the five individual WI rates along each transect as subsamples and averaged them across each transect so as to avoid spatial autocorrelation among subsamples. This resulted in a sample size of $n = 24$, where each *n* was the mean of five subsamples.

Plant Community: To test the hypothesis that collaborative grazing management increases above-ground plant biodiversity, the Daubenmire cover class method was used to collect data on plant species richness, evenness, and composition (Coulloudon et al. 1999). Every living or standing dead plant was identified (Appendix B), except for three unidentifiable plants which had single occurrences and were omitted from statistical analysis as outliers. Along the right side of each 50 m transect a random point between 0-100 cm was selected for the placement of the first 20 cm x 50 cm Daubenmire frame. Consecutive frames were placed every 1 m thereafter for a total of fifty subsamples per transect. The rectangular frames were placed perpendicular to the transect to improve capture of biological variability.

Canopy cover class of each plant species was determined in each frame, and the mean value (%) of each class range was entered into statistical analysis (Table 2.2). Bareground, litter, rock, and manure were also notated in sampling when applicable. We treated the fifty Daubenmire cover class estimates along each transect as subsamples and averaged them across each transect so as to avoid spatial autocorrelation among single subsamples. This resulted in a sample size of n = 24, where each n was the mean of fifty subsamples.

We calculated Shannon Diversity Index (SDI) as a proxy for plant biodiversity. SDI integrates both plant species richness and evenness using the equation: $H' = -\sum_{i=1}^{s} p_i \ln p_i$ (Shannon 1948). We calculated the relative abundance of five species functional groups: a) cool season graminoids (C3) b) warm season graminoids (C4) c) annual graminoids (AnGram) d) forbs (Forb) e) shrubs (Shrub), and two species origin groups: a) native species (Native) b) exotic species (Exotic), with which to examine plant community patterns.

Table 2.2. Daubenmire cover class score conversion to mean value of relative abundance (%).

Cover Class	**Range of Coverage (%)**	**Mean Value (%)**
1	0-5	2.5
2	6-25	15.0
3	26-50	37.5
4	51-75	62.5
5	76-95	85.0
6	96-100	97.5

Forage Quality: For the purposes of this study, forage nutritive quality was defined by three components: CP, ADF, and NDF, with higher forage quality defined as higher CP/ADF and CP/NDF ratios. To test the hypothesis that collaborative grazing management improves forage nutritive quality, forage samples were collected within 0.25 m x 0.25 m frames at 8 m intervals (six subsamples per transect), alternating sides of the transect and 2-10 m from each transect. All standing biomass rooted within the frame was clipped at ground level. Each sample was stored in an individual paper bag. This method was adapted from established literature on forage quality measurements (Dubbs et al. 2003; Milchunas et al. 1995).

Forage samples were oven-dried at 55°C for a minimum of three days and ground to pass through a 1-mm sieve using a Wiley Model 4 grinder. These finely ground samples were analyzed with Near Infrared Reflectance Spectroscopy (NIR) (Norris 1996) using a Spectrastar XT 2600 XT-R (KPM Analytics, Westborough, MA, USA). Sample preparation was conducted in CSU's NREL EcoCore facility, and NIR analyses were conducted in CSU's Department of Animal Sciences' Nutrition Lab. We treated the six individual forage samples along each transect as subsamples and averaged the results of their nutritional analysis across each transect so as to avoid spatial autocorrelation among single subsamples. This resulted in a sample size of $n = 24$, where each n was the mean of six subsamples.

Statistical Analysis

R Studio Version 1.3.1093, was used to conduct the statistical analyses for detecting patterns and differences among historically grazed and ungrazed areas of the four study sites (R Core Team 2019). Multivariate analyses were conducted using the R *vegan* package.

Permutational Multivariate Analysis of Variance (PerMANOVA) was used to detect differences between grazed and ungrazed areas in three *soil health* metrics (TN, OC, WI), three *plant community* metrics (SDI, functional groups, origin groups), and three *forage quality* metrics (CP, ADF, NDF). PerMANOVA is a multivariate statistical method incorporating a hypothesis test of group differences that compares group centroids or dispersion. We implemented this robust method on a Bray-Curtis dissimilarity matrix, which resulted in an R^2 statistic and p-value. PerMANOVA was conducted using the R adonis() function and 999 permutations until a convergence of data was found. We applied the significance level $\alpha = 0.05$ and a "strata" argument of *site* to incorporate the random factor of study site location in the analysis.

Non-Metric Multidimensional Scaling (NMDS) was used to elucidate regional patterns in plant community data (Oksanen 2007), including species functional groups and species origin groups, while incorporating SDI, and soil health and forage quality measures as environmental gradients. NMDS is an indirect ordination method that does not predict data on a defined gradient, yet various continuous variables may be "laid over" the model as vectors post-analysis. For NMDS we used a Bray-Curtis dissimilarity matrix, which preserves ecological distances in rank order. NMDS was conducted using the R metaMDS() function. One-thousand permutations were scripted with various starting configurations, until a convergence of data and a close-to-perfect ordination was found. A stress plot was used to assess appropriateness of "fit" between the ordination space and actual ecological distances. An NMDS scatterplot was then created using three dimensions to illustrate the distribution of plant species in ordination space. Ten gradients were laid over the scatterplot using weighted averaging: TN, OC, SDI, C3, C4, Forb, Shrub, Native, Exotic. This further illustrated patterns between plant species composition and co-existing gradients in relation to unique study sites, grazed areas, and ungrazed areas.

RESULTS

Grazed vs. Ungrazed Area Differences

There was considerable variation in spring precipitation levels between 2020 and 2021; with March, April, and May precipitation in 2021 25-50% greater than in 2020 across our study region (Colorado Climate Center 2022). The annual precipitation was slightly above the historical average for the 2021 water year (October-September), and 2020 experienced a below-average water year, with some study areas only receiving 75% of the average annual precipitation (Colorado Climate Center 2022). Therefore, we evaluated 2020 and 2021 data both separately and as an aggregated 2-year dataset to account for this environmental influence. Spring precipitation also informed our interpretation of results, since this environmental factor is known to heavily influence plant and soil dynamics (McCuistion et al. 2014; Teague et al. 2011).

Grazed vs. Ungrazed Area Patterns

Soil Health: Soil samples were analyzed by year (2020 and 2021) and by sample depth (0-10 cm and 10-20 cm) in the laboratory (Appendix C). However, the 2-year aggregated dataset was used for PerMANOVA because of observed similarities in means and standard deviations among the years and the slow speed of soil nutrient content change over long periods of time (Table 2.3). PerMANOVA indicated a statistical difference ($p < 0.01$) in the centroids and dispersion of soil TN and OC data in grazed and ungrazed areas, with grazed areas demonstrating higher percentages of TN and OC than ungrazed areas (Table 2.3).

Table 2.3. Results of multivariate PerMANOVA tests for differences between grazed and ungrazed areas in three groups of variables measured across two years, 2020 and 2021. Upper horizon = 0-10 cm depth. Lower horizon = 10-20 cm depth. $\alpha = 0.05$.

Group	Variables Included	R^2	p-value
Soil Nutrients 2-yr	Total nitrogen (upper horizon) Total nitrogen (lower horizon) Organic carbon (upper horizon) Organic carbon (lower horizon)	0.21	<0.01
Water Infiltration 2-yr	Water infiltration rate	0.03	0.20
Plant Community 2-yr	Shannon Diversity Index Species Relative Abundance Functional Groups Origin Groups	0.01 <0.01 <0.01 <0.01	0.82 0.32 0.96 0.98
Forage Quality 2020	Crude protein Acid detergent fiber Neutral detergent fiber	0.01	0.47
Forage Quality 2021	Crude protein Acid detergent fiber Neutral detergent fiber	0.31	<0.01

Mean values across both soil TN and OC measures were consistently higher in grazed areas compared to ungrazed areas (Table 2.4). WI rates were not statistically different in grazed vs. ungrazed areas (p = 0.20). We note that variability within WI sampling groups was high, indicated by large standard deviations. (Table 2.4).

Table 2.4. Means and standard deviations of soil health variables across two sample years and two soil depths. TN = total nitrogen. OC = organic carbon. Upper horizon = 0-10 cm depth. Lower horizon = 10-20 cm depth.

Sample	n	Grazed Mean (%)	Grazed Std Dev	Ungrazed Mean (%)	Ungrazed Std Dev
2020 TN upper horizon	24	0.19	0.07	0.13	0.08
2020 TN lower horizon	24	0.14	0.05	0.11	0.05
2020 TN average	24	0.16	0.06	0.12	0.06
2021 TN upper horizon	24	0.20	0.07	0.13	0.07
2021 TN lower horizon	24	0.15	0.05	0.10	0.05
2021 TN average	24	0.17	0.06	0.12	0.06
2-yr TN upper horizon	48	0.20	0.07	0.13	0.07
2-yr TN lower horizon	48	0.14	0.05	0.10	0.05
2-yr TN average	48	0.17	0.06	0.12	0.06
2020 OC upper horizon	24	1.99	0.75	1.32	0.78
2020 OC lower horizon	24	1.28	0.48	0.93	0.49
2020 OC average	24	1.63	0.60	1.13	0.61
2021 OC upper horizon	24	1.98	0.65	1.30	0.65
2021 OC lower horizon	24	1.43	0.49	0.95	0.49
2021 OC average	24	1.71	0.56	1.12	0.56
2-yr OC upper horizon	48	1.99	0.70	1.31	0.71
2-yr OC lower horizon	48	1.36	0.48	0.94	0.49
2-yr OC average	48	1.67	0.57	1.13	0.58
		Grazed Mean (min)	**Grazed Std Dev**	**Ungrazed Mean (min)**	**Ungrazed Std Dev**
2020 water infiltration	24	6.78	5.79	4.73	4.00
2021 water infiltration	24	3.89	2.40	2.11	2.17
2-yr water infiltration	48	5.33	4.60	3.42	4.68

Boxplots of soil measures aggregated across 2020 and 2021 samples illustrate significant differences in TN ($p < 0.01$) and OC ($p < 0.01$) and non-significant differences in WI ($p = 0.20$) between grazed and ungrazed areas (Figure 2.4a). Scatterplots of the 2-year aggregate dataset of TN and OC allow us to take a closer look at patterns within each of the four study sites, further illustrating grazed and ungrazed area differences (Figure 2.4b). Both Figures 2.4a and 2.4b summarize TN and OC averages across upper (0-10 cm) and lower (10-20 cm) soil horizons for illustrative purposes, however PerMANOVA tested each depth as a unique variable in the multivariate analysis (Table 2.3).

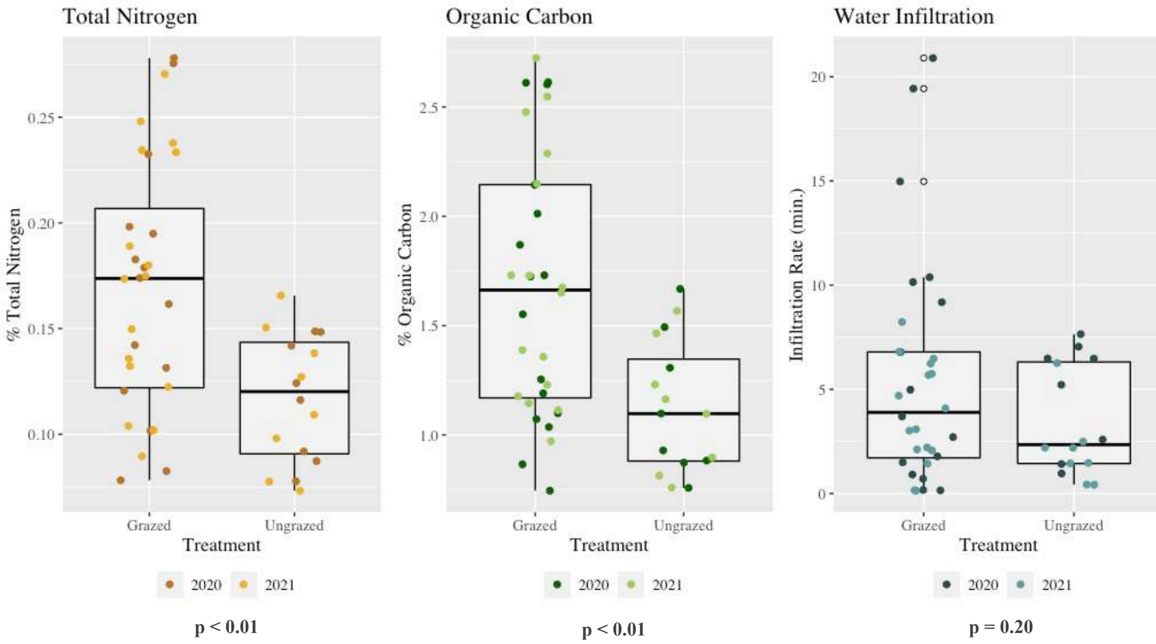


Figure 2.4a. Boxplots of soil health variables used in PerMANOVA analysis. For nitrogen ($p < 0.01$) and organic carbon ($p < 0.01$), data points represent averages of the total sampled depth (0-20 cm). All variables represent aggregated data from two sampling years (2020 and 2021) and illustrate the comparison between grazed and ungrazed areas.

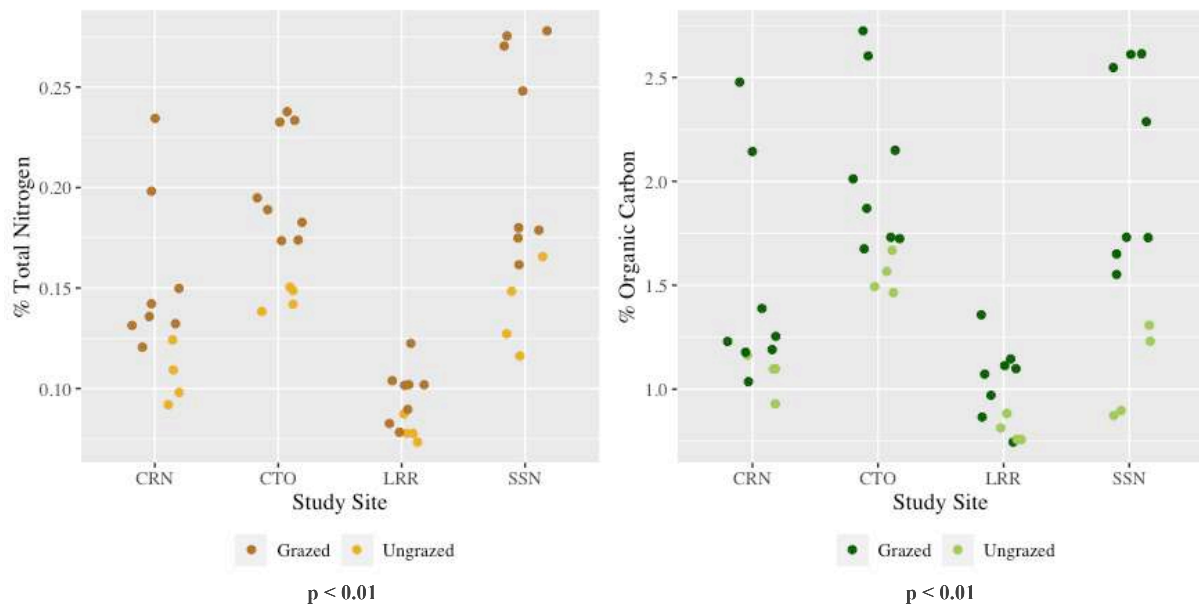
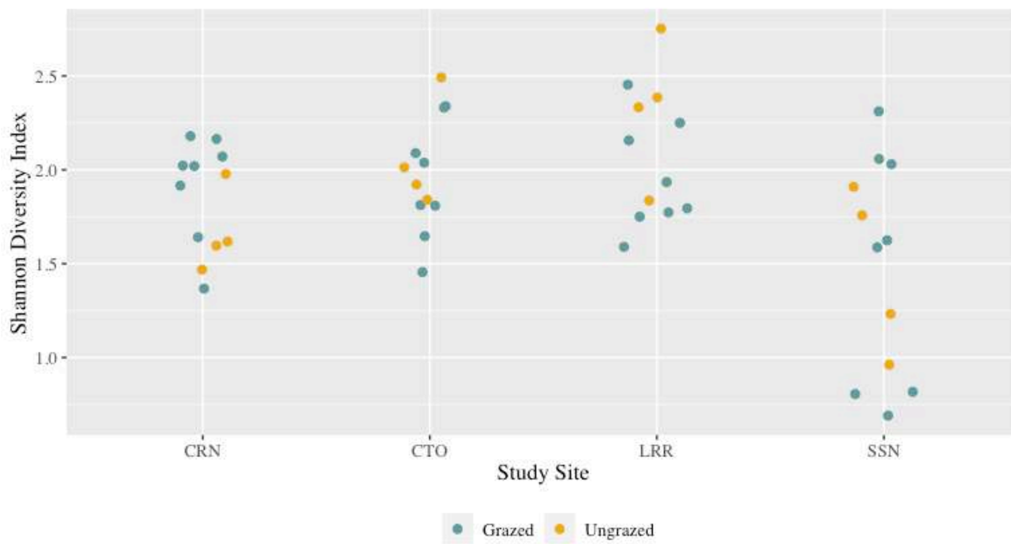


Figure 2.4b. Scatterplots of soil nitrogen and organic carbon used in a PerMANOVA analysis ($p < 0.01$). Data points represent the total sampled depth (0-20 cm) averaged across 2 sampling years (2020 and 2021) and illustrate the comparison between grazed and ungrazed areas on each of 4 study sites.

Plant Community: We inventoried a total of 104 plant species, over a 2-year sampling period. Because changes in plant community composition occur slowly over long periods of time, the 2-year aggregated dataset was used for statistical analysis (Table 2.3). PerMANOVA analyses of plant community composition measures of SDI, species relative abundance by functional groups and origin groups indicated that there were no statistical differences in the centroids or dispersion of these measures in grazed vs. ungrazed areas (Table 2.3). Examining a scatterplot of SDI data ($p = 0.82$) in grazed and ungrazed areas across the four study sites conveys that plant species diversity was not significantly different among grazed and ungrazed areas (Figure 2.5). Means of plant species abundance categorized by functional groups and origin groups demonstrate relative values of grazed and ungrazed areas (Table 2.5).



p = 0.82

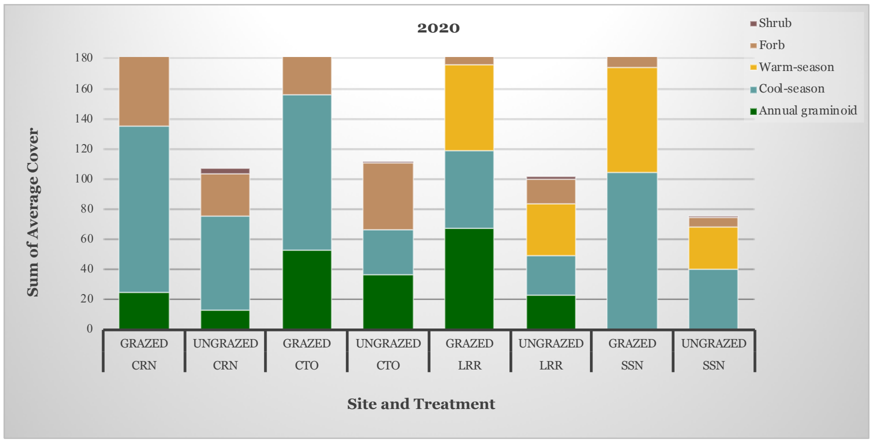
Figure 2.5. Scatterplots of Shannon's diversity used in a PerMANOVA analysis. Data points represent averages of fifty subsamples along each transect, collected in two sampling years (2020 and 2021) and illustrate the comparison between grazed and ungrazed areas on each of four study sites with no detectable difference.

Table 2.5. Relative abundance means and standard deviations of plant community groups in grazed and ungrazed areas, including two sampling years, 2020 and 2021.

Functional Groups	**n**	**Grazed Mean (%)**	**Grazed Std Dev**	**Ungrazed Mean (%)**	**Ungrazed Std Dev**
Cool season	48	28.02	14.74	25.95	11.01
Warm season	48	9.47	11.54	9.00	10.45
Forb	48	14.93	11.16	14.21	9.07
Shrub	48	1.45	1.85	1.42	1.34
Annual Graminoid	48	8.68	7.57	9.68	7.34
Origins Groups					
Native	48	36.97	19.43	35.71	20.04
Exotic	48	25.58	23.11	24.55	21.31

Bar charts illustrate patterns in species relative abundance by functional groups (Figure 2.6) and origins groups (Figure 2.7) by sampling year and by study site suggesting differences between sites that cannot be tested for significance because of small sample size.

a)



b)

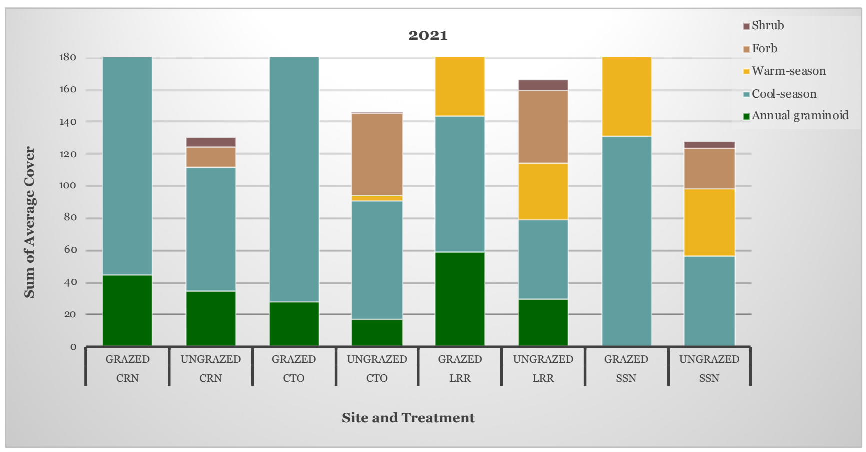
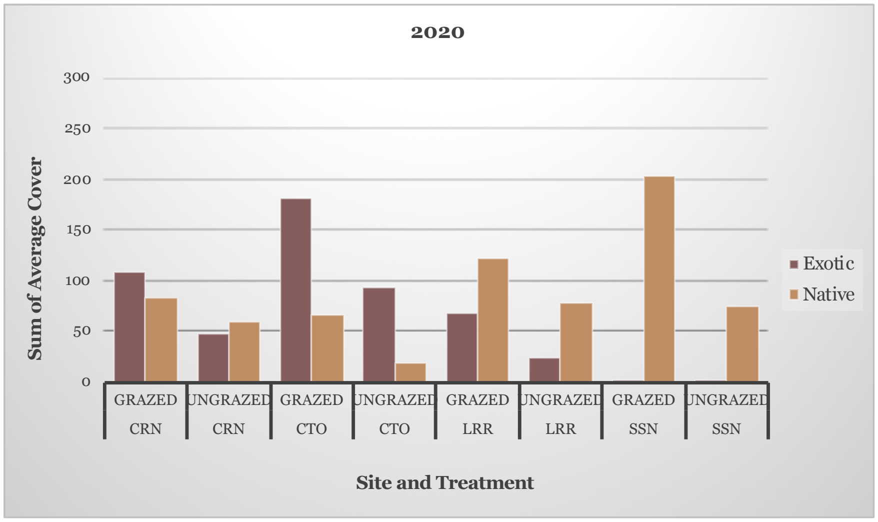


Figure 2.6. Sums of average species canopy cover by five functional groups (Shrub, Forb, C3, C4, Annual Graminoid) in year a) 2020 and b) 2021, illustrating comparison between grazed and ungrazed areas on each of four study sites.

a)



b)

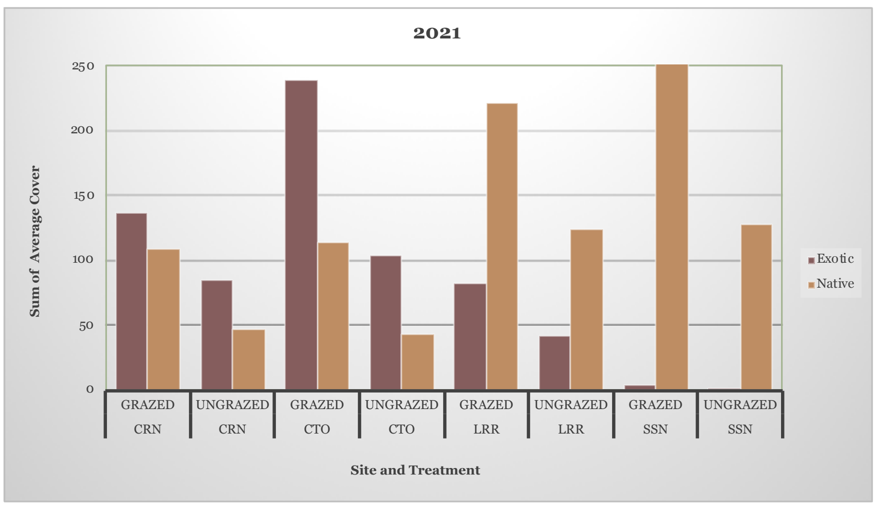


Figure 2.7. Sums of average species canopy cover by origin groups (native and exotic) in year a) 2020 and b) 2021, illustrating comparison between grazed and ungrazed areas on each of four study sites.

Forage Quality: Because fluctuations in forage quality are highly dynamic and linked to periodic events such as precipitation or grazing, each sampling year, 2020 and 2021, was analyzed separately with PerMANOVA (Table 2.3). Statistical differences in the centroids and dispersion of forage nutrient measures in grazed and ungrazed areas were found in 2021 ($p < 0.01$) but not in 2020 ($p = 0.47$) (Table 2.3). Means of CP, ADF, and NDF show a consistent grazed vs. ungrazed pattern (Table 2.6). In 2021, the significant difference in forage quality between grazed areas and ungrazed areas is visible in boxplot illustrations, where percent CP is higher in grazed forage samples, and percent ADF and NDF is lower in grazed samples (Figure 2.8).

Table 2.6. Means and standard deviations of three forage nutritive quality components: crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), in 2 sampling years, 2020 and 2021.

Nutritive Component	n	Grazed Mean (%)	Grazed Std Dev	Ungrazed Mean (%)	Ungrazed Std Dev
2020 CP	144	10.25	1.48	9.96	1.85
2021 CP	144	9.44	1.97	7.50	2.10
2020 ADF	144	38.34	3.11	39.04	2.49
2021 ADF	144	26.07	3.58	30.87	5.67
2020 NDF	144	63.87	4.79	63.82	5.71
2021 NDF	144	55.80	4.43	60.33	5.56

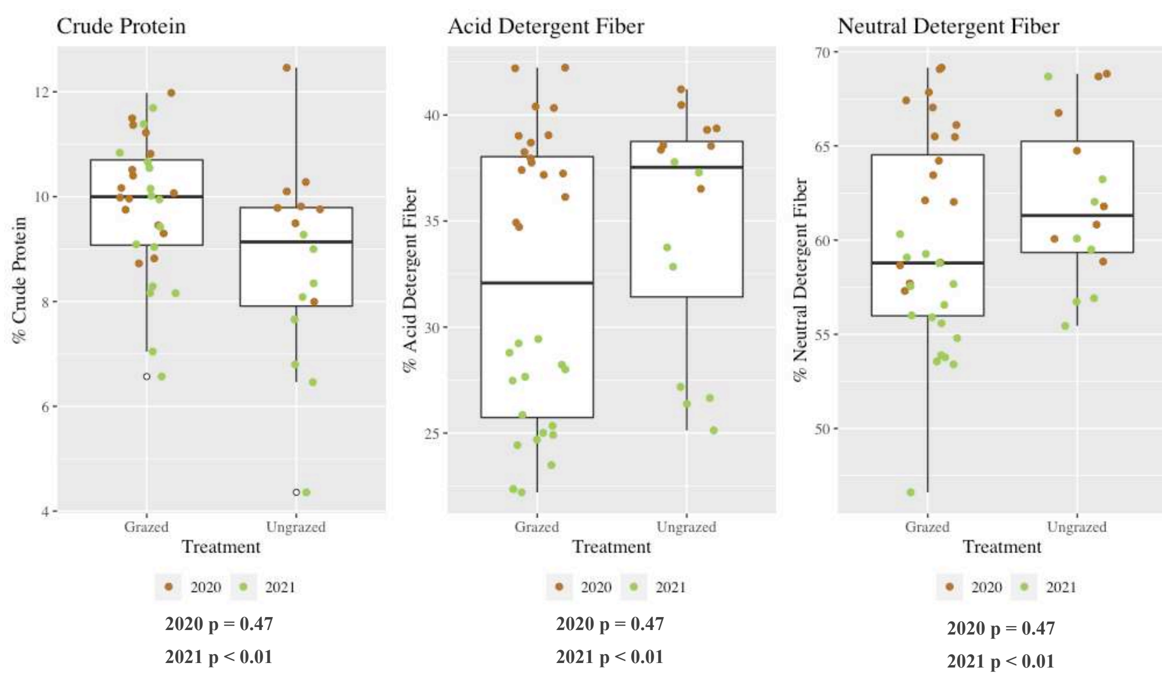


Figure 2.8. Boxplots of forage nutritive quality used in PerMANOVA analysis. Data points represent averages of six subsamples per transect, collected in two consecutive years, and illustrate the significant differences between grazed and ungrazed areas in 2020 ($p = 0.47$) and 2021 ($p < 0.01$).

Regional Patterns

We looked at broader patterns across our study areas and multi-variate dataset with NMDS. Soil health, plant community, and forage quality metrics were used as gradients or vectors that were overlaid on a plant species ordination plot (Figure 2.9). This plot revealed patterns among variables in an interrelated correlational space. Native species were most highly correlated to the SSN grazed areas, which is consistent with our interpretation of Figure 2.7. Shrubs were most highly correlated to the LRR study site. C4 species were most tightly linked to SSN and LRR sites. The greatest SDI and AnGram measures correlated to LRR and CRN ungrazed areas. Exotic species were highest in CRN and CTO sites. Forbs and C3 species were most highly associated with CTO grazed areas. Higher TN and OC were most correlated with CRN grazed areas. SSN and LRR plant species compositions were each unique and distinguishable from all the other sites, while CRN and CTO shared similarities in plant species composition.

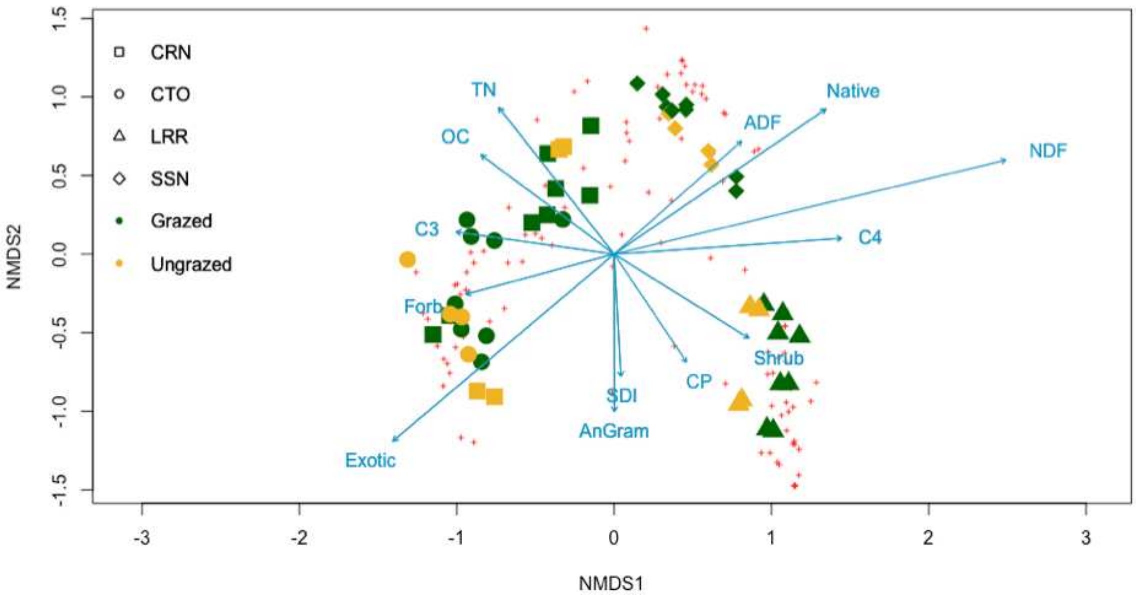


Figure 2.9. Scatterplot of two axes, resulting from a three-dimensional Non-Metric Multidimensional Scaling (NMDS) analysis of plant species distribution on four grazed (green) and ungrazed (yellow) study sites correlated with ten gradients (blue) Shannon's Diversity Index (SDI), five functional groups: C3 (cool season), C4 (warm season), forb, shrub, and annual graminoid(AnGram); two origin groups: native and exotic; two soil health components: percent total nitrogen (TN) and organic carbon (OC); and three forage quality components: crude protein(CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF). Created in R Version 3.6.1.

DISCUSSION

There is considerable debate over the use of government-owned and public lands for cattle grazing. Contributing to this is in an inconsistent body of literature and the challenge of conducting research across extensively variable geophysical landscapes and diverse social-ecological dynamics. Over a two-year period, we studied four government-owned conservation landscapes on the Colorado Front Range to learn about ecological differences and patterns among areas that had been managed by collaborative grazing management versus grazing exclusion. We looked at our metrics at multiple temporal and spatial scales, which revealed to us that scale of analysis is important.

The primary challenge of our study was to implement scientific rigor and a sound research design while honoring the inherent complexity and heterogenous realism of grazing systems. Our sample size was limited due to geographic constraints in our ungrazed areas, which were small in size and subject to spatial autocorrelation issues. This necessitated statistical analysis be performed on an aggregated dataset across all four study sites, instead of examining differences between grazed and ungrazed areas both across sites and within each site. Our tradeoff for a relatively small sample size was to broaden the spectrum of variables in our inquiry. This allowed us to approach our study from a more holistic perspective where human, plant, soil, and animal components were integrated.

Our intent was to study each collaboration as-is, without constraining managers to a contrived set of conditions and actions. By allowing for this level of complexity, we were able to study real-time, real-scale scenarios, producing information and learning opportunities that were meaningful and contextually applicable. We incorporated variables that were important to our partnering ranchers and government agency personnel. Understanding abundances of native versus exotic species, the potential sequestration of atmospheric carbon, and the effect of management on forage quality were all curiosities that were derived from stakeholders in these systems and which were incorporated into the research design.

Research Component 1: Soil Health

The soil health component of our study revealed a clear difference in the cycling of nutrients like TN and OC in areas that had been managed with cattle grazing compared to areas that had been excluded from grazing. The higher TN content recorded in grazed areas is congruent with findings in other studies, whose results addressed the addition of nitrogen-rich inputs like bovine urine and manure (Knapp et al. 1999). Our analysis supports the theory that manure inputs and mechanical breakdown of plant biomass from herbivore trampling are among the ways in which livestock may also contribute to higher soil OC in grazed areas (Reinhart et al.

2021, Teague et al. 2011). We detected higher percentages of TN and OC in the upper soil horizon (0-10 cm) compared to the lower horizon (10-20 cm), which was expected, since the upper horizon and soil surface are where nitrogen deposits and decomposing organic matter are in the highest concentrations.

WI rates were highly variable and lacked statistical difference among grazed and ungrazed areas. This is consistent with some research (Teague et al. 2013), whereas other studies have suggested that rotational grazing improves WI (Döbert et al. 2021). Still, significant spatial variability in WI rate may be due to vegetation cover (Chartier et al. 2011), which is impacted heterogeneously by grazing. Our finding suggests that long-term cattle grazing these landscapes has not resulted in extensive soil compaction nor has it reduced the capacity of the soil to absorb water at comparable rates to areas that have been excluded from grazing.

Future research on these landscapes would benefit from expanding the sample size to capture greater detail within each site and greater variability across the study region while following the same or similar protocols. While we concentrated our efforts primarily on clayey and sandy loam soils, research that tests soil nutrient content and WI measures across various soil types may broaden learning for heterogenous landscapes. We are learning that soil microbiology and other micronutrients, like phosphorus and sulfur, play a greater role in soil-plant dynamics than previously understood, and therefore research that seeks to understand these components would contribute further to our understanding of the impacts of cattle grazing on arid and collaboratively managed rangelands.

Our soil health analysis builds on existing evidence and contributes to a clearer understanding of the ways in which livestock may contribute to higher soil TN and OC in grazed areas, while avoiding negative impacts like reduced WI. **The direct relationship between cattle**

grazing and soil health indicators in our study implies that good cattle management has the potential to contribute to and improve natural ecological processes like nutrient cycling.

Research Component 2: Plant Community

Our plant community component examined a biodiversity index (SDI) as well as species composition through analysis of abundance of functional groups (C3, C4, Forb, Shrub, AnGram) and origin groups (Native and Exotic). **Our analysis did not show significant differences in plant community composition among grazed and ungrazed areas. This indicates that long-term cattle grazing did not measurably alter plant biodiversity or community composition over time.** Furthermore, decisions made by collaborative stewardship and ranching partnerships on these landscapes have not reduced landscape capacity for plant community dynamics like maintaining species diversity or resilient functional group composition.

It is important to note that statistical analyses were performed on a regional scale, using aggregated plant species' abundances across four study sites. However, alternative data illustrations (Figures 2.6 and 2.7) suggest there may be site-specific patterns that could not be tested for statistical significance due to small sample size. For example, C3 (Figure 2.6) and native plant species (Figure 2.7) lean toward greater abundance in grazed areas compared to ungrazed areas within every study site. Additionally, we note a greater abundance of C4 (Figure 2.6) and native plant species (Figure 2.7) at the LRR and SSN sites, compared to CRN and CTO. These kinds of observations, despite non-significant statistical results, raise questions for future investigations and expansions of this work. Our aggregation of the data may have homogenized potential site-to-site and within-site differences. Therefore, for future studies we recognize that a larger sample size at each study site would allow better exploration of this spatial scale, which may illuminate important points of learning for stakeholders associated with each unique site.

Our study was designed to decrease confounding biological variables by carefully selecting locations with similar soil profiles, geography, and topography. Yet, the high spatial and temporal heterogeneity of grassland ecosystems, especially in plant community composition, may have evaded attempts to identify close-to-perfect biological replicates on vast landscapes. In fact, the ordination plot derived from NMDS analysis underscores the conclusion that there were observable spatial patterns and clustering around study sites, emphasizing site-specific characteristics.

Additionally, long-term grazing studies in our region have illuminated that changes in plant communities happen very slowly and are vulnerable to environmental events unrelated to grazing, like drought (Augustine et al. 2017; Porensky et al. 2017). In one study, researchers learned that differences in plant community composition only became detectable after approximately fifty years of grazing (Porensky et al. 2017). This provides potential insight into the lack of significant differences found in our plant species composition analysis. Hence, ongoing research that examines plant community composition across managed landscapes, including diverse spatial and temporal scales, will allow us to more fully understand the long effects of collaborative grazing management in our study region.

Another limitation of our study was that plant community composition was inventoried at one point in the grazing season. At this time of peak vegetative growth, we would expect to identify the majority of plants in our study region. However, we acknowledge that other annual and early season graminoids and forbs may not have been detected at the time of our sampling. Therefore, we expect that the total species richness may actually be higher than was detected across study sites.

With a comprehensive plant species dataset like the one we used, there are additional themes that may be explored to further this research. Future studies may benefit from taking an even closer look into plant community specifics, such as rare or endangered species, total cover versus bare ground, invasive or noxious species, and effects around congregational areas. Decades of research of bison on the Konza Prairie Biological Station in Kansas, USA, provides examples of this (Collins et al. 1998; Knapp et al. 1999; Ratajczak et al. 2022).

Overall, our findings support the use of collaboratively managed cattle grazing as a conservation method since grazed areas may sustain similar levels of biodiversity, functional group composition, and native versus exotic species abundance relative to ungrazed areas. Healthy plant communities support more than cattle on these landscapes. Through a systems perspective we acknowledge that they may contribute to wildlife and pollinator habitat, as well as resilience and biodiversity in belowground soil and microbiotic communities. This implies that rangelands in the Front Range region may benefit from multi-use management, sustainably supporting conservation and natural resource goals while contributing to livestock agriculture production for local food systems.

Research Component 3: Forage Quality

The *forage quality* component of our project was an important element from both a cattle management perspective and a wildlife habitat perspective. **Our statistical analysis revealed a clear positive relationship between forage nutritive value and cattle grazing.** Rather than reducing forage quality available to wildlife, cattle grazing in these management scenarios was correlated with improved forage quality over time, as indicated by higher CP content and lower percent ADF and NDF. Other research on large herbivore grazing has produced similar results (Geremia et al. 2019; Knapp et al. 1999; Milchunas et al. 1995; Rhodes and Sharrow 1990).

Our methodological choices, such as sample size and sample frequency, were constrained by various resources. To avoid the confounding effects of recent grazing or lack thereof, we collected samples from pre-grazed forages. Due to the various grazing schedules on our study sites, this restricted us to late spring sampling only. Therefore, results were temporally specific and likely reflect the previous year's precipitation events and aggregated past management. Steps for future studies would be to a) increase the sample size in order to examine dynamics more thoroughly within study sites as well as among them; and b) sample forage multiple times throughout the year to capture a more comprehensive inventory of annual, cool-season, and warm season forages as well as a spectrum of stages of forage maturity.

Our results provide further insight into forage quality dynamics on landscapes managed in part by cattle grazing. **These data also contribute a clearer understanding of the long-term impacts of cattle exclusion from these landscapes, which suggests a decline in forage quality in the absence of grazing.** Our results support the notion that domestic livestock may do more than sustainably share valuable forage resources with wildlife on rangelands; they may even improve them. From a systems perspective, this level of impact is beneficial for habitat maintenance and the support of ecological dynamics on all trophic levels of the animal kingdom, from soil microorganisms who benefit from thriving plant communities, to carnivores who rely on healthy prey populations. Additionally, good forage quality positively affects ranch operation viability and rancher livelihoods by meeting the nutritional needs of cattle at various phases of production. **When there is collaborative management and joint oversight of natural resource and cattle performance objectives, grazing intensity is more likely kept at a moderate level or a more appropriate level for specific ecosystems, reducing negative impacts.**

CONCLUSIONS

Our study responded to the overarching research question: *Are there significant differences in soil nutrient composition, plant community and species diversity, and forage quality between historically grazed and ungrazed areas?* Our results tell a consistent story about the relationship between ecological variables and collaborative grazing management, which lead to two principal conclusions. First, collaborative cattle management, integrating diverse knowledge sources and objectives from ranchers and government-agency partners has contributed to optimal ecological outcomes, including improved soil health and higher forage nutritive quality. Secondly, plant community composition that did not differ between grazed and ungrazed areas indicates that cattle have not been destructive, nor significant modifiers of plant species dynamics on these landscapes.

Our study illuminates that long-term cattle grazing on these landscapes has not harmfully impacted a spectrum of important resource rangeland health indicators. Instead, our results support the conclusion that soil nutrient cycling, plant species composition, biodiversity levels, and forage quality can be maintained or improved. We revealed potential patterns that are hidden when sites are combined for analysis as if they are a single, homogeneous unit. Scale of analysis is important. It has been made clear that management needs to be customized and responsive to local conditions rather than applied broad-brush as if regions are homogeneous. This project's four study sites are all located on the Colorado Front Range. However, they each have their own ecological characteristics that should inform management.

This study contributes to a growing body of literature illustrating how objectives of both private ranchers and government lands agencies can be met through effective grazing management partnerships. Our approach to research through the lens of social-ecological systems illuminates relationships in the dynamic web of rangeland ecosystems.

Our results demonstrate how collaborative grazing management may achieve the goals of ranchers and natural resource managers alike by increasing potential benefits of grazing and minimizing potential harms. We build on existing evidence that effective cattle management may improve ecosystem function and stability, as well as provide climate change mitigation strategies, like carbon sequestration, nitrogen cycling, and prevention of biodiversity loss.

Importantly, the benefits of these stewardship partnerships are not exclusively environmental. Maintaining thriving ranch operations is vital in supporting community livelihoods and economies at multiple scales. Furthermore, the collaborative process among stakeholders enhances social learning, community building, and collective understanding of diverse perspectives. The outcomes of our study support the conclusion that rangeland ecosystems can be managed to achieve dual objectives of food production and natural resource conservation, especially through a collaborative stewardship approach that integrates ecological, economic, and social components, a model for a sustainable land management future.

CHAPTER 3: EXPLORING THE HUMAN DIMENSION OF COLLABORATIVE RANGELAND MANAGEMENT THROUGH ECOSYSTEM SERVICES EVALUATION

INTRODUCTION

Shortly after the turn of the new millennium, hundreds of scientists worldwide culminated their efforts in a global assessment of life on Earth (Millennium Ecosystem Assessment 2005). The Millennium Ecosystem Assessment (MEA) was the first of its kind and … sobering. The idea that Earth's resources were finite and rapidly degrading and diminishing was not new. However, because such a large proportion of humans and global centers of power inhabited places relatively disconnected from nature, an appropriate sense of urgency was lacking and not enough was being done to protect these resources. More clear, urgent, and targeted individual, community, and governmental action would be needed. The proposed framework for communicating MEA findings was a newly articulated concept of *ecosystem services* (ES), which has now grown into the most important trend in modern conservation science (Fisher and Brown 2015).

ES are foundationally defined as "conditions and processes through which natural ecosystems, and the species that comprise them, sustain and fulfill human life" (Daily 1997), a concept that builds off of social-ecological systems theory to give both monetary and non-monetary value to these benefits. Social-Ecological Systems (SES) theory addresses the innate coupling of society and nature, and that humans and bio-physical processes interact at multiple temporal and spatial scales (Berkes and Folke 1998). Over the past seventeen years, the ES concept has spurred countless research and scholarly efforts, policy initiatives, and educational programs (Aryal et al. 2022; Carpenter et al. 2009; Chan et al. 2012; Daily 1997; Díaz et al.

2018; Jacobs et al. 2016; Jones et al. 2020; Kremen 2005; Lovins et al. 1999; Pascual et al. 2017; Peterson et al. 2018; Tallis et al. 2011; Xu and Peng 2022).

In 2015, the International Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) modified and expounded on the MEA to pervasively integrate into ES the role of culture, social values, indigenous and diverse world views, replacing the ES term with "Nature's Contributions to People" (NCP) (Bruley et al. 2021; Dean et al. 2021; Díaz et al. 2015; Díaz et al. 2018; Kadykalo et al. 2019; Pascual et al. 2017). ES and NCP both highlight the linkages between ecosystems and people by directly addressing human beings' relationship with nature and demystifying the deep and multifaceted connections between human wellbeing and the state of the environment. Throughout this paper, we will use the term ES for ease of language, unless we address concepts explicitly from the NCP literature.

ES has become a powerful concept, implying that human wellbeing drives management and conservation of the natural world (Menzel and Teng 2010). The anthropomorphic tone here is not unintentional. In a seminal pitch for the ES concept, Gretchen Daily (1997), expressed that:

> *The close of the twentieth century represents a period in history that demands not just a carefully tuned focus on crises of the moment but also a long-term perspective on challenges to the human future*…(and)…*that society is poorly equipped to evaluate environmental tradeoffs*…(and)…*decision-making frameworks must ensure the protection of humanities' most fundamental source of well-being: earth's life support systems (p. 2).*

Likewise, Richard Dawkins describes how difficult it is for humans to understand very "slow, cumulative processes like evolutionary or ecological change, which demand sensitivity to the long-term consequences of small changes" (Ophuls 2011). In his preface to a special journal issue, Richard Knight et al. (2011) asserted that the ES concept captures the "dynamic interplay of an expanding human population and rising standards of living on a finite planet in which land and waters continue to degrade."

The ES concept provides shared language about value flows from nature to people. We cannot force people into biospheric altruism, therefore the process of ES valuation capitalizes on the self-interest and self-preservation aspects of human nature to encourage a conservationist mentality and action (Fisher and Brown 2015). The ecosystems of our planet and the way we understand them are shifting and require critical and adaptable attunement by people.

The ES concept may be a catalyst for bringing ecological issues into immediacy in western cultures by striking personal and emotional chords, bringing into focus the fact that our existence is part of a social-ecological web. When the United Nations addressed the issue of *sustainability* in 2005, it was purported that for SES to be sustainable, they had to be "socially equitable, economically viable, and environmentally bearable" (Carpenter et al. 2009; Dawson et al. 2010). If SES was the tinder box, the ES concept would be the match igniting action. We are no longer able to turn away from the role our decisions have in the future of Earth's natural resources.

ECOSYSTEM SERVICES & RANGELANDS

Since the dawn of human evolutionary history, global pastoral systems and *rangelands* have been functional SES due to their strong human-nature connections (Dean et al. 2021). Rangelands are defined as "land supporting indigenous vegetation that either is grazed or that has the potential to be grazed and is managed as a natural ecosystem. Range includes grassland, grazable forestland, shrubland and pastureland" (Society for Range Management 1998). Rangelands cover about 54% of the Earth's surface (ILRI 2021), supporting human and animal life, as well as global ecological processes. They support global livestock production systems including pastoralists, hunter-gatherers, and ranchers, and provide nearly 70% of total forage for livestock production (Holechek 2013). Rangelands are rich in a plethora of ES that span the spectrum in its entirety (Dean et al. 2021; Díaz et al. 2015). Ecological, social, and economic linkages are pervasive in rangeland SES and therefore provide ideal contexts for the study of ES and NCP (Dean et al. 2021).

In the United States, approximately 30% (770 million hectares) of total land cover consists of public and private rangelands (Natural Resource Conservation Service). Since the Taylor Grazing Act of 1934, the cattle industry has maintained a longstanding relationship with United States Government public land management agencies to allow seasonal grazing of private herds on public rangelands (Sayre 2017). The value of these grazing leases to cattle operations cannot be understated as they increase the forage available to them, and therefore their potential herd capacity, as well as opportunities to rest privately-held grazing landscapes during their summer leases. However, in states like Colorado with expanding human populations, rangeland livestock production will continue to compete for limited space with housing development, other forms of agriculture, energy production, conservation spaces, and recreation. According to the 2017 Agriculture Census, Colorado reported a total of $3.9 billion in cash receipts for sold cattle and maintained an inventory of 2.8 million head of cattle managed on nearly 15,000 farming operations. Colorado is ranked 10th in the country for total cattle, of which nearly 65% include cattle being raised in a rangeland setting (United States Department of Agriculture 2017). Cattle being raised in a rangeland setting tend to be in the cow-calf or growth phases of production. While some of these cattle continue into grass-finishing operations, most of them enter into confined feeding operations for the finishing phase of production, making room for the next generation.

A large portion of Colorado's local economy and culture is entwined with the cattle industry. Effective collaborative management between private ranchers and public lands agencies has been shown to support the sustainability of rural communities and the quality of life for producers and consumers through a sustainable food chain and effective natural resource management (Roche et al. 2015; Sulak and Huntsinger 2007; Talbert et al. 2007; Wilmer et al. 2019). For example, a study based in California determined that up to 44% of annual income and 50% of ranching acreage in the Bay area came from government land leases (Sulak and Huntsinger 2007). This is possible due to increased flexibility for grazing schedules, increased operational carrying capacity, as well as the provision of valuable rest and recovery periods for pastures on private ranch land. Large public landowners, such as the United States Forest Service and the Bureau of Land Management collectively subscribe over 299 million acres of land to grazing allotments (Glaser et al. 2015). Likewise, smaller public landowners in the West, such as states, counties, and municipalities, also frequently collaborate with local ranchers for grazing leases.

Leases are typically granted through an application process, which varies greatly across agencies and regions. For example, the Colorado State Land Board opens up the application process for their properties every ten years. On the other hand, the United States Forest Service does not open applications for their grazing leases until the current lessee chooses not to renew, which may not happen for decades. Applications may be ranked according to the prospective lessee's level of experience, monetary bid, and/or a grazing management plan or ecological stewardship plan. Typically, agencies monitor ecological outcomes of the grazing management, but their methods for doing so and the consequences for mismanagement vary greatly across the board. Some ranchers may experience very little involvement by government lands personnel, while others may receive an annual report and be required to attend regular meetings with agency representatives.

Through livestock grazing, these partnerships contribute valuable revenue to public and private entities, while providing an ecological and public service. An *ecological* service of livestock grazing might include the mitigation of fire fuel loads, and a *public* service of livestock grazing may be the provision of food and other animal byproducts to local markets. Additionally, public-private grazing partnerships may play a significant role in maintaining "land use buffers" around government-owned lands that resist conversion and development (Talbert et al. 2007).

Because there is evidence both in support of and against grazing as a management tool on government-owned lands, this continues to be a controversial issue. We believe that in addition to environmental and economic concerns, the controversy is perpetuated by diverse sociocultural value systems related to ES and rangeland management approaches. The socio-cultural valuation of ES on government-owned rangelands in Colorado have not been extensively studied, yet effective collaborative management is likely to benefit from increased understanding of how stakeholders value and prioritize various ES, especially related to land use programs, including cattle grazing. Understanding stakeholder values in specific collaborative contexts may aid in a solution-focused approach and improved group cohesion for effective decision-making and partnership success as we attempt to best match approaches to needs of landscapes and people.

The objective of our inquiry was to evaluate a) how stakeholders in public-private partnerships perceive and value ES on government-owned lands and b) their level of consensus or discord toward management approaches, and c) how these perceptions may influence collaborative decision-making. We contemplated questions such as: *Do stakeholders tend to place higher value on some ES over others? Do stakeholders perceive cattle grazing as an important land management tool or a detriment to conservation objectives? Do stakeholder groups (i.e. ranchers, government agency personnel, recreationers) exhibit distinct value typologies? Do stakeholders tend to agree or disagree on rangeland management styles and approaches? For which management issues do stakeholders find the most and least consensus?*

Our research study was situated on the Colorado Northern Front Range, a western region of the North American Great Plains. We investigated and illustrated the interconnected pathways of rangeland ES and their people, specifically addressing the role of humans and their value systems regarding rangeland management and conservation. Due to the broad-reaching and complex nature of Western rangelands, we expect our results to be of value to a wide audience with direct and indirect interest in rangeland ecosystems, such as government lands managers, ranchers, public lands recreationers, conservation biologists, natural resource specialists and economists, local food cooperatives, sustainable agriculture proponents, and the general public.

We use the term *government-owned lands*, not to devalue the role of taxpayer funded *public* lands, but to encompass all of our study areas, which are all owned by government entities, but which do not all allow public access nor receive funding from taxpayer dollars.

BACKGROUND

Ecosystem Services Valuation

It is widely accepted that there is increased need to engage the human dimension in ES research (Bennett et al. 2015; Carpenter et al. 2009; Chan et al. 2012; Coleman et al. 2021; Iniesta-Arandia et al. 2014; Kenter et al. 2015; Menzel and Teng 2010). One way of accomplishing this is through investigating human value systems. Value assessment, in this case, elucidates the effect of ES on social and economic well-being—understanding economic and sociocultural drivers of ecosystem use, evaluating the relative impact of alternative actions, raising awareness and interest, analyzing policy, engaging in land use planning, and understanding our common assets (Costanza et al. 2014; Daily and Matson 2008; Daily et al. 2009; Lovins et al. 1999; Millennium Ecosystem Assessment 2005; Tallis et al. 2011). In a special feature editorial, Managi et al. (2022) explains, "Valuation of nature forms a solid basis for conservation policy across the globe, and institutions as diverse as the United Nations (UN) and the World Bank (WB) embrace-related activities." However, a downside to the integration of economic and sociocultural values in ecological decision making is that it shifts the nature-human relationship to an anthropocentric one (Hermelingmeier and Nicholas 2017).

Specifically, the idea of commodifying nature is fraught with moral and ethical challenges and likely conflicts with various cultural worldviews. This is most evident in the dynamic evolution of literature regarding *payments for ES*, where monetary valuation of nature and natural processes is criticized for contributing to an ethical dilemma (Bruner and Reid 2015; Chan et al. 2017; Jones et al. 2020; Kallis et al. 2013). The ES concept originated from the fields of environmental economics and ecology, where monetary values were emphasized more than non-monetary values to inform the management and governance of natural resources

(Millennium Ecosystem Assessment 2005). While economic valuation of ES can be important in certain decision contexts, it is limited by a unidimensional approach to analysis, lack of cultural insight, and the fact that some ES are difficult to monetize (Bockstael et al. 2000; Chan et al. 2017; Chan et al. 2012; Torell et al. 2013; Van Riper et al. 2012).

Research following the original MEA and NCP publications emphasized a more pluralistic approach to valuation (Chan et al. 2012; De Chazal et al. 2008; Díaz et al. 2015; Himes and Muraca 2018; Jacobs et al. 2016; Kenter et al. 2015; Managi et al. 2022; Pascual et al. 2017). A unidimensional approach that economizes ES solely through instrumental or monetary-valuation excludes a pluralistic perspective that can help acknowledge cultural and social-ecological complexities (Chan et al. 2012; Jacobs et al. 2016; Kallis et al. 2013; Pascual et al. 2017). A pluralistic approach may be more effective in inducing long term social and political change, yielding equitable policy outcomes, and increasing SES resilience (Pascual et al. 2017; Van Riper et al. 2012). Therefore, non-monetary methods and metrics, like those used in our study, may improve multidimensional and holistic insight into valuation of complex SES, like rangelands (Bruner and Reid 2015; Chan et al. 2012).

An individual's unique values are a concert of one's own life experience and culture (Kenter et al. 2015). Values are inherently drivers of human decision-making, and understanding the values humans associate with nature allows us to simultaneously understand why humans make the decisions they do in terms of ecosystem use. Evaluating non-monetary human values or sociocultural values (intrinsic, instrumental, and relational values) as drivers of decision-making is an aspect of emerging importance in ES research and sustainability science (Bruner and Reid 2015; Chan et al. 2017; Grillos 2017; Hein et al. 2006; Iniesta-Arandia et al. 2014; Van Riper et al. 2012). According to Pascual (2017) intrinsic values are those that are inherent in nature and independent of human opinion or judgement (e.g., animal welfare, ecological processes, biodiversity), instrumental values are those that are means to satisfy human needs (e.g., food, materials, energy, habitat), and relational values are those that are derived from our relationships with and toward nature (e.g., physical and emotional health, sense of place, cultural identity, inspiration). Scholte et al. (2015) claim that sociocultural valuation is not meant to replace unidimensional, monetary valuation because market-based valuation can provide important economic information. Rather, a pluralistic approach to valuation, including monetary and non-monetary drivers provides a wealth of information regarding "how" and "why" people value certain ES so that effectively assessed values can be extrapolated for decision-making (Scholte et al. 2015).

For the study of grazing systems–mosaics of social, ecological and economic dynamics–it would behoove us to utilize assessment methods that capture the deeper complexities of our value systems and how they motivate human decision-making and behavior towards nature and conservation. For example, in a 2002 study conducted in the American West, researchers discovered that while ranchers valued the forage (feed for cattle) that public lands leases provided, they had reasons beyond monetary gains to engage in such partnerships (Bartlett et al. 2002). In fact, ranchers indicated "quality of life" as their primary reason for ranching on public lands. In a study conducted by Arizona Extension, researchers used a pluralistic approach to assessing viewpoints and perspectives to improve their outreach and education on contentious issues and complex natural resource challenges (Lein 2018). These pluralistic value studies can be compared to those which only assessed monetary values, such as one in San Antonio, Texas, USA, where land cover changes were linked with ES in a 2001 study that used a monetary valuation approach (Kreuter et al. 2001). The economic value of rangeland ES was extensively reviewed in a 2021 study focusing on monetary assessments, in which researchers did not consider sociocultural values, except to make note in the Introduction that they exist (Maher et al. 2021). These unidimensional approaches may conclude with an incomplete take-home message compared to studies that engage multi-dimensional valuation.

Rangeland ES valuation studies have also been conducted in other parts of the world. In China researchers assessed myriad rangeland ES, from ecological processes to recreation and cultural services, and their overall monetary value to society (Gaodi et al. 2001). An Iranian study took an economic approach to assessing the total value of forest and rangeland ES (Karimzadegan et al. 2007). A study based in the Hindu Kush Himalayan Region reviewed and discussed the challenges and opportunities of rangeland ES across the entire ES spectrum, although sociocultural valuation played a minor role (Joshi et al. 2013). An extensive rangeland study conducted in Botswana, assessed both monetary and non-monetary outcomes (Favretto et al. 2017). The Botswana study included both communally-managed and protected rangelands, whose significance was based on the integration of a wide spectrum of sociocultural ES values.

Q-methodology

Q-methodology is an approach that provides a context-based, semiquantitative analysis for sociocultural valuation that has been used in fields ranging from business economics and education to natural resources, medical science and public policy. It provides a "systematic study of subjectivity" and social perspectives (Brown 1993), offering a powerful approach to ES and conservation research that reveals pluralism in complex and dynamic systems (Armatas et al. 2014; Lein 2018; Rost 2021; Zabala et al. 2018). Q-methodology encourages critical reflection and prioritization of a multitude of values and viewpoints that underpin conservation approaches and decision-making (Roberts et al. 2020; Zabala et al. 2018). Sociocultural valuation methods, like Q-methodology, may improve the efficacy of solely monetary or market-based valuation in ES research, as the latter may fall short at capturing pluralistic values inherent in social-ecological systems and thus lead to ineffective decision-making (Armatas et al. 2014; Scholte et al. 2015).

The fundamental steps of Q-methodology should be carefully implemented in sequence to ensure procedural integrity, outcome rigor, and derive meaningful structure and form from subjective viewpoints (Webler et al. 2009) (Figure 3.1).

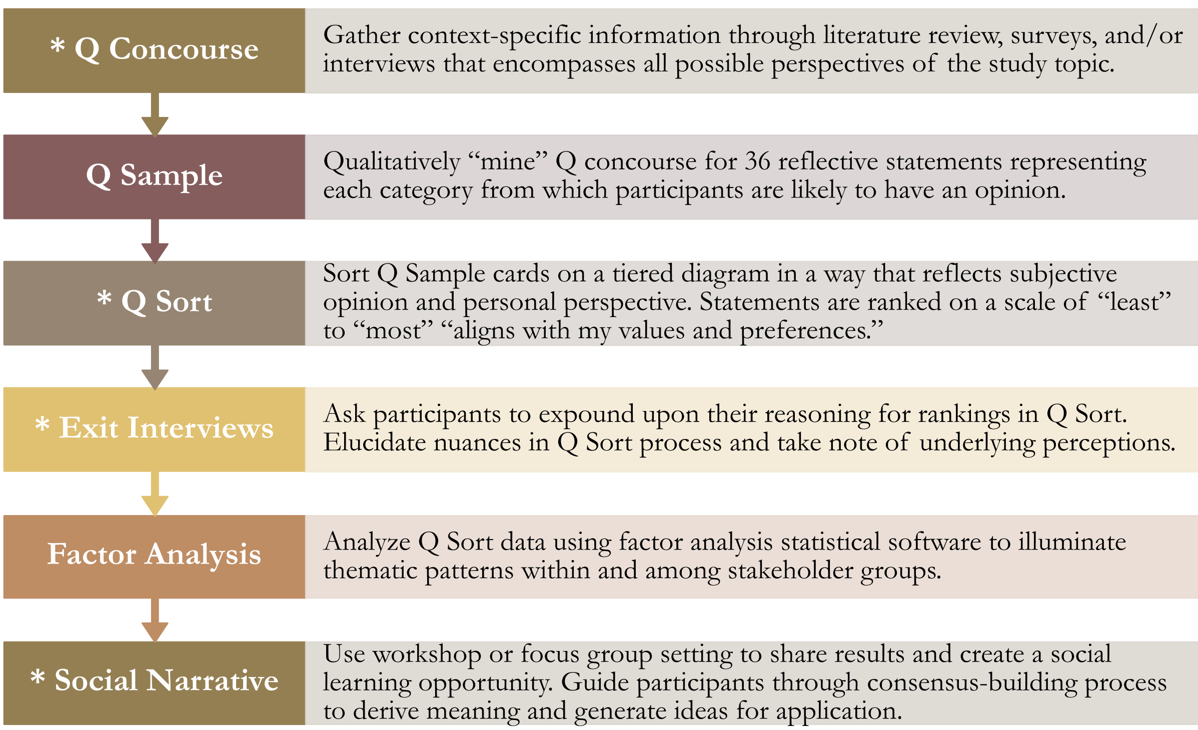


Figure 3.1. Six steps of Q-Methodology (Armatas et al. 2014; Lein 2018; Webler et al. 2009). * Signifies a step involving direct stakeholder participation.

First, the researcher gathers essential context-specific information through an in-depth literature review, surveys, and/or interviews with experts and stakeholders to create a Q *concourse*, an emergent set of conceptual categories that encompasses all perspectives of the study topic (Webler et al. 2009). Second, the concourse is qualitatively mined to develop a reflective Q *statements* from each category of which participants are likely to have an opinion (Webler et al. 2009). A large initial set of Q statements is narrowed into a Q *sample*, where select statements from each category will be presented to participants in the Q *sort* (Webler et al. 2009).

The Q sort forces participants to distinguish and rank their priorities relative to each other, and to reveal their interdependent preferences (Webler et al. 2009). This is where pluralistic valuation comes into play. Participants are asked to sort Q statement cards on a tiered diagram in a relative way that reflects their subjective opinion or authentic perspective (Figure 3.2) (Webler et al. 2009). This is done on a normally distributed curve, where fewer statements may be ranked in extreme positions. The number of statements in the Q sort may vary but must always follow this distribution (Brown 1993). It is also recommended that the Q sort process involve an additional *exit interview*, where participants are asked to expound upon their reasoning for ranking statements (Armatas et al. 2014).

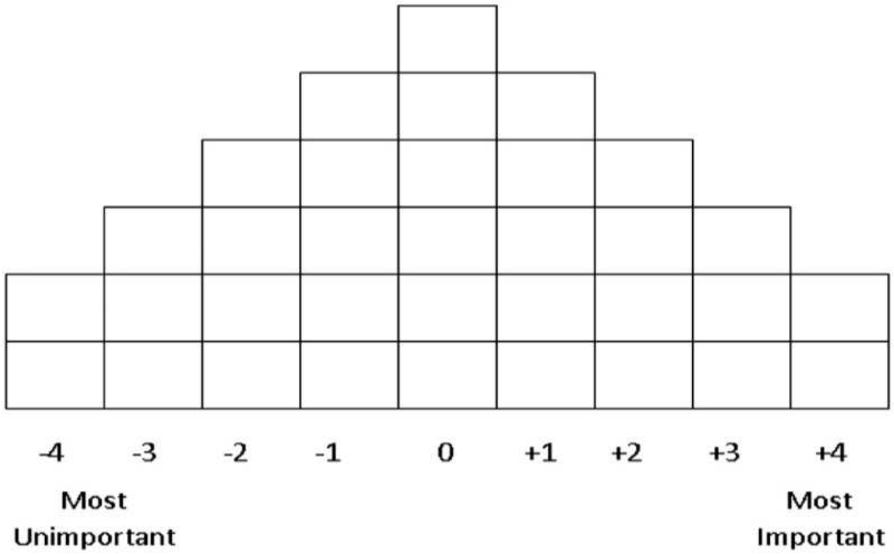


Figure 3.2. Example Q sort diagram: a key step in Q methodology using participant involvement (Armatas et al. 2014), although other variations may exist depending on number of statements in the Q sample.

The Q sort data are analyzed using *factor analysis*, a technique used to illuminate thematic patterns, and in this case social perspectives (Webler et al. 2009). The factor analysis results will ultimately develop a social narrative about participant beliefs, values, and prioritization (Webler et al. 2009). The final step is to validate the narrative and disseminate results to the Q participants (Webler et al. 2009). This can be done in a group setting, where stakeholders are guided through a consensus-building process. This is where participants can observe their relative fit within the community, derive meaning from the Q narrative, and generate ideas for application of their group's learning.

Q methodology provides a foundation for the systematic study of human subjectivity and is, therefore, one of the prominent ways social perspectives are evaluated in environmental studies (Brown 1993; Webler et al. 2009). It does not always provide broadly generalizable results, but rather an in-depth "portrait" of social narratives and perspectives that predominate in a given context (Steelman and Maguire 1999). It is an "objective, transparent, easily replicable, and statistically-rigorous approach to qualitative research" (Armatas et al. 2014), and for these reasons it pairs nicely with sociocultural valuation of ES. Whereas other methods may highlight differences in social perspectives, Q methodology underscores shared solutions, consensus areas, and value clusters (Lee et al. 2017; Roberts et al. 2020; Zabala et al. 2018).

PREVIOUS APPLICATIONS OF Q METHODOLOGY

Q methodology has been used in various fields to understand patterns of thinking among groups of people, and Q studies have been published on a diverse spectrum of topics, including ES. In regard to governance of ES, a study based in an Australian mangrove ecosystem looked specifically at how ES valuation influences policy (Simpson et al. 2016). The authors explained that stakeholder perceptions were categorized using Q methodology to illuminate shared-values among diverse stakeholder groups (Simpson et al. 2016). Researchers claimed that focusing on shared-values, as opposed to conflictual viewpoints, increased the saliency of certain ES, which could progress coastal policies using prioritized decision-making (Simpson et al. 2016).

A group of researchers used Q methodology to explore how the concept of ES is being applied in the field (Hermelingmeier and Nicholas 2017). The analysis revealed that there is significant variation in how ES are interpreted and perceived by practitioners (Hermelingmeier and Nicholas 2017). This plurality could remove barriers for collaboration, but it could also lead to ineffective collaboration efforts due to lack of "conceptual common ground" – an insightful conclusion that might not be immediately apparent to land managers (Hermelingmeier and Nicholas 2017).

The most common application of Q methodology in the ES literature over the past decade is with the evaluation of "cultural services." This group of studies used Q methodology to explore stakeholder perceptions and values in various ecological systems across the globe: urban parks in the Netherlands (Buchel and Frantzeskaki 2015), mud flats in Korea (Lee et al. 2017), marine protected areas in Canada and the United Kingdom (Pike et al. 2015), and vineyards in California and England (Winkler and Nicholas 2016). Largely, these analyses concluded that Q methodology brought about a wealth of information that was context-specific and arguably undetectable by traditional evaluation methods (Pike et al. 2015). Understanding various stakeholder perspectives may inform land use planning, cooperative decision-making, and the optimization of ES management (Buchel and Frantzeskaki 2015; Lee et al. 2017; Pike et al. 2015; Winkler and Nicholas 2016).

Another common area of Q application is forest and watershed management. From the Chattooga Watershed in the southern Appalachians and the National Forest in West Virginia to the National Forests and Watersheds of the Rocky Mountain west, researchers claimed that forest service(wo)men have historically struggled to integrate public perceptions and values into management planning. In these cases, Q methodology has proven to be an effective method for public involvement and filling the gap in human value-relevant data (Armatas et al. 2014; Roberts et al. 2020; Steelman and Maguire 1999).

For example, in 2014 Q methodology was used in a case study that explored water-related ES of the Shoshone National Forest (Armatas et al. 2014). A monetary valuation method would have fallen short at capturing the broad array of stakeholder values discovered and thus led to ineffective decision-making or unintended consequences (Armatas et al. 2014). A more recent study used Q methodology to examine motivations that contribute to watershed partnerships in the intermountain western United States (Roberts et al. 2020). Researchers found that internal motivators were more influential than external motivators in partnership participation (Roberts et al. 2020). This finding contradicts other literature on environmental management and confirmed that individuals' unique values are significant components of collaborative management (Roberts et al. 2020).

Q METHODS & CONTEXT

Study Areas

Four multi-use conservation areas that include cattle grazing leases in their management plans were selected for this study: Coyote Ridge Natural Areas (CRN) and Soapstone Prairie (SSN) in Larimer County, Coalton Trailhead Open Space (CTO) in Boulder County, and Lowry Ranch (LRR) in Arapahoe County (Figure 3.3).

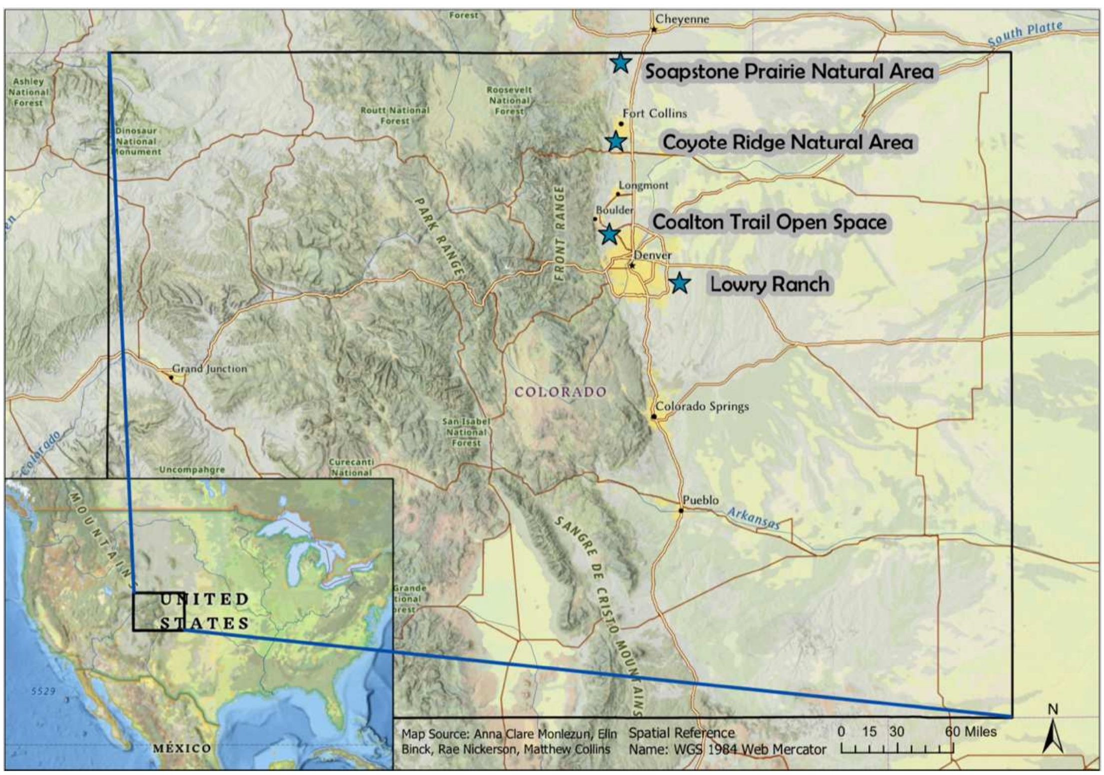


Figure 3.3. Map of four Colorado Northern Front Range study sites located in Larimer, Boulder, and Arapaho counties. Study sites were located within government agency properties and managed in part through cattle grazing leases.

CRN was once a private ranch, homesteaded and operated by the same family since 1959. They were "pioneers" in ecologically-oriented ranch management and partnered throughout their ownership with the Natural Resource Conservation Service (formerly the Soil Conservation Service) for land health and soil improvements. The family donated the property to the City of Fort Collins Natural Areas Department in 2017, and it has been collaboratively managed with a rancher lessee since 2019.

SSN is an expansive and diverse landscape acquired by the City of Fort Collins Natural Areas Department in 2004 and has been collaboratively managed with the Folsom Grazing Association since then. The Folsom Grazing Association, formerly known as the Soapstone Grazing Association, had actually owned and managed the territory since the 1950s, when they bought it from a private ranch.

CTO is a large contiguous property that was acquired by Boulder County Parks and Open Space in small parcels over time. It has been collaboratively managed with the same rancher lessee since 1995. CRN, SSN, and CTO are all government-owned lands located in the vicinity of populated urban areas, and are therefore popular recreation sites for hiking, biking, and horseback riding.

LRR is a property of the Colorado State Land Board acquired in three separate transactions over twenty-seven years. It has a diverse history as an experimental bombing range and an army airfield until it was converted back into ranch land. It was managed by a continuous grazing approach until 2007, when ranching ceased for seven years. In 2014 with a new sustainability initiative, LRR's management transitioned to holistic management and rotational grazing. Although LRR is a government-owned property whose revenue supports public interests, it is not open to the public for recreation.

These lands are classified within two Major Land Resource Areas (MRLA): a) 49, Southern Rocky Mountain Foothills (CRN, CTO, SSN), and b) 67B, Central High Plains (CTO, SSN, LRR) (USDA 2006). Importantly, they are physically situated very near the thresholds of these two MRLA's. Therefore, we must acknowledge that their geophysical, soil, biological, and climatic properties are more appropriately associated with an ecotone that comprises characteristics of both MRLA's, and research results may be extrapolated across these regions. MRLA 49 is characterized as a foothills region with an annual average precipitation of 305-635 mm (12.0-25 in) but can range as high as 820 mm (32.3 in) (USDA 2006). The average annual temperature is 0.9-11.4 C (33.6-52.5 F), and the frost-free period ranges from 75-165 days (USDA 2006). MRLA 67B is characterized as semi-arid and is within the Colorado Piedmont section of the Great Plains. Average annual precipitation is 32.0-51.0 cm (12.6-20.1 in) with high interannual fluctuations (USDA 2006). The average annual temperature is 7-13 C (44.6-55.4 F), and the frost-free period ranges from 130-180 days (USDA 2006).

The following additional descriptions characterize both MRLA 49 and 67B: Historically, rainfall events are typically intense and short-duration and occur mainly in spring and early summer, while snow makes up winter precipitation (USDA 2006). Soils have a mesic temperature regime, a ustic or aridic moisture regime, are very shallow to very deep, well drained, and loamy (USDA 2006). Nearly 50% of these land areas is composed of grassland and pasture used for farming and ranching, while supporting native vegetative species like blue grama (*Bouteloua gracilis*), buffalo grass (*Buchloë dactyloides*), needle-and-thread (*Hesperostipa comata*), western wheatgrass (*Pascopyrum smithii*), prairie junegrass (*Koeleria macrantha*), and threeawn (*Aristida purpurea*) (USDA 2006).

Study Participants

To capture the dynamics of management and decision-making from the perspectives of diverse stakeholders within these four collaborative grazing systems, we included from each site a combination of participants representing three stakeholder groups: a) *rancher/producer,* b) *agency/professional*, and c) *community/recreationer*. Stakeholder participants were recruited using purposive sampling, a nonprobability technique appropriate for in-depth research pertaining to complex sociocultural domains (Battaglia 2008). The rancher/producer group was composed of private ranching partners, who were actively participating in grazing leases with the government agencies who participated in our study. The agency/professional group was made up of a range of government employees, from wildlife biologists and environmental planners to agriculture and resource specialists, from the agencies that participated in our study. The community/recreationer stakeholder group was comprised of community members who spent time recreating or volunteering at the properties involved in our study. These stakeholders came from a wide range of professional backgrounds with varying levels of knowledge regarding rangeland ecology or livestock agriculture.

We executed the 6-step Q methodology process with a total sample of forty stakeholders. These included ten rancher/producers, eighteen agency/professionals, and twelve community/recreationers. We had one-hundred percent participatory follow-through from all stakeholders throughout the Q method. Because this study was conducted during the coronavirus global pandemic, we offered participants multiple modalities, described below, for completion of each step of the process to provide flexibility and ensure public health measures were maintained throughout the study.

Develop Q Concourse

The first step was to survey participants for values, opinions, and beliefs about the ES associated with relevant study areas. We created an initial questionnaire made up of seven broad items to mine participants for this information (Appendix D). We emailed these questionnaires as both PDFs and Microsoft Word documents, while also offering standard mail delivery with return postage for the completed questionnaire. We also offered an oral questionnaire via phone call, for those who preferred more personal contact. In addition to the questionnaire responses of our forty participants, we incorporated other expert knowledge, conversations with stakeholders, and background research to amass the Q Concourse.

Refine Q Sample

The Q Concourse was then thematized, where we extracted major themes and condensed them directly into statements. We made an effort to retain original language and word phrases directly from participant questionnaires to strengthen the iterative research process and reduce bias. The final statements derived from the Q Sample were organized into the three NCP ES categories: material, nonmaterial, and regulating (Díaz et al. 2018) (Table 3.1) (Appendix E). Materials ES include substances and objects from nature that directly contribute to our physical existence or material assets (Díaz et al. 2018). Nonmaterial ES are the psychological effects of nature on our quality of life and subjective sense of wellbeing (Díaz et al. 2018). Regulating ES are the structural and functional aspects of ecosystems and environmental conditions that indirectly affect our experiences and quality of life (Díaz et al. 2018). These categories were aligned with recent NCP ES valuation theory, including instrumental, intrinsic, and relational value categories (Díaz et al. 2018; Jacobs et al. 2016; Pascual et al. 2017) (Table 3.1).

Table 3.1. Table of rangeland NCP ES, their benefits to humans, and associated values embedded in and extracted from stakeholder-derived information. Categories and values are labeled according to the Nature's Contributions to People (NCP) framework (Díaz et al. 2015).

Category	Ecosystem Service	Benefits to Humans	Associated Values
Material	Food and fiber production (agriculture)	income, sustenance, lifestyle, clothing	Instrumental, relational
	Timber production	income, sustenance, lifestyle	Instrumental, relational
	Grazing leases	income, release of pressure on private lands, lifestyle	Instrumental, relational
	Renewable energy production	income, achieve climate goals, "clean" energy	Instrumental
	Oil and gas extraction	income, supports industrialized society	Instrumental
	Subjects of inquiry	research, education	Instrumental, intrinsic, relational
Nonmaterial	Hiking, biking, camping, hunting (recreation)	Income, Physical health, psycho-emotional wellbeing, quality of life	Instrumental, intrinsic, relational
	Beauty	psycho-emotional wellbeing, quality of life, inspiration	Intrinsic, relational
	Undisturbed open space	psycho-emotional wellbeing, quality of life, inspiration, spiritual identity, place for exercise	Instrumental, intrinsic, relational
	Sustainability for future	quality of life, peace of mind, familial continuity	Instrumental, relational
	Wilderness and wild spaces	psycho-emotional wellbeing, quality of life, inspiration, spiritual identity	Intrinsic, relational
	Place of peace, solitude, renewal, and relaxation	psycho-emotional wellbeing, quality of life, inspiration	Intrinsic, relational
	History and cultural heritage	familial continuity, inspiration, education	Instrumental, intrinsic, relational
	Buffer to urban development	psycho-emotional wellbeing, quality of life, inspiration, place for exercise	Instrumental
Regulating	Wildlife habitat and migration corridors	Income, recreation, inspiration	Instrumental, intrinsic
	Water infiltration, storage, and erosion control	forage production, reduced irrigation costs, drinking water, surface water quality improvement, flood damage attenuation	Instrumental, intrinsic
	Biodiversity (plant and animal)	genetic variation, medicinal, ceremonial, and cultural products, pollination, mitigate climate change	Instrumental, intrinsic
	Carbon sequestration	carbon storage, agriculture productivity, mitigate climate change	Instrumental, intrinsic
	Soil health	nutrient cycling, erosion control, productivity, mitigate climate change	Instrumental, intrinsic
	Pollination	reduce agriculture production costs, sustenance, quality of life	Instrumental, intrinsic

We considered the NCP categories as the most appropriate existing ES framework for our analysis and study context. While the Q Sample was organized and analyzed using NCP ES concepts, we were careful to use common language that was accessible to the diverse experience and knowledge of our participants. In our correspondence with them, concepts were framed in non-technical language and comprehensible to a broad spectrum of stakeholders. In the end, the Q Sample consisted of a set of thirty-six statements that reflected concepts for which the majority of participants expressed an opinion or perspective in their questionnaire responses, regardless of the implications or tone of that opinion (Figure 3.4).

Facilitate Q Sort

The next step was the Q Sort exercise, during which each stakeholder had the opportunity to complete their unique prioritization of statements and rank relative values of statements from the Q Sample (Figure 3.4). Traditionally, this is done in-person, in a group or individual setting using physical materials including scissors and glue, a Q Sort diagram (Figure 3.1), and statements printed on pieces of paper (the Q Sample) (Figure 3.4). Participants sorted statements onto the diagram with relatively lower value statements placed to the left, and higher value statements to the right (Figure 3.5). To help with this process, participants could first sort into three piles of: low importance, neutral, and high importance. Due to the conditions of the global pandemic, which was now in its second year, we adapted the Q Sort exercise to an online platform, Google Jamboard (Google Jamboard) (Figure 3.6). This offered a private virtual Q Sort diagram option, although some participants still followed through with using the paper and scissors version. We also offered to meet with participants one-on-one over the phone, video, or in a COVID-19-safe setting, where we could verbally facilitate the Q Sort exercise.

*** Please note that "GOL" = government-owned lands**

We have a moral and ethical duty to preserve America's prairie and grassland ecosystems. 1	GOL provide essential wildlife habitat and migration corridors. 2	I support public access of GOL for recreation opportunities like hiking, camping, and hunting. 3	It is important that GOL continue partnerships with local private agriculture operations via leases. 4	I value GOL for providing buffers to urban development & industrialization. 5	GOL should be maintained as multi-use, working landscapes. 6
I believe ranchers need to be able to make a profit from leasing GOL. 7	Beauty and undisturbed open space are qualities that attract me to GOL. 8	Increasing carbon sequestration through grazing management should be a focus of GOL. 9	Control of noxious and invasive species is a joint responsibility of GOL staff and ranchers. 10	GOL should be used for research and educational purposes. 11	The top priority of GOL should be protecting natural resources. 12
GOL are places for diverse plant species (i.e. native, rare, endangered) to thrive and be protected. 13	A benefit of GOL is public access to connect with nature for peace, renewal, solitude, and relaxation. 14	Managing water quality and riparian areas should be a priority of GOL. 15	GOL are important places for the public to exercise outdoors. 16	Beef is an important product that comes from GOL. 17	GOL should continue to be spaces for the production of food/meat and fiber/wool. 18
GOL should also be used for the production of timber. 19	GOL are important for preserving history and cultural heritage (i.e. ranching heritage). 20	I believe that GOL should also be used for oil & gas extraction. 21	The balance between underuse and overuse of grazing areas should be a major focus of GOL management. 22	GOL management should focus on maintaining natural ecosystem functions and processes. 23	GOL should continue to be used for crop agriculture. 24
I believe that GOL should also be used for renewable energy production (i.e. wind, solar, and hydro power) 25	We need GOL for pollination and pollinator habitat. 26	GOL should provide public access to clean air, natural, "green", and unpolluted landscapes. 27	Livestock grazing plays an important role in the maintenance of GOL 28	GOL should be managed for long-term sustainability goals with future generations in mind. 29	Soil health (stability and structure) is of major importance to GOL management. 30
GOL can be used to help mitigate the effects of climate change. 31	There is spiritual value in GOL. 32	Maintaining plant and animal biodiversity is important to GOL management. 33	Pesticides and herbicides should play a role in GOL management. 34	Fire management should be a focus of GOL. 35	GOL play a significant role in preserving wilderness and wild spaces. 36

Figure 3.4. Q Sample paper version of the statement array. Participants were instructed to cut out squares and arrange them according to personal values on the Q Sort diagram.

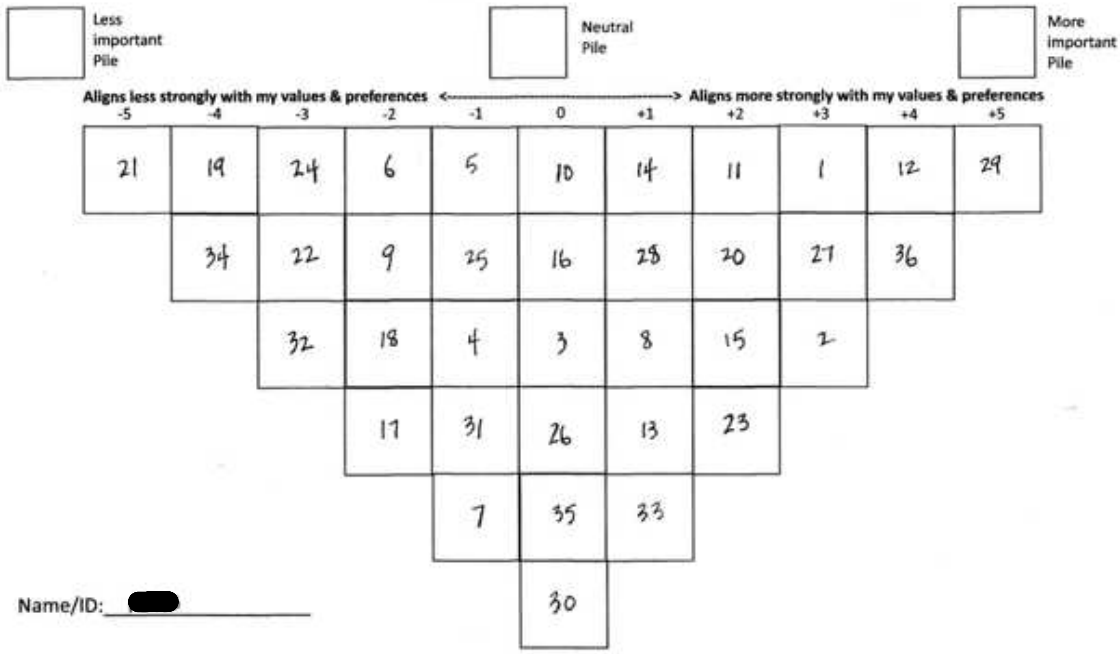


Figure 3.5. Example of completed Q Sort diagram: a key step in Q methodology using participant involvement. Each number in the diagram corresponds with a Q statement in the Q Sample.

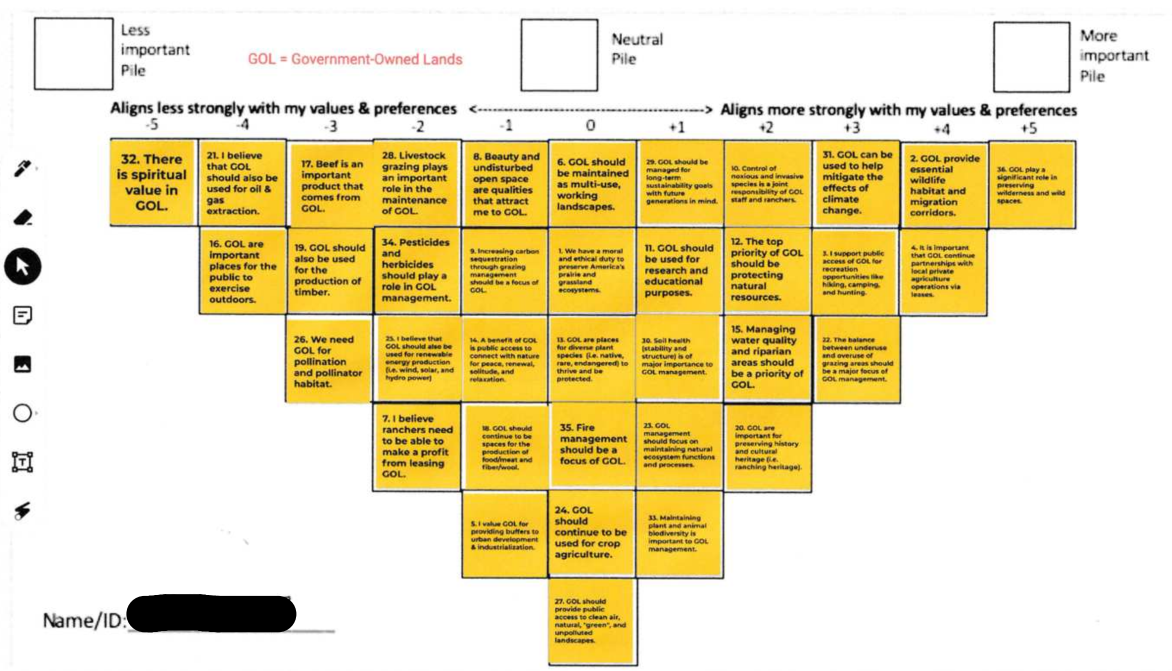


Figure 3.6. Example of a completed Q Sort diagram on the virtual platform, Google Jamboard. Participants were instructed to arrange squares according to personal values and download their final sort.

Conduct Exit Interviews

Within two weeks of completing their Q Sort, each participant took part in a semi-structured exit interview so that more details about each unique Q sorting process could be understood and clarified. The exit interviews were essential to understanding nuances in the Q Sort process, which informed interpretation of results. We offered to conduct interviews by phone, video conference on multiple platforms, or in person in a COVID-19-safe setting.

Perform Factor Analysis

Q Sorts were analyzed using factor analysis with the software, KADE (Banasick 2019). We used Principle Components Analysis followed by Varimax rotation on three factor levels that were determined by examination of an Eigenvalue scree plot and elimination of factors with Eigenvalues <2 (Banasick 2019; Webler et al. 2009). This analysis illuminated three *types* in our stakeholder typology. We also examined how stakeholder groups prioritized each of the three ES categories (material, nonmaterial, regulating), which added a thematic dimension to the interpretation of the results and explored the question: *Do stakeholders tend to place higher value on ES that are material, non-material, or regulating?* This step was important in understanding the value basis for management decision-making approaches.

Interpret and Create Social Narrative

The final Q step was to present factor analysis results to the stakeholder participants, which was done in the form of a workshop. With facilitated discussion, stakeholders were encouraged to think critically about the results and assist in the calibration of researcher interpretation based on personal on-the-ground experiences. The interpretation process involved the creation of a social narrative, incorporating areas of discord and consensus among the three factors or types.

MANAGEMENT SURVEY

During the process of developing the Q Concourse from stakeholder questionnaires, we noted a cluster of stakeholder responses that did not fit under ES categories, but rather, pertained to management approaches. These opinions and perspectives were slightly tangential to questionnaire prompts, and therefore, unexpected. To retain this emergent content in the study, we added to the Q Methodology process a supplementary management survey that further explored stakeholder views regarding management approach themes. The survey (Appendix F), which was distributed in tandem with the Q Sort exercise, asked participants to rate a list of eleven individual management statements (Table 3.2), on a 5-point Likert scale, from "Strongly Disagree" to "Strongly Agree" (Likert 1932). This exploration of management perspectives and how they related to our ES valuation typology falls outside standard Q-methodology procedure but proved to be crucial to our final analysis, as it probed for further nuances in the harmony and dissonance stakeholders may face when attempting to manage government-owned lands collaboratively. Our adaptive approach allowed us to take advantage of these data we were not expecting to improve the usefulness of our outcomes for management specifically.

Table 3.2. Supplementary management survey statements and associated abbreviations. Stakeholder participants rated statements on a Likert scale.

Statement	Abbreviation
Management decisions on government-owned lands should be based on **science** (education and **knowledge**).	**Science-education**
Management decisions on government-owned lands should be based on **research (**surveying and **monitoring).**	**Research-monitoring**
Management decisions on government-owned lands should be based on **local knowledge** (rancher **experience** and knowledge, intergenerational wisdom).	**Local knowledge-experience**
Government-owned lands management should be **holistic**, incorporating ecological, social, and economic **drivers** and outcomes.	**Holistic-drivers**
Government-owned lands management should be **flexible** and **adaptive**.	**Flexibility-adaptivity**
Enforcing **rules** and strict **oversight** of government-owned lands is important in their preservation.	**Rules-oversight**
Setting **goals** and **objectives** is important for government-owned lands management.	**Goals-objectives**
A hands-off approach, allowing **unlimited** use by **grazing** livestock would be detrimental to government-owned lands.	**Limited-grazing**
A hands-off approach, allowing **unlimited** use for **recreation** would be detrimental to government-owned lands.	**Limited-recreation**
I believe that the management of government-owned lands also entails dealing with **conflicting interests**.	**Conflicting-interests**
Government-owned lands should be places of **collaborative** and cooperative management, as opposed to **prescriptive** management.	**Collaboration-not prescriptions**

RESULTS

Factor Analysis

The final three ES valuation types were distinguishable and interpretable. They each had an eigenvalue > 2 and cumulatively accounted for 63% of the study variance. Types were labeled according to their overarching themes and ES valuation approach. They included: Type I) ecocentric naturalist, Type II) sustainable utilitarian, and Type III) multi-use steward. We evaluated the top five distinguishing statements associated with each emergent type, their Q sort value (mean reported score of negative to positive value -5 to +5), and z-score (relative difference from the overall mean) (Table 3.3). A correlation matrix among types reveals that the strongest correlation can be found between Type I and Type III (r = 0.62). Type II was found to be weakly correlated with Type III (r = 0.26), and to not be correlated with Type I (r = -0.07) (Table 3.4). These correlations, or lack thereof, are indicators of similarity of the various types to each other in regard to values. Therefore, types that are dissimilar may have more challenges negotiating management with each other compared to types that are more similar. Having Type III at the negotiation table might help with finding common ground, since they share values with both the other Types, albeit more affinity to Type I.

Table 3.3. Distinguishing statements, Q sort values, and z scores associated with three stakeholder "types" resulting from factor analysis. Distinguishing statements are defined as having significance levels $p < 0.05$ and z-scores higher than in all other factors. "GOL" = government-owned lands.

Type I: Ecocentric Naturalist		
Distinguishing Statements	***Q sort value***	***Z-score***
We have a moral and ethical duty to preserve America's prairie and grassland ecosystems.	+5	1.53
GOL provide essential wildlife habitat and migration corridors.	+4	1.45
GOL are places for diverse plant species (i.e., native, rare, endangered) to thrive and be protected.	+3	1.32
Maintaining plant and animal biodiversity is important to GOL management.	+3	1.27
Beauty and undisturbed open space are qualities that attract me to GOL.	+2	0.64
Type II: Sustainable Utilitarian		
Distinguishing Statements	***Q sort value***	***Z-score***
Livestock grazing plays an important role in the maintenance of GOL.	+5	2.38
It is important that GOL continue partnerships with local private agriculture operations via leases.	+4	1.69
Beef is an important product that comes from GOL.	+4	1.69
GOL should continue to be spaces for the production of food/meat and fiber/wool.	+3	1.57
I believe ranchers need to be able to make a profit from leasing GOL.	+3	1.05
Type III: Multi-use Steward		
Distinguishing Statements	***Q sort value***	***Z-score***
GOL should be managed for long-term sustainability goals with future generations in mind.	+5	2.28
The top priority of GOL should be protecting natural resources.	+4	1.55
GOL can be used to help mitigate the effects of climate change.	+3	1.01
I support public access of GOL for recreation opportunities like hiking, camping, and hunting.	+2	0.86
GOL should be maintained as multi-use, working landscapes.	+2	0.72

Table 3.4. Correlation matrix of three factors (the three stakeholder types) resulting from Q methodology factor analysis, indicating degrees of similarity (higher values) and difference (lower values) between them.

	Type I	**Type II**	**Type III**
Type I	1	-0.0736	0.616
Type II	-0.0736	1	0.2645
Type III	0.616	0.2645	1

Type I: Ecocentric Naturalist

The first identified type, labeled *ecocentric naturalist,* was characterized by perspectives and opinions that clustered greatly around prioritizing regulating and non-material ES. Q Sorts from these stakeholders ranked material ES and an economic focus on rangelands at the lowest end of the Q Sort, indicating that those relative statements least aligned with their values and perspectives (Figure 3.7). Stakeholders that comprised this type exhibited strong intrinsic and relational values like preserving wilderness, minimizing human use while recognizing nature's importance for human wellness, and that nature should be protected simply because it exists. Statements incorporating human use of rangelands were ranked in the lower two-thirds of the Q sort (Figure 3.7). Twenty-four out of forty Q Sorts were associated with the *ecocentric naturalist* type, all of which were associated with the agency/professional and community/recreationer groups, and none of which included members of the rancher/producer group. Exit interviews with stakeholders whose Q Sorts were most highly weighted in this type confirmed our interpretation and also revealed nuances in the Q Sort process (Table 3.5).

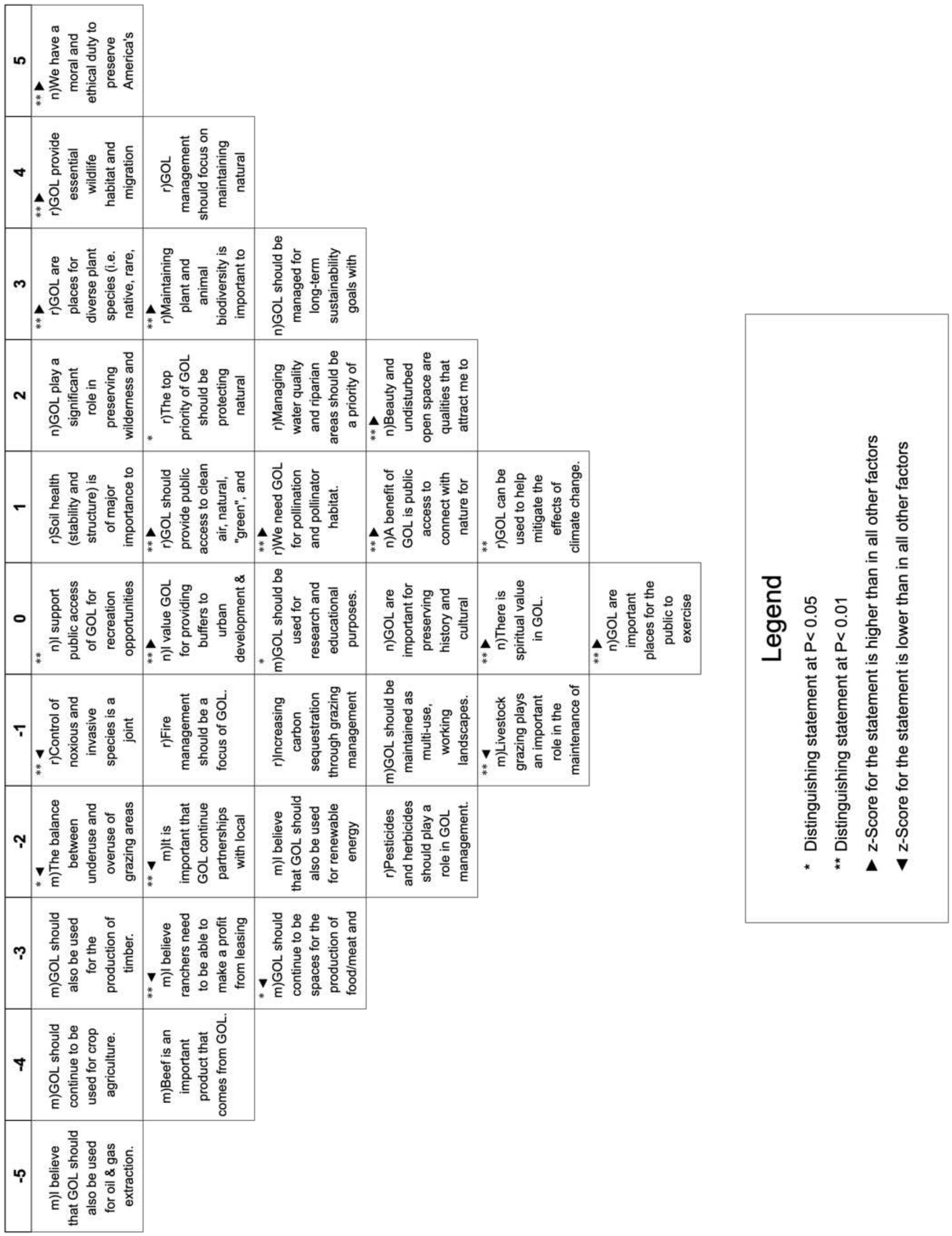


Figure 3.7. Composite Q Sort of Type I: Ecocentric Naturalist, resulting from factor analysis using Kade software. Statements are preceded by an *m*, *n*, or *r*, representing material, non-material and regulatory ecosystems services respectively.

Table 3.5. Excerpts transcribed from Q methodology exit interviews made by participants whose Q Sorts contributed strongly to the Ecocentric Naturalist type.

Stakeholder comments
One thing that really guides what I do is to protect and stitch together what we haven't messed up.
I also think that we overvalue recreation in our culture. Public access maybe needs to be rethought.
I think our society at least, in its treatment of open lands, has gone too far to the matter of what can we extract to earn more money. It's money driven.
I'm an environmentalist. These places need to be preserved. Agriculture and making money are not important here. This is not about beauty and what I like. This is about nature.
We need to all keep in mind that we can overburden the land with use.
The moment that you add people to any scenario, you begin to disturb the environment. Even me. I am a disturbance simply by being there.

Type II: Sustainable Utilitarian

The second identified type, labeled *sustainable utilitarian,* was characterized by perspectives that prioritized material ES and a strong instrumental and relational value system. Some non-material and regulating ES were also ranked in the upper 50% of Q Sort columns, but material ES overwhelmingly took the highest ranks and were less frequently placed in negative Q Sort columns (Figure 3.8). Stakeholders whose Q Sorts fell into this type were from the agency/professional and rancher/producer groups. There were no community/recreationer group Q Sorts represented in this type. Ten out of forty Q Sorts comprised the *sustainable utilitarian* type. While this type highly valued material ES, stakeholders were also clear about prioritizing sustainability and ecological function, while minimizing ecological disturbance (Figure 3.8). Statements involving public access were ranked low, while ranching use was ranked highest (Figure 3.8). Exit interviews with stakeholders whose Q Sorts were weighted the highest for this type illustrated an integrative perspective (Table 3.6).

-5	-4	-3	-2	-1	0	1	2	3	4	5
** ◄ n)There is spiritual value in GOL.	** ◄ r)GOL should provide public access to clean air, natural, "green", and	** n)GOL are important places for the public to exercise	r)Pesticides and herbicides should play a role in GOL management.	** ◄ n)I support public access of GOL for recreation opportunities	r)We need GOL for pollination and pollinator habitat.	** ◄ n)GOL play a significant role in preserving wilderness and	r)GOL provide essential wildlife habitat and migration	** ► m)GOL should continue to be spaces for the production of food/meat and	** ► m)It is important that GOL continue partnerships with local	** ► m)Livestock grazing plays an important role in the maintenance of
	** ◄ r)GOL can be used to help mitigate the effects of climate change.	m)GOL should continue to be used for crop agriculture.	n)Beauty and undisturbed open space are qualities that attract me to	n)GOL are important for preserving history and cultural	r)Fire management should be a focus of GOL.	r)Maintaining plant and animal biodiversity is important to	** n)We have a moral and ethical duty to preserve America's	n)GOL should be managed for long-term sustainability goals with	** ► m)Beef is an important product that comes from GOL.	
		n)A benefit of GOL is public access to connect with nature for	** ◄ r)GOL are places for diverse plant species (i.e. native, rare,	** ► m)I believe that GOL should also be used for oil & gas extraction.	** ◄ r)Managing water quality and riparian areas should be a priority of	r)Control of noxious and invasive species is a joint	r)Soil health (stability and structure) is of major importance to	** ► m)I believe ranchers need to be able to make a profit from leasing		
			** ◄ m)GOL should be used for research and educational purposes.	n)I value GOL for providing buffers to urban development &	** ◄ r)GOL management should focus on maintaining natural	** ► m)GOL should also be used for the production of timber.	** ► m)The balance between underuse and overuse of grazing areas			
				m)I believe that GOL should also be used for renewable energy	r)Increasing carbon sequestration through grazing management	** ◄ r)The top priority of GOL should be protecting natural				
					m)GOL should be maintained as multi-use, working landscapes.					

Legend

* Distinguishing statement at P< 0.05

** Distinguishing statement at P< 0.01

► z-Score for the statement is higher than in all other factors

◄ z-Score for the statement is lower than in all other factors

Figure 3.8. Composite Q Sort of Type II: Sustainable Utilitarian, resulting from factor analysis using Kade software. Statements are preceded by an *m*, *n*, or *r*, representing material, non-material and regulatory ecosystems services respectively.

Table 3.6. Excerpts transcribed from Q methodology exit interviews made by participants whose Q Sorts contributed strongly to the Sustainable Utilitarian type.

Stakeholder comments
It's going to be more and more important that we are good stewards and highlight to the public why it's good to have livestock on the land.
Lands need to be managed on science and a plan – not only rules and regulations.
I think that land ethic is more of a driver for me than most ranchers. I was surprised that the ecological goals took more priority for what my own livelihood is.
The preservation of land and production of beef go hand in hand. With preserving wild spaces, with grazing, wild animals can still eat and thrive and cattle can benefit.
It's our job as ranchers to say we produce a good product in an environmentally sound way. I don't' think we're doing that. I don't think we're doing enough of that, and it's going to bite us if we don't change.
These are human problems. Wicked problems. Do I value stewardship over financial or is there somewhere in the middle? The complexity is what's killing us.

Type III: Multi-Use Steward

The third identified type, the *multi-use steward*, was characterized by a general blend and integration of material, non-material, and regulating ES across the entire Q Sort (Figure 3.9). Six out of forty Q Sorts comprised this type and all three stakeholder groups were represented. The *multi-use steward* type was based in a holistic approach with a balanced distribution of relational, intrinsic and instrumental values. This type prioritized human use, as well as natural resource conservation. Value focus was on less extractive uses of rangelands while acknowledging society's relationship with the environment (Figure 3.9). Material ES were mostly ranked toward the center and negative columns of the Q sort, whereas non-material and regulating ES were ranked more positively (Figure 3.9). Exit interviews with stakeholders whose Q Sorts fell into this type supported this interpretation (Table 3.7).

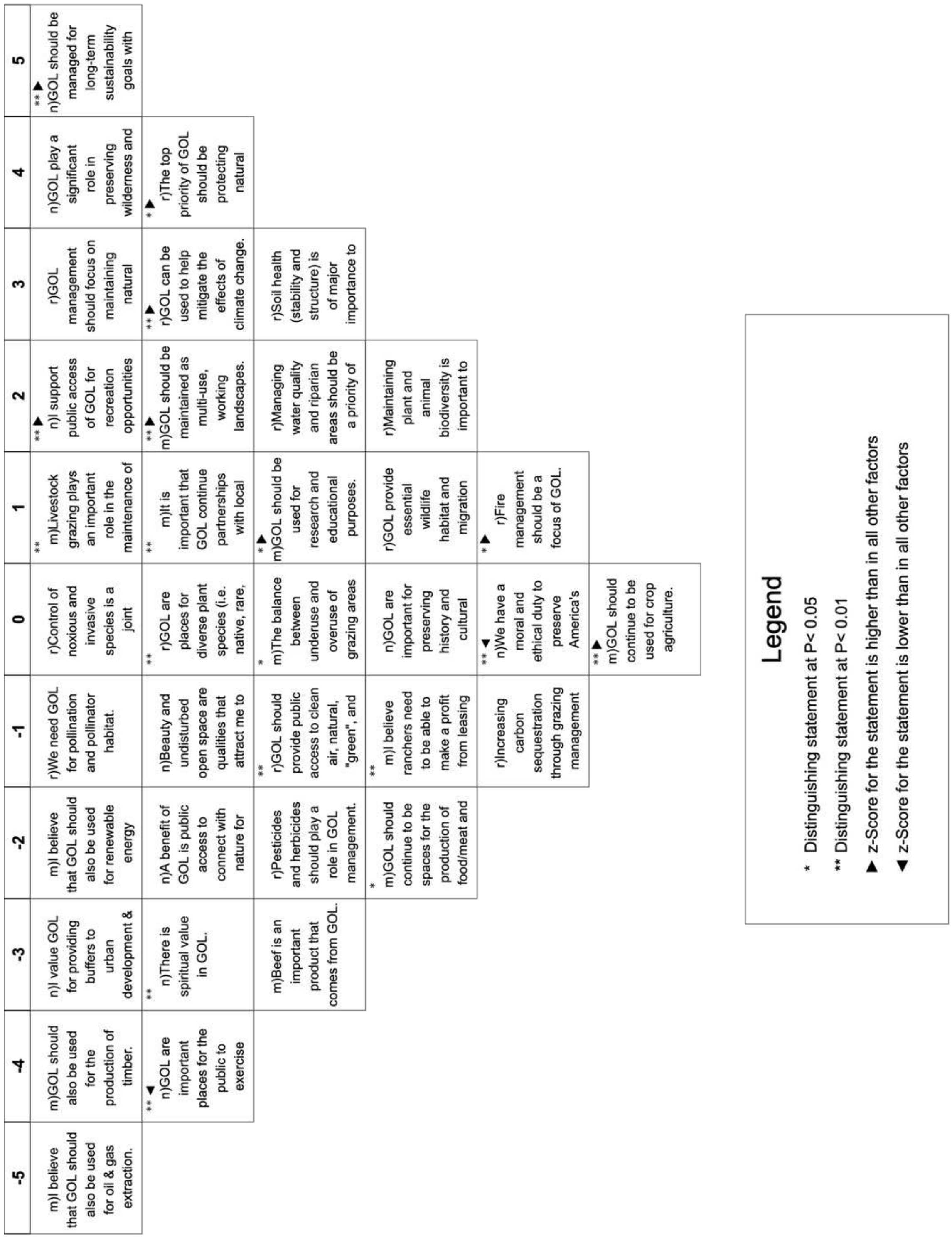


Figure 3.9. Composite Q Sort of Type III: Multi-Use Steward, resulting from factor analysis using Kade software. Statements are preceded by an *m*, *n*, or *r*, representing material, non-material and regulatory ecosystems services respectively.

Table 3.7. Excerpts transcribed from Q methodology exit interviews made by participants whose Q Sorts contributed strongly to the Multi-Use Steward type.

Stakeholder comments
[This region] finds a nice balance between recreation and conservation. I find that here, most people here have similar values. We want to live in a clean environment.
It's hard for the public to understand the depth and complexity both from a scientific perspective and a general management perspective.
We shouldn't just be focusing on beef production or recreation. This sort of industry is not THE thing. It's more complex than that.
If you can stay out of politics and try to be good stewards of the land… that's one thing. It's hard to separate the politics anymore.
I worry about the whole American culture – go for the gold right now. Even recreation is so dominant, their unwilling to regulate the use.
Recreation overuse is a big problem and they didn't know how to manage it. Sometimes they're yielding to public pressure instead of what's best for the land. The first stand the organization should take is "what's best for the land" then get public input after that.
The more that we keep the land intact, that land will be healthier in the long-term.
It would be an ecological catastrophe if we eliminated grazing. I feel like our society has gotten so polarized. We get entrenched and don't want to change our opinions. I think education is really important.

Management Survey

Results of the emergent management survey summarized stakeholder perspectives on key management approaches to government-owned lands. These perspectives illuminated areas of discord as well as areas of consensus. Examining the Likert scale analysis (Figure 3.10), we see that all forty stakeholders were in general agreement with each other on the role of these issues in government rangelands management.

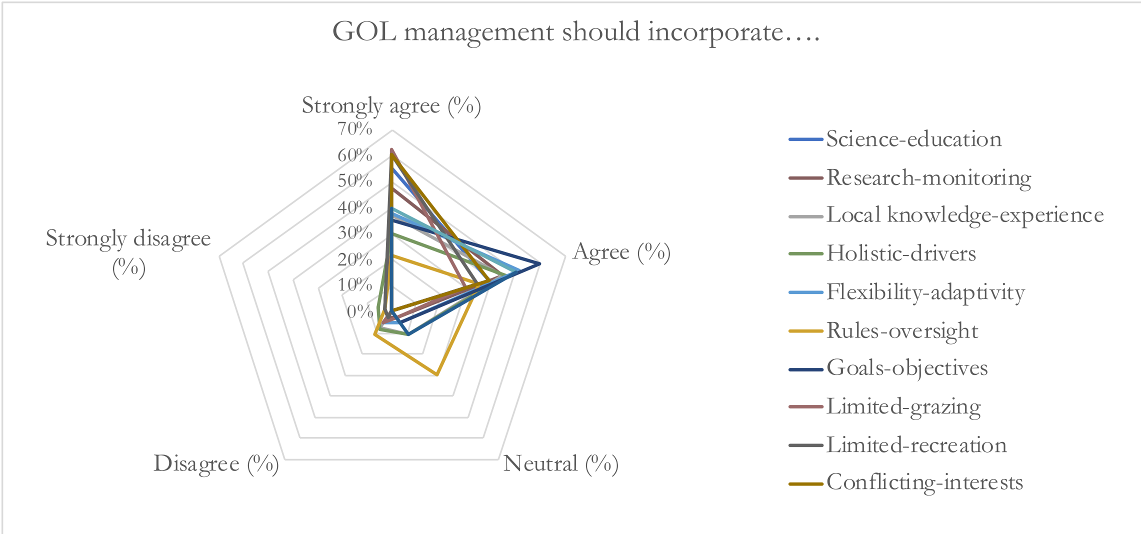


Figure 3.10. Management survey results, where stakeholder participants rated eleven items on a Likert scale. The theme on the right side of the figure reflected rangeland management issues for which stakeholders would have a personal opinion or perspective.

On closer examination of the results (Figure 3.11), we are able to identify three themes that had the greatest level of agreement (Conflicting-interests, Collaboration-not prescriptions, and Goals-objectives) and two themes (Rules-oversight and Holistic-drivers) that underscored areas of disagreement among stakeholders.

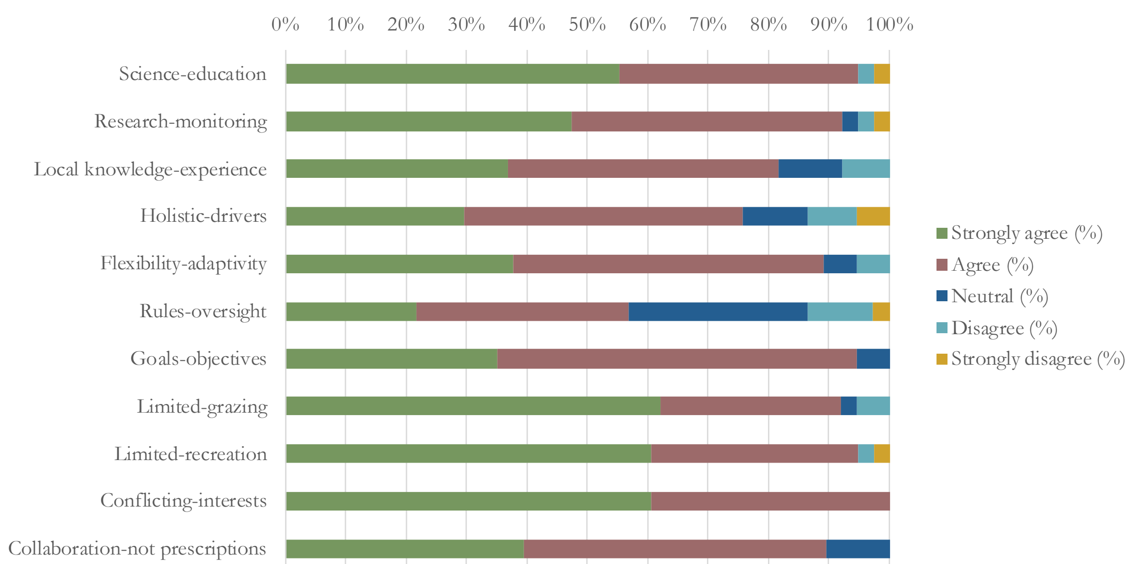


Figure 3.11. Management survey results, where stakeholder participants rated eleven items on a Likert scale. The items reflected rangeland management issues for which stakeholders would have a personal opinion or perspective.

Statements with the greatest level of agreement among stakeholders included: 1) “I believe that the management of government-owned lands also entails dealing with conflicting interests,” 2) “Government-owned lands should be places of collaborative and cooperative management, as opposed to prescriptive management,” 3) “Setting goals and objectives is important for government-owned lands management.”

Two statements resulting in the greatest level of disagreement among stakeholders were 1) “Enforcing rules and strict oversight of government-owned lands is important in their preservation” 2) “Government-owned lands management should be holistic, incorporating ecological, social, and economic drivers and outcomes.”

Radar charts for these items further illustrate patterns among stakeholder groups (Figure 3.12a-e). In these five cases, representing extremes of the spectrum, the rancher/producer stakeholder group less strongly agreed or most often disagreed, with statements whereas the agency/professional and community/recreationer stakeholder groups displayed more agreement or neutrality.

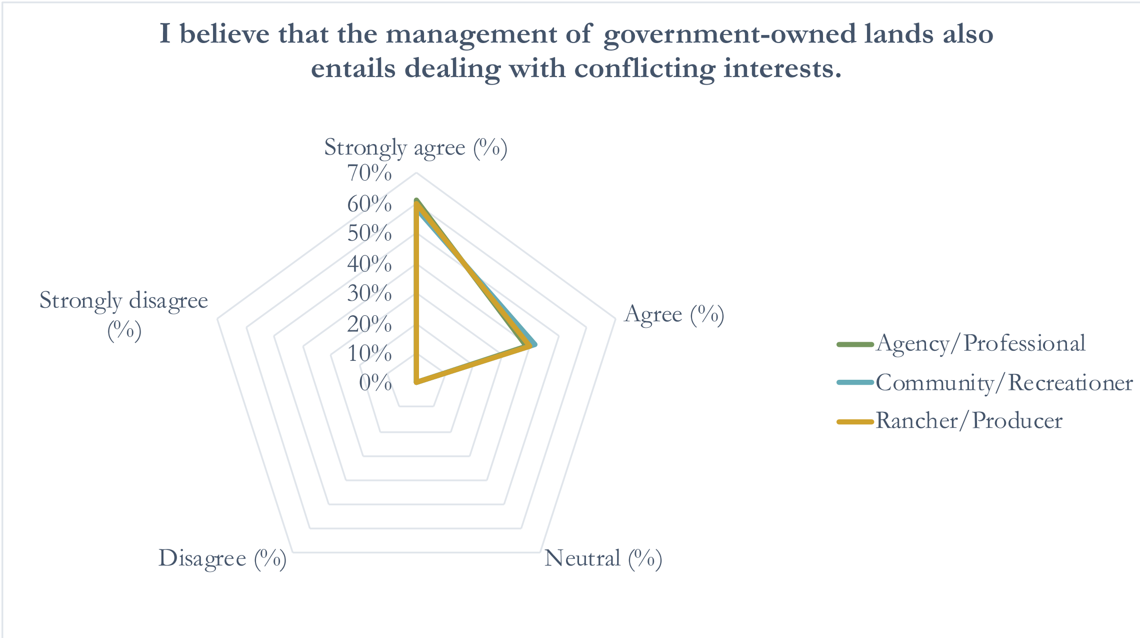


Figure 3.12a. Management survey results indicating the area of greatest agreement was the belief that government-owned lands management entails dealing with conflicting interests. Stakeholder participants rated statements like this one on a Likert scale.

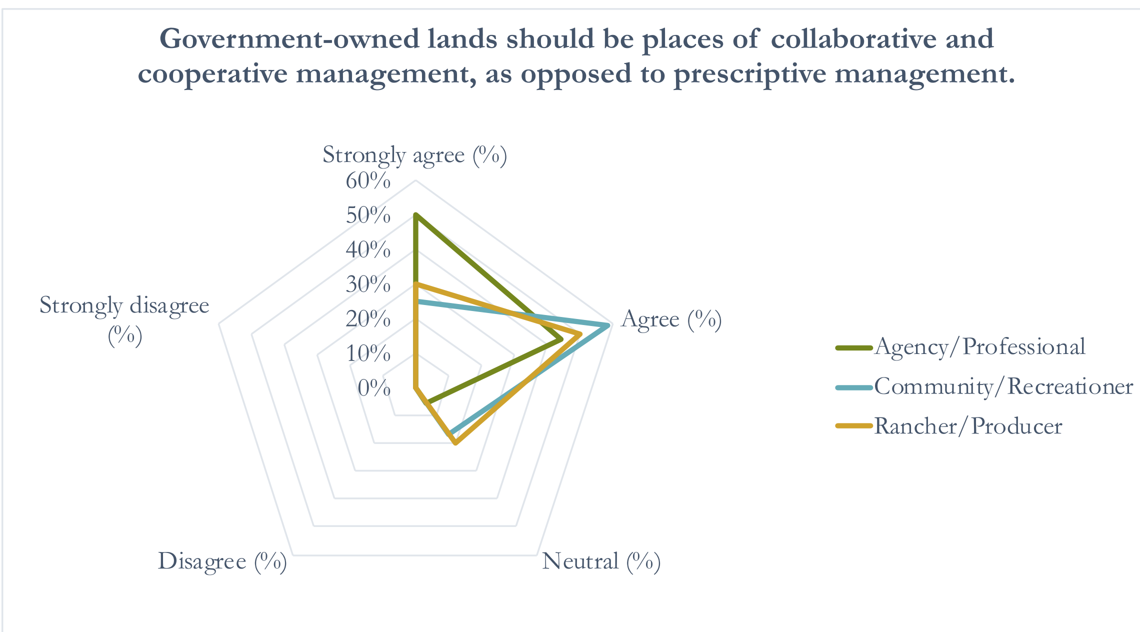


Figure 3.12b. Management survey results indicating the second area of greatest agreement was that government-owned lands should be "places of collaborative and cooperative management." Stakeholder participants rated statements like this one on a Likert scale.

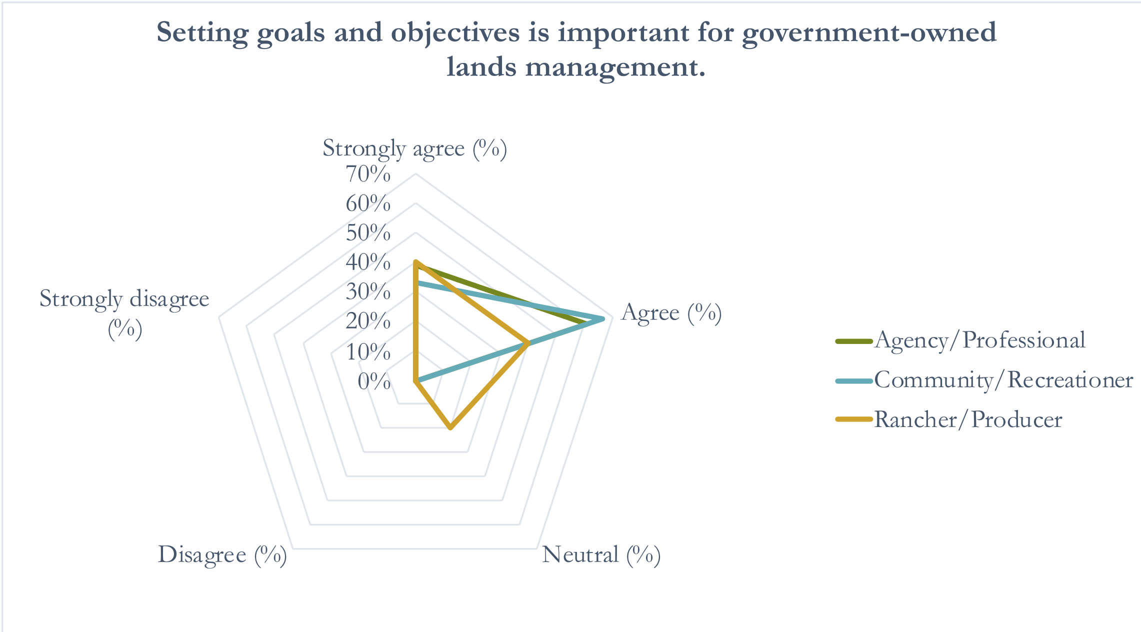


Figure 3.12c. Management survey results indicating the third area of greatest agreement was the importance of "setting goals and objectives" on government-owned lands. Stakeholder participants rated statements like this one on a Likert scale.

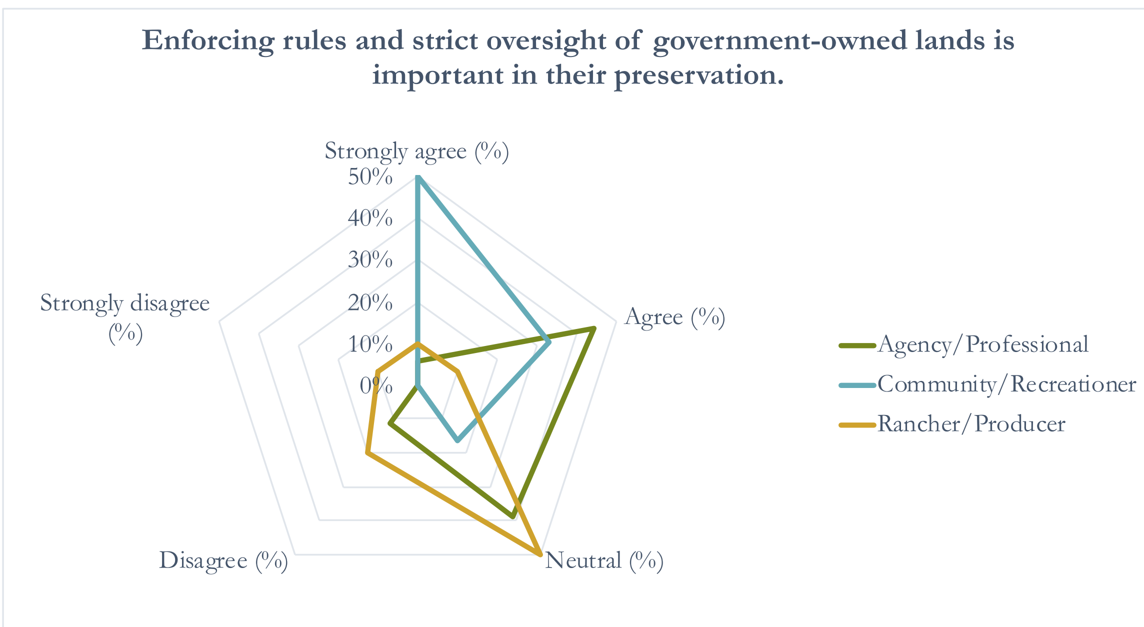


Figure 3.12d. Management survey results indicating the area of greatest disagreement was the importance of "enforcing rules and strict oversight" on government-owned lands. Stakeholder participants rated statements like this one on a Likert scale.

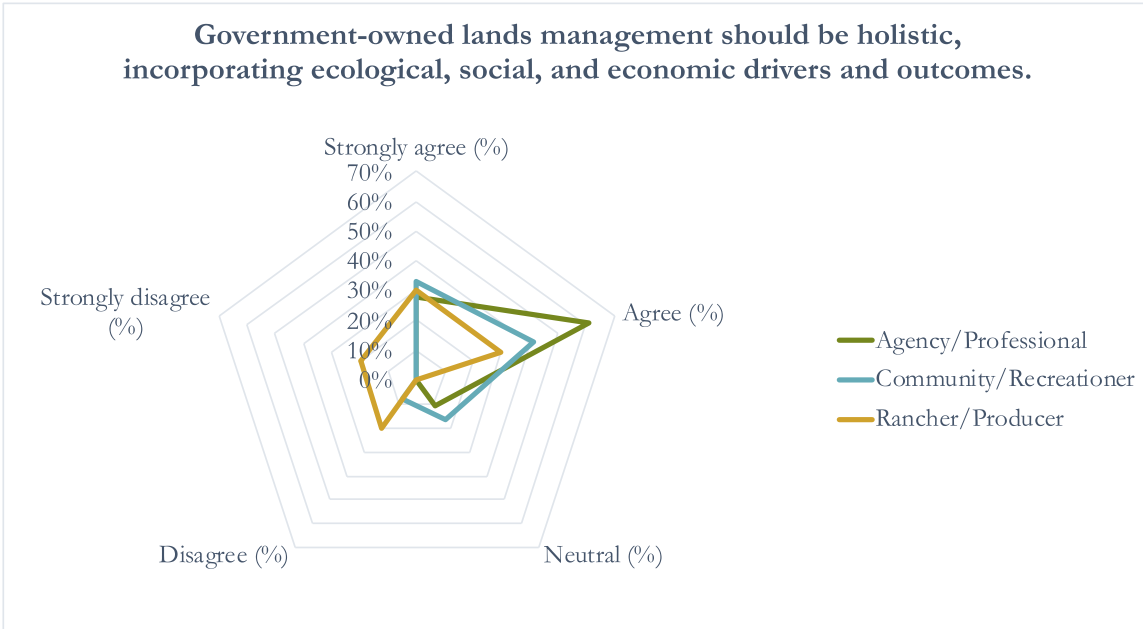


Figure 3.12e. Management survey results indicating the second area greatest disagreement was that management of government-owned lands should be "holistic, incorporating ecological, social, and economic drivers and outcomes." Stakeholder participants rated statements like these on a Likert scale.

Exit interviews with stakeholders further supported researcher interpretation that there was overall agreement among stakeholders on these management issues. Most stakeholders expressed in one way or another that the Q Sort activity was challenging because it forced them to prioritize things that were all important on some level. Stakeholders commented that they wished they had more room on the "right side" of the Q Sort because they desired to rank certain statements higher, but the constraints of the diagram forced them to make tradeoffs. We explained that the purpose of the Q Sort was for the participant to sort by relative value, rather than think of the sort as assigning positive or negative value. The values themselves are less meaningful to the participant, and more important for the researcher as they help to quantify these relative values. The themes most commonly expounded upon in exit interviews were the importance of collaboration, consensus-building, and the integration of diverse sources of knowledge at the decision-making table (Table 3.8).

Table 3.8. Excerpts transcribed from Q methodology exit interviews made by stakeholder participants, describing themes of collaboration, consensus-building, and integration of diverse sources of knowledge.

Collaboration	Consensus Building	Knowledge integration
"Trust and collaboration are the critical factors in preserving land condition and providing flexibility of operations which are needed by lessees."	*"Meaningful management is when everyone can sit down together, make compromises, and then everyone can leave the room and make it work."*	*"I value [experiential knowledge a lot, almost as much as science. Someone that has their bottom line vested on that landscape and intends for it to be there."*
"Any time you can get collaboration, it's better. Collaboration is far more beneficial that enforcement."	*"Prescriptive management doesn't create "buy-in" opportunities for all involved."*	*"Lands need to be managed on science and a plan – not only rules and regulations."*
"Agencies often lack the capacity to enforce and really monitor closely how lands are being used. Almost has to be more of a collaborative thing."	*"Sometimes you have to bring people in the tent who don't necessarily agree with your own beliefs."*	*"I don't believe [science] should be the only part of the conversation. There are different ways of knowing and how do we bring in indigenous knowledge. I don't like being exclusive."*
"All decision makers from the owner to the operator need to be at the table for making sound management decisions."	*"So much of the decision-making authority is informed by short-lived trends in these types of agricultural pursuits or a vocal group of community members that are loud enough to drive their agendas. Often time the voices of the producers and division staff aren't as loud and don't get the authority that they should and are actually very affected by these decisions, as opposed to those who actually have stake in the game."*	*"Conflicts are inevitable in properties with broad ownership interests. A representative decision-making authority such as an open space department has to exist to provide expertise and direct suitable land uses and collaborate with lease holders to implement those uses."*
"Collaborative provides a greater opportunity for all to come to the table and meet the collective goals and objectives for the group, while ensuring sound ecologically managed rangeland goals are met."	*"The goal for success is finding common ground solutions in a holistic framework."*	*"There's that person that doesn't follow science but just has years of experience on that landscape and knows what works. I've always valued those individuals and their opinion when I'm making a management decision."*

DISCUSSION

The objective of our study was to explore in a context-specific way the human dimension of collaborative grazing management on the Colorado Front Range. We evaluated how stakeholders in public-private partnerships perceive the value of ES on government-owned lands and how their perceptions may influence decision-making. We used a robust semiquantitative approach, Q methodology, to investigate and illustrate pluralism in the interconnected pathways of rangeland ES and its people, specifically addressing the role of humans and their value systems as they pertain to government-owned lands, natural resource management, and sustainable food production. While our study was situated in a specific geographical context, our overall approach to ES valuation may be applied to rangeland SES elsewhere in the United States or abroad. In other words, we expect results to be most relevant to socio-ecologically similar regions as ours, yet our methods may be more universally applicable and impactful.

Conducting Q methodology during a global pandemic required us to engage creatively and adaptively with the research methods. This was a catalyst that also broadened our receptivity and awareness of emergent data and the possibility of additional learning opportunities outside of traditional Q methods. **We recommend that researchers using Q-methodology be responsive to unexpected emergent data and not restrict their process to only the predefined approach, which may reduce representativeness and comprehensiveness of research outcomes**. Through our adaptive approach, we were able to uphold the structure, depth, and integrity of traditional Q methodology, while further exploring contextualized nuances through another semi-quantitative method, Likert scale analysis.

We conceptualized and interpreted Q Sort results in two ways: through the lens of ES categories (material, non-material, regulatory) and through associated value clusters (instrumental, relational, intrinsic) (Table 3.1). **We noted patterns in how each stakeholder group tended to prioritize certain ES over others and how this prioritization reflected pluralistic value systems.** These observations align with findings in other studies and the notion that stakeholder perspectives and values are directly linked to decision-making and management approaches (Bruner and Reid 2015; Chan et al. 2017; Grillos 2017; Hein et al. 2006; Iniesta-Arandia et al. 2014; Van Riper et al. 2012). All three value categories were represented in stakeholders' perspectives of government-owned rangeland ecosystems. This supports previous efforts in the literature promoting a pluralistic approach to ES valuation so that a more comprehensive understanding may be attained (Chan et al. 2012; De Chazal et al. 2008; Díaz et al. 2015; Himes and Muraca 2018; Iniesta-Arandia et al. 2014; Jacobs et al. 2016; Kallis et al. 2013; Kenter et al. 2015; Pascual et al. 2017). Hermelingmeier and Nicholas (2017) noted that plurality could remove barriers for collaboration, but it could also underscore the lack of common ground. In the concluding stages of our study, we observed an emphasis on the former, where plurality could open doors to collaboration by acknowledging where diverse value systems overlap.

Of the ES addressed by study participants in the Q Concourse and summarized in the Q Sample, instrumental values could be linked to 85% of them, intrinsic values could be linked to 60%, and relational values could be linked to 45% (Table 3.1). The dominant value cluster was instrumental, which includes ES like food, wool, energy, and timber production, as well as recreation and other forms of public access and use. **In fact, for this study region, the majority of ES identified by stakeholders were tied to instrumental human values.** This was not surprising and confirmed the popularity of economic-based incentive programs since instrumental values are more easily linked to monetary or economic outcomes than intrinsic or relational values (Bruner and Reid 2015; Chan et al. 2017; Cleveland et al. 2006; Maher et al. 2021).

To the contrary, however, rangeland stakeholders, specifically rancher/producers, may also prioritize relational values equally or more so than instrumental values (Bartlett et al. 2002).

It is important to acknowledge the cultural context here. Whereas some societies may uphold stronger instrumental values of nature, such as for agriculture or recreational use, indigenous or even pastoralist communities may hold stronger relational or intrinsic values of nature (Himes and Muraca 2018). Therein lies the significance of context-specific or place-based pluralistic ES valuation inquiry.

The emergent management survey gave us the opportunity to learn in more detail about questions such as: *Do stakeholders perceive cattle grazing as an important land management tool or a detriment to conservation objectives? Do stakeholder groups (i.e., ranchers or government agency personnel) exhibit a distinct value typology? Do stakeholders tend to agree or disagree on rangeland management styles and approaches? With which management issues do stakeholders find the most and least consensus?* **Results illuminated that while there is general consensus and significant overlap in opinions on publicly controversial issues such as cattle grazing and recreational use, the rancher/producer stakeholder group upheld perspectives that were less correlated and less aligned with the other stakeholder groups.** This pattern is commonly played out in controversies between agriculture and conservation groups, and specifically public lands use by cattle producers (Brunson and Huntsinger 2008; Curtin et al. 2002; Donahue 1999; Provenza et al. 2013; Timmins 2002; Wilmer et al. 2019).

From this survey, we also learned that as a result of pluralistic value systems, there is more overall consensus than discord in how diverse stakeholders perceive and value the ES of government-owned rangelands. To some, this may be a surprising outcome, especially since mainstream media, with headlines like "The Real Problem with Beef" (Carroll 2019) and "Are My Hamburgers Hurting the Planet?" (Kaplan 2019), likes to sensationalize the agriculture-conservation divide. Yet it makes sense that organizations and their members who are already incorporating a collaborative model in their management – like our participants – would be standing more on common ground. Reid et al. (2021) found that established collaborations in rangeland SES foster positive social processes like co-production of knowledge, relationship building, social learning, and polarization reduction.

It also makes sense that various stakeholders similarly value rangeland ES because conservation and ranching endeavors share similar challenges, such as highly variable weather and land use conversion threats (Wilmer et al. 2019). Finding points of agreement and shared interest can help to build a healthy collaboration, and our process identified some important commonalities for our diverse participant groups.

In the management survey, areas of greatest stakeholder consensus actually provided potential solutions for the areas of greatest discord. For example, there may be conflict in the degree of rules and oversight, as well as management approaches imposed on public rangeland use. However, if we acknowledge that conflicting interests exist, then we may bring these diverse views together in a collaborative effort and approach management cooperatively, using shared interests to build camaraderie and develop shared goals. This is, in fact, what collaboration is meant to do, where diverse opinions and perspectives are used synergistically and stakeholders assume shared responsibility to develop equitable solutions and resiliency (McIvor 2019; Schlosberg 2009; Walker and Salt 2012; Whyte 2016; Woodmansee et al. 2021).

Stakeholders were interviewed as a last qualitative step in the Q methodology process and then participated in an interactive workshop, where we presented study results and gained even more contextual insight into stakeholder experience in the study. During the workshop, a one-hour prepared slide show presentation ended up consuming nearly three hours due to the abundance and quality of emergent questions and discussion. One stakeholder commented, "We have a lot of goals but not all can be prioritized to the same extent…This was the most challenging aspect of this exercise." Participation in the Q methodology relative ranking process underscored this reality. For example, government land use and management initiatives are limited by economic and physical constraints and force decision-makers to make tradeoffs and prioritize certain issues over others. Likewise, the Q Sort process constrained participants to prioritize their needs and values in a finite space. This proved to be an insightful exercise and a catalyst for group discussion. **We believe this increased their level of empathy for those in positions of decision-making power and will lead to increased willingness to actively seek and participate in rangeland management discourse and partnerships in the future.**

Because we integrated stakeholder ideas and interests directly into the development of the Q Concourse and then concluded the method together in an interactive workshop, we completed a circle of process, dedication, and partnership. Participatory research is a "shared process of learning by doing" (Wilmer et al. 2018; Wilmer et al. 2019). It took considerable commitment from participants to follow through with a multistep research method, especially in the midst of a global pandemic. There was no monetary compensation offered to Q participants, and therefore their perseverance was proof that they held the stewardship of rangelands in high regard and importance. Throughout the process stakeholders expressed their interest and anticipation of results. Wilmer (2018) explains that a participatory approach connects researchers and participants throughout the process and empowers stakeholders to develop a sense of ownership regarding results and knowledge development. As Porensky (2021) describes, collaborative research tends to have greater relevance to stakeholders, where researchers may address a wider range of perspectives and translate real-world problems into research questions. Collaboration can broaden our worldviews and reconcile multiple and seemingly paradoxical truths (Porensky 2021).

Moving forward, **the broader ES research community may use this study as proof-of-concept that a pluralistic approach to valuation offers a more comprehensive and holistic opportunity for learning.** This learning may be applied to program, policy, and incentive development. The Q methodology process itself, ending with a stakeholder workshop provided an educational opportunity that seemed to enhance group cohesion and empathy. **The broader scientific community may benefit from this model of a context-specific, place-based study hybridized with a broadly-applicable method.** Results have local significance to specific stakeholders and communities yet could also be compared and contrasted with parallel studies in other parts of the world. The ES valuation typology we uncovered may even be broadly generalizable to the majority of collaboratively managed multi-use landscapes. As previously noted, stakeholder-driven research generates scientific contributions that are "incremental or regional" but where the "potential for real-world impact" is elevated (Porensky 2021). This could provide insight, significance, and learning that traverses multiple spatial, temporal, institutional, and political scales. The use of Q methodology as an ES valuation tool provides such an opportunity.

CONCLUSIONS

Over the last seventeen years, the ES and NCP concepts have assisted people, from local communities to international government, in their navigation of a sustainable future. A sustainable future will be largely dependent upon a harmonious relationship between people and nature, one that is based in respect, forethought, and the intentional balancing of needs and values. Human valuation of rangeland ES is pluralistic and contextually bound by complex and diverse stakeholder relationships with the natural world. We found great value in the implementation of Q methodology, using modified virtual tools and an additional emergent survey, to explore these socio-cultural values on the Colorado Northern Front Range.

Our study demonstrates that stakeholders involved in the management and use of government-owned rangelands share more values than not and agree on more issues than not. Stakeholders agree that the management of government-owned lands inevitably involves some conflict, but they also agree that cooperative management and collaboration is key to success. We learned that collaboration, the inclusion of diverse voices and sources of knowledge around the decision-making table, is an auspicious approach and may open doors to solutions. Strategies employed to carry out natural resource management and conservation initiatives, while supporting ranching livelihoods and sustainable food systems may differ from stakeholder to stakeholder, agency to agency. Comprehensive solutions may arise from focusing our efforts on understanding complexity, even embracing it, and recognizing each other's perspectives by integrating the multiple facets of what we each hold as true. Diverse perspectives are likely rooted in shared value systems that acknowledge our interdependence with and response-ability toward the natural world. Sustainable rangeland management is not only about ecological underpinnings. It is also about supporting the well-being of people and communities who are in direct relationship with those landscapes.

CHAPTER 4: AGENT-BASED MODELING AS A TOOL FOR COLLABORATIVE GRAZING MANAGEMENT IN SOCIAL-ECOLOGICAL SYSTEMS

INTRODUCTION

Rangelands cover about 54% of the Earth's surface (ILRI 2021), supporting human and animal life, and global ecological processes. Rangelands are defined as "land supporting indigenous vegetation that either is grazed or that has the potential to be grazed and is managed as a natural ecosystem. Range includes grassland, grazable forestland, shrubland and pastureland" (Society for Range Management 1998). Rangelands are water-limited ecosystems with <50-600 mm (<2.00-23.62 in) of annual precipitation (United States Environmental Protection Agency), where seasonality, intensity, and high interannual variability of precipitation define land use practices (Ellis and Galvin 1994; Hobbs et al. 2008). Through pastoralism and ranching, humans are able to turn sun energy and native-plant communities of agriculturally unproductive tracts of land into high quality protein sources in the food chain (Hobbs et al. 2008). Because of this, rangelands are home to global livestock systems including pastoralists, hunter-gatherers and ranchers, and provide nearly 70% of total forage for livestock production (Holechek 2013); the other 30% comes from crop agriculture systems.

For millennia, Western United States rangelands have supported migratory herds of large herbivores. Prior to European settlement, millions of bison (*Bison bison*) grazed these lands, sustainably shaping plant communities, forage quality, wildfire patterns, and soil nutrient cycling (Bell 1971; Collins et al. 1998; Geremia et al. 2019; Knapp et al. 1999). Large herbivores have co-evolved with these landscapes, yet today large herds of migrating herbivores have largely diminished on the rangelands of the American West. Without disturbances like herbivory, these landscapes are vulnerable to soil erosion, invasive species, decreased soil quality, and decreased biodiversity (Environment Colorado Research and Policy Center 2006; Environmental Defense Fund 2019; Rondeau 2001).

In the United States, approximately 30% (770 million hectares) of total land cover consists of public and private rangelands (Natural Resource Conservation Service). The rangelands of Colorado's Front Range are sensitive transitional landscapes forming a patchwork of mixed grass prairie that lie wedged between two ecoregions, the Southern Rocky Mountain Steppe to the west and the Great Plains to the east (City of Fort Collins 2005). This region comprises some of the most severely modified and fragmented ecosystems in the Rocky Mountain region due to its desirability for multiple land uses (City of Fort Collins 2005; Rondeau 2001).

A challenge to modern grazing systems here, where urbanization is taking over historical agricultural lands at an estimated rate of more than 36,000 ha per year (Drummond et al. 2019), is the availability of intact grassland ecosystems to support adaptive and sustainable cattle management. Aside from food production, open rangelands also provide other essential ecosystem processes for the state's growing population, such as maintaining plant and animal biodiversity, water and air purification, and climate regulation (Environment Colorado Research and Policy Center 2006). Furthermore, cattle are evidenced to be an effective substitute for bison, the historical ecosystem engineers of the North American prairie (Environment Colorado Research and Policy Center 2006; Knapp et al. 1999; Towne et al. 2005). Removing the natural disturbance of grazing would contribute to an ecological imbalance and ultimate degradation of these ecosystems (Environment Colorado Research and Policy Center 2006; Knapp et al. 1999; Towne et al. 2005).

Today, livestock grazing can contribute to the maintenance of grassland ecosystems, while producing food for growing local and global populations (Gibson 2009). The grass-fed and rangeland beef sectors of the livestock industry are growing in response to societal demands for sustainably-raised meat and improved natural resource management (Cheung and McMahon 2017; Galyean et al. 2011). However, agriculture and natural resource conservation objectives can be paradoxical. This is complicated by a body of literature regarding the dynamics of cattle grazing and the environment that present conflicting evidence and conclusions (Abdalla et al. 2018; Cusack et al. 2021; Daniel et al. 2002; Derner et al. 2018; Derner et al. 2006; Pietola et al. 2005; Reeder et al. 2004; Sharrow 2007; Teague et al. 2016; Teague et al. 2011). Inconsistencies in research results are likely due to using a reductionist approach rather than a systems-thinking approach that integrates the complexity of adaptive social-ecological dynamics of grazing systems (Briske et al. 2008; Teague et al. 2013).

In Colorado, cattle are the top agricultural commodity and evaluating their role in grassland ecosystem sustainability is crucial (United States Department of Agriculture 2017). However, such evaluation has historically excluded the dynamic human decision-making dimension in favor of adhering to more controlled scientific methods (Briske et al. 2008; Teague et al. 2013). As Nathan Sayre, a human geographer and author of *Politics of Scale: A History of Rangeland Science*, said, “There’s a growing recognition that, in fact, our environmental problems and challenges have more to do with people than they have to do with ecosystems and the bio-physical sciences per se.” (1:16:12) (Hudson 2019, March 28) This belief suggests the importance of incorporating the human decision-making component rather than excluding it.

Colorado’s Front Range is characterized by a semi-arid climate with mild winters, low annual precipitation, low humidity, high evaporation, and periodic droughts (Mladinich 2006;

Montgomery et al. 2016; Soil conservation service 1975). Because Colorado grasslands are water-limited systems, drought greatly impacts forage availability for livestock and wildlife. Climate models predict that the frequency and duration of drought in this region will continue to increase throughout this century (Evans et al. 2011), posing increased challenges for rangelands. Forage productivity and nutritive quality in rangeland ecosystems is of particular interest to livestock producers and wildlife biologists alike. Understanding the potential of rangelands to provide or even improve wildlife habitat while also providing abundant forage for domestic livestock is essential for both ranching livelihoods and natural resource conservation.

Our study aimed to embrace the social-ecological complexities of grazing systems on Colorado conservation landscapes. Using a coupled approach to system dynamics modeling combining geospatial and climate data with agent-based simulation, our objective was to model human-environment-animal-forage dynamics of typical rangeland grazing systems. Our model, Ecological Co-management of Rangelands, *ECo-Range*, allows users to create scenarios with options for environmental conditions (precipitation level and seasonal precipitation pattern) and management decisions (cattle numbers, and landscape fragmentation level), which correlate to stock density and rotational grazing intensity. ECo-Range simulates a single 5-month grazing season of 150 days, and produces measurable outcomes including variables reflective of both livestock and environmental outcomes. These include quantity of residual forage biomass, cattle weight gain, and degree of residual vegetation heterogeneity which is a significant indicator for the preservation of wildlife habitat (Toombs et al. 2010). The intentional utility and adaptability of ECo-Range lies in its ability to answer a multitude of stakeholder questions.

SIMULATING SOCIAL-ECOLOGICAL SYSTEMS

In complex and highly dynamic socio-ecological systems, collecting data is one thing, but synthesizing and applying data to real-time, real-scale challenges and opportunities is another level of complexity. System dynamics modeling was first conceptualized in 1961 by J.W. Forrester (1961) in the field of industrial management. Forrester's basic premise was that we can better understand complex phenomena if we examine the behavior of a system over time and under various conditions (Doerr 1996). Forrester claimed that we can only achieve this level of understanding and avoid conflict between short-term and long-term goals through systems modeling (Doerr 1996; Forrester 1961). Modeling complex social-ecological systems poses many challenges due to nonlinear feedbacks, interactions that lack independence, and spatial and temporal heterogeneity (Levin et al. 2013; Miller and Frid 2022). Through the conceptualization of emergent and adaptive relationships among key variables, modeling may be used to analyze dynamics that would have been too difficult or taken much longer to observe in practice (Roberts et al. 1983; Turner et al. 2013).

The social and ecological outcomes of complex systems are not easily predicted nor understood (Jablonski et al. 2018; Lynn et al. 2010; Miller and Frid 2022; Schrieks et al. 2021). Today, systems modeling assumes various forms in the literature, including symbolic modeling, simulation modeling, computational simulation, and integrated modeling (Boone and Galvin 2014; Schlueter et al. 2012). A common denominator of all these approaches is that they can be used to better understand the role of humans in natural systems (An et al. 2021; Boone and Galvin 2014). The management of grazing systems involves theoretical, practical, and ecological variables, where domestic livestock are the agents of biophysical change. Their agency, however, is dependent upon human decision-making (i.e., management) and interactions with environmental stochasticity. This web-like complexity creates an ideal canvas for a unique form of modeling – agent-based modeling (ABM). ABM stems from a class of modeling called "discrete event simulation," where a series of computer codes, rooted in mathemetics and parameters derived from real life processes, are integrated into a virtual passage of time that ticks forward in descrete steps (An et al. 2021; Boone and Galvin 2014). This is different from continuous simulation or Monte Carlo simulation, for example. The analytical process that ensues in ABM reflects interactions among system components, such as decision-making and biophysical processes, and can deepen understanding of multiple relationships within a dynamic system (An et al. 2021; Boone and Galvin 2014; Boone and Lesorogol 2016; Miller and Frid 2022; Schrieks et al. 2021).

The overarching question posed by this study is one of sustainability. Sustainability science is a field born in the 21st century that examines social-ecological systems, often those that are human-engineered, to understand challenges that threaten the integrity and future of life (Kates et al. 2001). Sustainability science is unique in that it addresses real-world situations that can only be studied beyond the bounds of orthodox scientific method (Boone and Galvin 2014; Boone and Lesorogol 2016). Questions of sustainability focus on explicit problems in social-ecological systems that span large temporal and spatial scales and highly dynamic environments. Because of this, solutions necessitate an adaptive rather than prescriptive approach, and ABM provides the necessarily adaptive capacity. ABM is a dynamic tool where one may observe ways in which system components interact, evolve, and respond to changes in a simulated environment (An et al. 2021; Miller and Frid 2022). Parameters and thresholds may be modified by the click of a button to envision interacting components under various alternative conditions.

To complement a variety of parameters, agents and patches can be programmed to react adaptively to evolving stimuli in their virtual environment.

ABM offers a mode of investigating the outcomes of diverse scenarios in complex systems, through the integration of human, animal, and environmental realtionships. In ABM these relationships "come to life" through computational flexibility and an engaging interface where the user may visualize cartoon-like interactions and relationships. Therefore, it is particularly effective for the simulation of landscape processes in which individuals, or *agents,* interact with each other and in relation to an adaptive and constantly changing environment (An et al. 2021; Dumont and Hill 2004; Jablonski et al. 2018; Miller and Frid 2022; Schlueter et al. 2012; Schrieks et al. 2021). In grazing systems, ABM can integrate empiricially-based theories of individual foraging behavior, which then influence the global behavior of the system through an aggregated group or herd effect (Boone and Galvin 2014; Dumont and Hill 2004; Jablonski et al. 2018). The addition of manipulatable thresholds representing human decisions, such as the addition or subtraction of stock, pasture divisions, or watering locations, further complicate this system, yet represent the realities of managed grazing landscapes.

ABM has been applied to rangeland ecosystem research across the globe. In Australia, ABM was used to model highly variable, non-equilibrium dynamics in systems, where the model was able to illustrate trends in variables such as stocking rate, live weight gain, and biomass dynamics (Gross et al. 2006). Boone et al. (2011), created an ABM, DECUMA, and coupled it with an existing ecosystem model, SAVANNA (Coughenour 1993), to simulate decision-making of African pastoralists as a result of environmental stressors and the outcomes of those decisions. Using a similar ecosystem and simulation model linkage, researchers have also assessed land use and social patterns among Kenyan pastoralist communities as a result of changes in land ownership (Lesorogol and Boone 2016).

Another study situated in the Patagonian Steppe combined simulation modeling with remote sensing to investigate desertification and the dynamics of water, plants, and soil (Paruelo et al. 2000). Jablonski et al. (2018), created an ABM to represent spatially-explicit cattle grazing dynamics and lethal toxicosis by a rangeland plant, Geyer's larkspur (*Delphinium geyeri*), native to the Rocky Mountain region, USA. ABM was recently used in conjunction with state-and-transition simulation models of vegetation dynamics to explore questions about how social-ecological systems might respond to scenarios of global climate change and local management (Miller and Frid 2022).

Extensive literature reviews have been published over the past decade that assess ways in which ABM have been used to explore agriculture and rangeland social-ecological or coupled human and natural systems (An 2012; Schrieks et al. 2021). These reviews formulated conclusions in support of ABM's utility to address challenges in the multi-scalar, interdisciplinary, and dynamic relationships of humans and nature (An 2012; Schrieks et al. 2021). ABM can model individual decision-making while incorporating heterogeneity and feedbacks, which can be an insightful, knowledge-building approach in increasingly unpredictable environments.

ABM has the capacity to combine data-driven realism with the simulation of interactions and dynamic patterns of social-ecological systems (An et al. 2021; Miller and Frid 2022; Sakamoto 2016). This duet produces a model that is spatially explicit, while giving agency to interacting elements, and may be used to inform stakeholders with context-specific questions. In this sense, our ECo-Range model is not just a product of scientific inquiry, but a tool to be used for social learning and collaborative discovery. Grazing management on the Colorado Northern Front Range is highly complex, reflecting an alchemy of social and ecological values, drivers, and perceived outcomes. ECo-Range utilizes a combination of geospatial data and ABM to explore these complexities, embracing rather than excluding the variability and heterogeneity inherent in social-ecological systems, particularly rangeland systems.

The following application of ECo-Range represents a context-specific grazing landscape, Lowry Ranch. We created this landscape in NetLogo 6.2.0 (Wilensky 1999), using methods that can be easily replicated on other ranches, rangeland study sites, and other regions across the globe with proper parameterization to local conditions (Appendix H).

AGENT-BASED MODELING METHODS

The following description of methods follows a protocol of standard descriptions of ABMs, the Overview, Design Concepts, and Details (ODD) protocol (Grimm et al. 2017). The seven elements of Grimm's ODD protocol guide documentation, publication, and replication, although not every category will apply to every ABM (Grimm et al. 2020) (Figure 4.1).

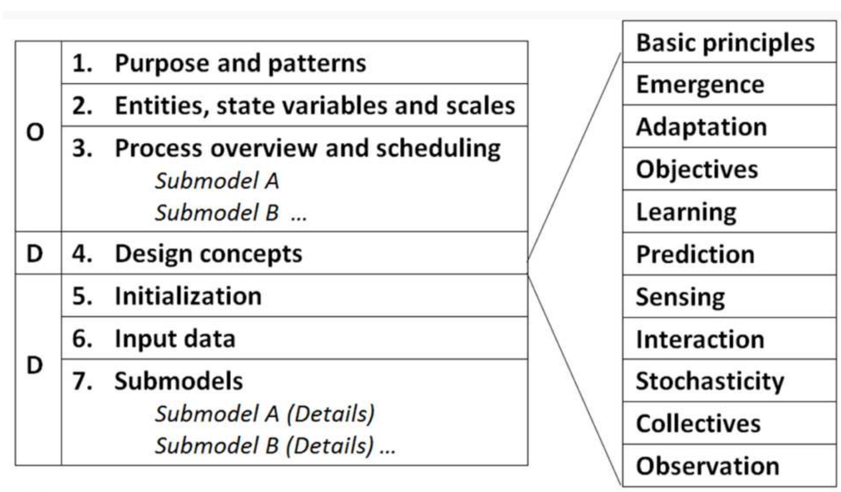


Figure 4.1. Standardized ABM model description structure including Overview, Design Concepts, and Details (ODD) protocol for Agent-Based Modeling. Design Concepts include a potential 11 sub-categories (Grimm et al. 2020).

Purpose

ECo-Range was developed as an investigative and educational tool for rangeland stakeholders to gain insight into human-environment-animal-forage dynamics of cattle grazing systems under various environmental and decision-making scenarios. We used the model to answer the overarching question: *How do select cattle management and land use decision scenarios affect grazing system outcomes under various environmental conditions?* ECo-Range is intended to simulate grazing system dynamics in specific ecological and geographical contexts, where the human decision-making dimension, the input of stakeholders or managers is influential in the ecological (animal and land-based) outcomes of cattle grazing. These dynamics are demonstrated through scenario manipulations involving cattle number, number and size of available pastures, water source locations, and forage availability using programmable manipulations in precipitation patterns, forage consumption, cattle weight gain/loss, forage growth rates, and pasture rotation thresholds.

Entities, State Variables, and Scales

ECo-Range contains two entities: *patches* representing the grazing landscape and *agents* representing cattle. The following landscape and cattle parameters were calibrated and verified through the local knowledge of the Lowry Ranch manager (N. Trainor, personal communication), as well as literature review. Multiple points of contact were made with the Ranch manager throughout the development of ECo-Range to ensure that realistic parameters were driving model scenarios.

Two components formed the foundation of the ECo-Range landscape. They contributed geographical and data-driven realism to modeling scenarios: 1) *area of interest* and 2) the *landscape texture*.

Area of interest: Lowry Ranch, located in Arapahoe County, is a property of the Colorado State Land Board acquired in three separate transactions in 1964, 1966, and 1991 (Colorado State Land Board 2020). It has a long diverse history as farm and ranch land prior to the drought of the 1930s, then as an army airfield and experimental bombing range from 1938 through World War II and the Korean War, with intermittent leases for livestock grazing (Sovell 2010). It was converted back into ranch land in 1998 under the state's Stewardship Trust and managed exclusively by a continuous grazing regime until 2008, when cattle use was discontinued for the following six years (Sovell 2010).

In 2014, with a new stewardship initiative in collaboration with the Colorado Natural Heritage Program and The Nature Conservancy, Lowry's management transitioned to holistic management, a rotational grazing framework that incorporates ecological-social-economic adaptive planning (Colorado State Land Board 2020). Although Lowry Ranch is a government-owned property whose revenue supports public education, it is not open to the public for recreation due to its focus on ecological stewardship and revenue-driven objectives (Colorado State Land Board 2020).

With its multi-use and sustainability objectives, Lowry Ranch is an ideal model landscape for our study of social-ecological systems (Figure 4.2). We attained shapefiles of the ranch boundary and various historical pasture and water location configurations. With the guidance of the ranch manager we used ArcGIS Pro (Esri Inc. 2020) to create additional hypothetical pasture configurations representing different levels of fragmentation for scenario development.

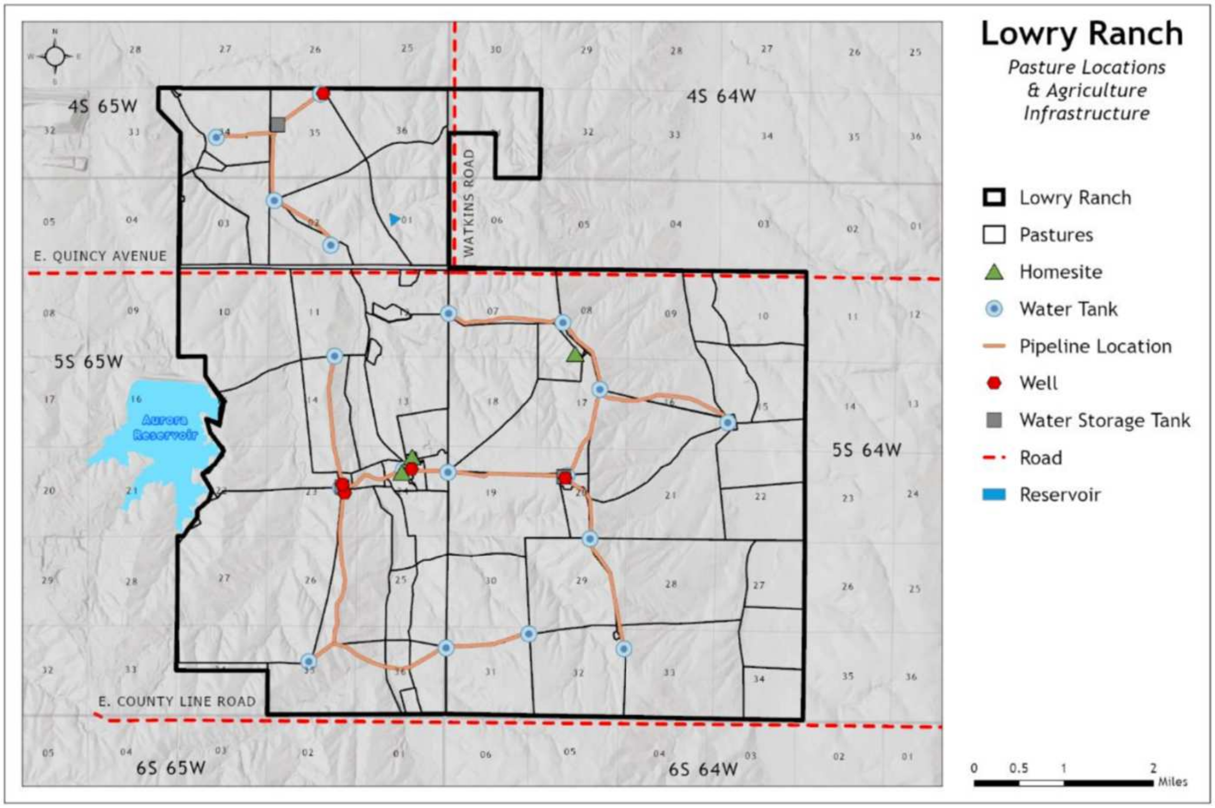


Figure 4.2. Map of Lowry Ranch, including agricultural infrastructure, used as the area of interest for agent-based modeling. Map provided by the Colorado State Land Board.

Landscape texture: To simulate various rangeland scenarios in which cattle could interact with the model world, we needed to represent forage as the *textural* aspect of the landscape. The typical interface of cattle and their forage is characterized by measures of carrying capacity, vegetation productivity, standing biomass, and forage quality. Traditional research methods to assess forage biomass and quality, such as clipping, weighing, and chemical lab analyses, are extremely laborious, and the timing of results may not align with the timing of important management decisions such as those involving stocking rates or pasture rotation schedules. The high temporal variability and spatial heterogeneity of rangeland ecosystems also poses a challenge for traditional field research design and methods (Sakamoto 2016). Therefore, our study utilized remote sensing technology and ArcGIS Pro (Esri Inc. 2020) geospatial analysis tools to evaluate Normalized Difference Vegetation Index (NDVI) as an alternative to field methods (Masek et al. 2006).

NDVI is a graphical indicator of reflected or re-emitted radiation used to assess vegetation presence and/or health (Camps-Valls et al. 2021; Rouse et al. 1974). NDVI data are collected by satellite sensors as the level of radiation reflected back from the earth's surface (Rouse et al. 1974). The light-spectrum of radiation reflected back to the satellite sensors depends on the presence and greenness of the vegetation below (Camps-Valls et al. 2021). NDVI is calculated from individual pixel characteristics of near infra-red (NIR) and red (R) bands. Thus, the equation for calculating NDVI is: NDVI = (NIR - red) / (NIR + red) (Myneni et al. 1995). This equation accounts for the difference in reflectance based on the chlorophyll content of leaves and vegetative structures and is touted for its parametric accuracy (Camps-Valls et al. 2021). NDVI outputs range from -1.0 to 1.0. Within this range, -1.0 to 0 represents clouds, snow, water, etc., 0-0.1 represents bare soil and rock, and 0.2 -1.0 represents vegetation of varying "greenness."

Since the first NDVI application was developed in the 1970s (Rouse et al. 1974), it has continued to be vastly popular for use in ecological, biological, and agricultural research (Camps-Valls et al. 2021; Pettorelli et al. 2011). NDVI is commonly used as a proxy for landscape scale vegetation quantity and quality because of its "simplicity, availability, and demonstrated utility" in diverse ecosystems (Garroutte et al. 2016). Because NDVI provides an efficient means of assessing vegetation at diverse spatiotemporal scales, it has been established as a critical tool for herbivore-forage dynamics across many disciplines (Pettorelli et al. 2011). NDVI is particularly appropriate for the study of extensive rangeland systems, since it provides a measurable index that can be used to explore the relationship between plants and animals, while accounting for high environmental variability across time and space (Pettorelli et al. 2011). For these reasons, we selected NDVI as our model's landscape texture.

The ECo-Range landscape texture was created from 30-m resolution Landsat satellite imagery (Masek et al. 2006) of the Lowry Ranch site. Specifically, a graphical layer of mean NDVI from May 17 – June 17 of each year from 2010-2020 (except 2011 and 2015, where imagery was damaged due to faulty satellite sensors), was downloaded from Climate Engine (Huntington 2017). ArcGIS Pro (Esri Inc. 2020) was used to format imagery for application in NetLogo.

Annual water-year precipitation data from the Byers station of the Colorado Climate Center and the COCoRaHS Network (Community Collaborative Rain, Hail and Snow Network) Station ID CO-AR-314 on Lowry Ranch headquarters were used to classify *precipitation level* of each NDVI year layer as: *Dry*, <340 mm (13.39 in) below average annual precipitation; *Average*, 340-430 mm (13.40-16.93 in) average annual precipitation; or *Wet*, >430 mm (16.93 in), above average annual precipitation (Appendix G). These classes were based on a 45-year average of 391 mm (15.39 in) (Colorado Climate Center 2022).

Pastures on the NDVI landscape were created using fence and livestock water location shapefiles obtained from the Colorado State Land Board and formatted for NetLogo using ArcGIS Pro and Microsoft Paint 3D. This combination of input data sources resulted in a spatially explicit model interface reflecting a realistic, to-scale depiction of the Lowry Ranch grazing system (Figure 4.3). Each patch in the ECo-Range landscape represents a 30 m x 30 m pixel of NDVI. NDVI is used as a proxy for biomass in model simulation. This pixel-to-patch resolution allows consistency between geospatial data and the NetLogo interface.

Figure 4.3. Example of ECo-Range interface using Lowry Ranch, depicting a Landsat NDVI geospatial data-sourced landscape with to-scale fence and water point locations, illustrating mid-simulation points of observation and observed outcomes. Created in NetLogo 6.2.0.

In ABMs the passage of time is represented by discrete intervals at two scales. *Ticks* in our model represent the passage of time in 1-day increments, and ten progressive *redraws* are coded into each tick. Each *redraw* represents one hour of grazing per day. This represents the standard scenario where cattle spend approximately ten hours per day engaged in herbivory.

Each agent represents a single cow. Each cow initially represents a 250 kg (551.16 lb) individual with a forage consumption rate of 2.5% of its body weight in total biomass (Launchbaugh 2014; Rasby 2013). Each cow is coded to interact with ten patches per day (one patch per redraw), where the biomass of each patch is reduced to simulate that it has been grazed. This equates to each cow grazing 0.9 ha (approx. 2.2 acres) per day. Cattle are coded to either gain, maintain, or lose weight depending on available biomass of each patch with which it interacts as the simulation progresses. In the ECo-Range *setup* the user may manipulate the stocking density via the *cattle number*. A slider provides options for cattle number ranging from 100 – 1,500 head, in increments of one-hundred.

Process Overview and Scheduling

The ECo-Range process incorporates five phases to simulate a grazing season: Create Conditions, Make Decisions, Graze, Monitor, and Observe Outcomes (Figure 4.4).

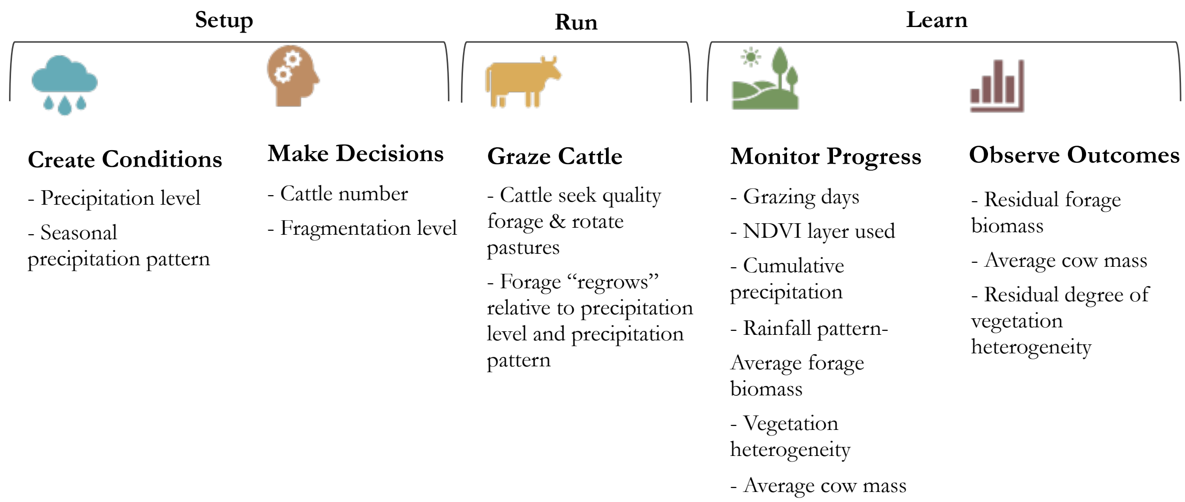


Figure 4.4. ECo-Range agent-based model process in five phases. Each phase incorporates sub-phases that are programmed and parameterized mathematically to represent an authentic social-ecological system.

Setup: The initial setup of ECo-Range provides landscape parameter manipulations that reflect complexities related to environmental variability, Create Conditions phase, and the human dimension, Make Decisions phase, in grazing systems. The user may select one option from each of the four categories in this phase.

Run: This Graze Cattle phase represents energy moving through the rangeland system from sunlight and precipitation to forage to cattle.

Learn: The Monitor Progress phase uses interface monitors and plots to allow the user to track quantitative data in real time as the simulation evolves. The Observe Outcome phase uses the NetLogo BehaviorSpace tool to evaluate three model outcomes.

Design Concepts

Basic Principles: Cattle grazing is a dynamic process that takes place on heterogenous landscapes. Forage availability is driven by environmental factors, and cattle utilization of that forage is dependent upon animal behavior, stocking rate, water location, and forage quality. The sustainability of rotational grazing systems relies on human decision-making to determine which temporal and spatial thresholds will result in 3 linked outcomes: 1) maximum residual forage biomass, 2) maximum cattle performance, or weight gain, and 3) maximum vegetation heterogeneity. It is understood that grazing distribution, stocking rate, precipitation level, and seasonal precipitation patterns are all variables that may affect these outcomes.

Emergence: Because of dynamic agent-patch interactions during ECo-Range model simulation, all resulting patterns could be considered emergent. Potential patterns may include relationships between cattle number and residual forage biomass, precipitation level and cattle weight-gain, landscape fragmentation level and residual vegetation heterogeneity, and precipitation pattern and cattle weight gain.

Adaptation: During simulation, agents (cattle) adapt to dynamic and stochastic environmental variables. They are encoded to locate the next closest patch of highest biomass in a constantly fluctuating and evolving landscape. There is no encoded learning or prediction associated with the model.

Sensing: Cattle are encoded to sense three variables during any given scenario: pasture boundaries, water location, and available biomass, based on the NDVI-derived biomass values associated with each patch.

Interaction: Individual cows interact indirectly with each other as they move from patch to patch. They are encoded to avoid patches occupied by another cow.

Stochasticity: A moderate level of stochasticity is used to represent spatial variability in forage biomass and growth rates across the landscape. While these variables are not randomized per se, they are variable and dynamic throughout model simulation in response to encoded coefficients, scales, and thresholds. Cattle are encoded to interact with this variability. User manipulation of the environmental parameters of precipitation level and precipitation pattern affects both vegetation heterogeneity and forage growth rates during simulation. This is conceptually reflective of real grassland systems.

Observation: Five types of data are monitored by plots in the ECo-Range model interface: *mean forage biomass*, *mean cow mass,* degree of *vegetation heterogeneity* based on an index of dispersion calculation ($D = \frac{\sigma^2}{\mu}$), a *precipitation tracker,* and a composite plot of *all outcomes*. Four monitors are also included to track: the *NDVI layer used* in the current scenario, the current number of *grazing days* in the simulation, *mean cow mass* and the *cumulative precipitation* since the start of simulation (Figure 4.3). Additionally, in the command center real-time data is printed to report total landscape mean biomass, current pasture mean biomass, and the current 50% threshold needed to trigger a pasture rotation. The Netlogo BehaviorSpace tool is used to report and synthesize outcome data. For our example protocol, these data were further organized in Microsoft Excel and prepared for statistical analysis. R Studio Version 1.3.1093 and the *tidyverse* and *ggplot2* packages were used to produce data summaries and conduct 4-Way Analysis of Variance (ANOVA) (R Core Team 2019).

Initialization

Landscape initialization starts with the user making 4 choices: 1) initial cattle number 2) precipitation level (i.e., wet, average or dry), 3) precipitation pattern 4) fragmentation level, and then clicking the *setup* button (Figure 4.5). The user first selects a *cattle number* contributing to a specific stock density scenario. Choosing a *precipitation level* randomly selects an available NDVI layer associated with that class.

The *precipitation pattern* options allow the user to create a scenario that reflects local or regional weather patterns or other hypothetical scenarios of interest (Figure 4.5). A series of 15 sliders, each representing a dekade (10-days) of time can be set to various precipitation quantities. These quantities represent daily rainfall on a normal distribution from the average daily rainfall derived from climate data as describe in the previous section. Alternatively, the user may select one of six preset precipitation patterns, including *constant*, *variable*, *observed*, *dry spring*, *wet spring*, or *monsoon*.

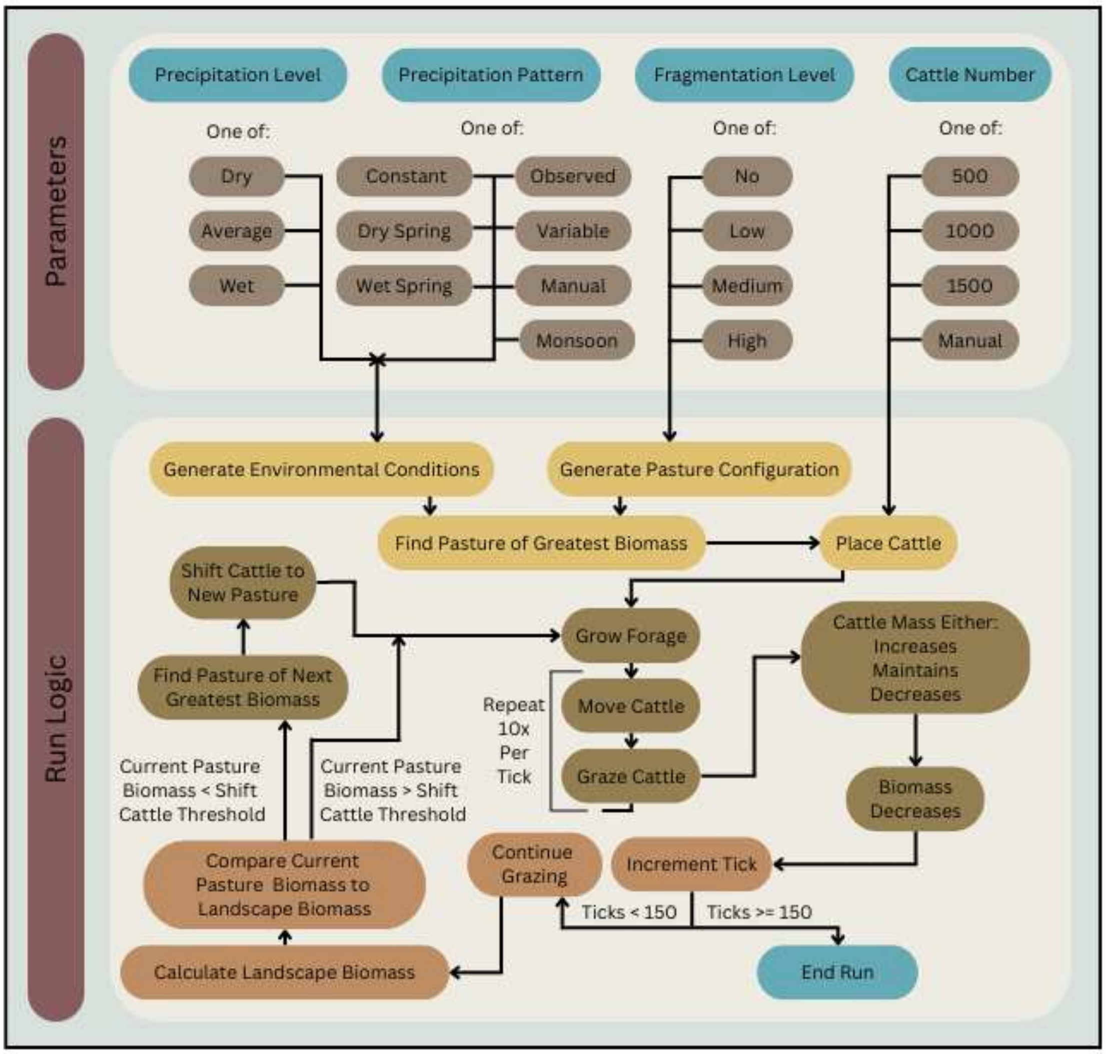


Figure 4.5. Flow chart describing initialization, "Parameters," and simulation, "Run Logic" phases and sub-phases of ECo-Range model of grazing systems.

The user may then select 1 of 4 *fragmentation levels* (Figure 4.5). These levels represent a theoretical rotational grazing program, which when combined with the cattle number, correlates to management intensity. The *no*, *low*, *medium*, and *high* fragmentation levels reflect a range of scenarios from the least intensive system of an open, non-fenced ranch to an intensive rotational grazing system with numerous small pastures (Figure 4.6). Pasture sizes range from one large 10,500 ha pasture in the no-fragmented scenario to approximately 208 ha pastures in the high-fragmentation scenario.

Figure 4.6. Four scenarios for landscape fragmentation level used in ECo-Range agent-based model grazing system. Each level represents a different degree of fragmentation on the Lowry Ranch landscape. The combination of this feature and the cattle number in any given scenario creates a specific "intensity" of grazing, due to stock density.

Based on the preceding selections, the landscape loads first with 1 of 9 NDVI layers associated with precipitation level. Based on observed rainfall in each year, years were assigned to the precipitation classes cited. Years 2012, 2017, 2018 and 2020 are allocated to *dry*. Years 2016 and 2019 are allocated to *average*. Years 2010, 2013, and 2014 are allocated to *wet* precipitation levels. Next, a fencing and water location map, based on the fragmentation level selection, will overlay the NDVI base layer. Maximum biomass production is encoded for each patch in the landscape based on a transformation applied to the NDVI, yielding appropriate forage units (g m^{-2}) while preserving the texture of the NDVI image. The final step is that cattle are encoded to initiate the simulation at the water source in the pasture with highest mean biomass on the landscape. At this point, the ECo-Range simulation is ready to be executed and will proceed as described in the Process Overview and Scheduling section above.

Simulation

In this phase, cattle are coded to move from patch to patch, selecting the closest patch within their current pasture with the highest available biomass (Figure 4.5). Only 30% of total biomass from NDVI is made available in this calculation. This takes into account the proportion of rangeland net primary productivity that is commonly lost to other impacts such as trampling, presence of unpalatable species, and utilization by wildlife. After 10 moves, representing 10 hours of grazing per day, the model ticks forward to the next "day." When a cow encounters a patch, the biomass of that patch decreases based on the estimated hourly intake of 0.625 kg. At the same time, cattle gain mass, maintain mass, or lose mass based on the current pasture's biomass relative to the overall initial ranch biomass (Figure 4.5). This takes into account the change in biomass throughout the grazing season relative to the state of it at the beginning of the season, representing an evolving landscape of forage availability and the link between cattle weight gain or loss and this ecological factor. For example, if the current pasture's biomass is above 90% of the initial ranch biomass, then the cattle will gain weight at a desired rate of 0.30% of body mass per day (Byrne 2020; Filley 2013). At the other end of the spectrum, if the current pasture's biomass is below 52.5% of the initial ranch biomass, cattle will lose weight at a rate of 0.33% of total body mass per day (Parish and Rhinehart 2009; Rhinehart 2020). There are two additional weight-gain intervals between these two extremes that are used to represent fluidity in animal-forage dynamics. ECo-Range assumes that cattle would access water outside of the 10-hour per day grazing period. Therefore, we did not model cattle use of water locations, except to dictate the location where cattle begin grazing in a new pasture.

Forage is coded to *grow* incrementally with each tick based on average daily rainfall estimates for the 3 precipitation levels (dry = 0.814 mm, normal = 1.059 mm, wet = 1.341 mm) that are constrained by a user-selected precipitation pattern (Figure 4.5). Forage growth is coded using a base equation derived from a study on similarly arid grasslands in the African Serengeti (Fryxell et al. 2005), and coefficients were modified to reflect biophysical patterns observed on the Lowry Ranch study site (Boone and Galvin 2014; Fryxell et al. 2005). When the mean biomass of the current pasture diminishes to 50% of the mean total landscape biomass, the cattle are encoded to *shift* (rotate) to a new pasture of highest biomass and continue grazing. This threshold can be manipulated based on the modeled landscape and grazing system in question but is designed to prevent the virtual livestock from overgrazing the ECo-Range landscape. ECo-Range is programmed to auto-stop at 150 ticks, representing 150 grazing days, or a 5-month grazing season. This characterizes a typical growing season on Lowry Ranch, May – September.

As proof-of-concept and for the purpose of testing the aptitude and functionality of our ABM as a rangeland management tool and application of social-ecological systems theory, we created and conducted a factorial simulation protocol from which to evaluate results. We used 72 unique scenario initial conditions combinations and replicated each combination 5 times for a total of 360 simulations (Figure 4.7).

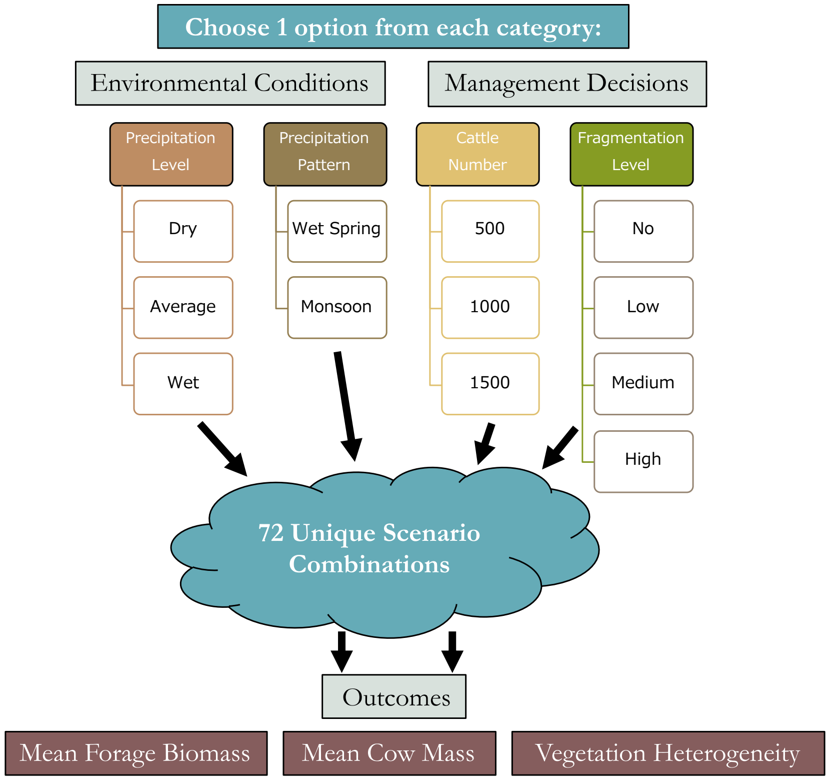


Figure 4.7. ECo-Range agent-based model simulation example protocol includes setup categories that combine to create 72 unique scenarios and allow us to evaluate three measurable outcomes. ECo-range incorporates the social and ecological dimensions of rangeland grazing systems.

RESULTS & DISCUSSION

Our ABM, ECo-Range, combines human decision-making, geospatial and climate data, and animal-forage landscape dynamics into a virtual ecosystem to simulate a spectrum of hypothetical environmental and management scenarios for Lowry Ranch in Colorado, USA. We tracked three outcome variables – residual forage biomass, cattle performance, and residual vegetation heterogeneity, where higher values of each variable were considered most beneficial. For example, from an ecological perspective, the greater the residual forage biomass and vegetation heterogeneity, the better the outcome for wildlife habitat and plant-soil nutrient cycling throughout the dormant season and into the next spring growth. From a cattle performance perspective, the greater the cattle weight gain, the better the outcome for cattle health and ranch profitability and economic sustainability.

Of our 72 scenarios, 36 were conducted under a “wet spring” precipitation pattern and 36 were conducted under a “monsoon” precipitation pattern. The following results were summarized across both precipitation patterns to provide the spectrum of interannual variability common in our study region. In fact, these patterns approximate the 2021 and 2022 grazing seasons of our study location. Our results illustrate several example pathways for how scenario outcomes might be studied (e.g. summary statistics, ANOVA), but do not exhaust all possible ways in which model outcomes could be evaluated or visualized. We encourage modelers to explore results in whichever ways will provide the most benefit for stakeholder learning, collaborative discovery, and knowledge-building.

Because of its capacity to integrate both categorical and continuous variables, we performed a 4-Way ANOVA for each of the three outcomes and direct effects of the four scenario conditions (Table 4.1). For mean forage biomass and mean cow mass, all four environmental (precipitation level and pattern and management conditions (cattle number and land fragmentation level) had a significant direct relationship. For vegetation heterogeneity, only fragmentation level created a significant direct effect.

Table 4.1. *Results of 4-way Analysis of Variance (ANOVA) for effect of scenario conditions on grazing system measures in ECo-Range agent-based model simulation. Scenario conditions include both environmental factors and management decisions. Three outcomes: mean forage biomass, mean cow mass, and vegetation heterogeneity (index of dispersion of biomass), were evaluated. F-values and p-values were used for statistical interpretation.*

Measures	Scenario Conditions		F-value	p-value
Mean Forage Biomass *(lbs/patch)*	Environmental	Precipitation Pattern	429.27	< 0.01
		Precipitation Level	3282.78	< 0.01
	Management	Fragmentation Level	37.83	< 0.01
		Cattle Number	2061.53	< 0.01
Mean Cow Mass *(Kg)*	Environmental	Precipitation Pattern	288.23	< 0.01
		Precipitation Level	65.85	< 0.01
	Management	Fragmentation Level	29.81	< 0.01
		Cattle Number	192.20	< 0.01
Vegetation Heterogeneity *(Index of Dispersion)*	Environmental	Precipitation Pattern	4.30	0.05
		Precipitation Level	3.21	0.06
	Management	Fragmentation Level	30.74	< 0.01
		Cattle Number	0.24	0.63

To further explore the implications of 4-way ANOVA and interpret the data for management application, we compiled a summary table of scenario conditions and results to assess patterns in grazing system dynamics (Table 4.2). For illustrative purposes we summarize data across both monsoon and wet spring precipitation patterns to focus on the effects of management decisions across three precipitation level scenarios.

Table 4.2. ECo-Range agent-based model example protocol summary of results. Outcomes measured and evaluated included: residual forage biomass, cattle performance, and residual vegetation heterogeneity. Highlighted cells in the last three columns indicate the management decision variable producing the best outcome for a given precipitation level scenario.

Precipitation Level	Management Decisions		Residual Forage Biomass *Mean Biomass (kg/patch)*	Cattle Performance *Mean Cow Mass (kg)*	Residual Vegetation Heterogeneity *(Index of Dispersion)*
Dry	Cattle Number	500	42.5	364.	5.35
		1000	29.6	348.	4.04
		1500	20.8	323.	4.91
	Landscape Fragmentation Level	No	28.9	347.	1.96
		Low	31.7	334.	5.30
		Medium	29.2	339.	6.43
		High	34.0	360.	5.38
Average	Cattle Number	500	68.6	367.	3.94
		1000	56.5	363.	3.85
		1500	45.4	350.	3.86
	Landscape Fragmentation Level	No	54.0	368.	1.90
		Low	56.8	353.	5.22
		Medium	57.1	356.	4.16
		High	59.3	363.	4.27
Wet	Cattle Number	500	80.8	368.	4.25
		1000	68.5	364.	4.52
		1500	59.4	357.	4.25
	Landscape Fragmentation Level	No	64.9	372.	2.13
		Low	69.1	358.	5.74
		Medium	71.8	358.	4.81
		High	72.4	364.	4.69

Residual forage biomass: We observe an indirect relationship between residual forage biomass and cattle number, and a direct relationship between biomass and land fragmentation level. (Table 4.2) For example, residual biomass is greater in scenarios with the lowest cattle number and highest land fragmentation level, whereas the lowest residual biomass is correlated with the highest cattle number and the lowest land fragmentation level. Model behavior related to residual biomass is congruent with our knowledge of forage utilization, where higher cattle stocking rates will remove greater amounts of biomass if other environmental conditions are held constant. Additionally, we observe that cattle number had a more dramatic effect on residual forage biomass outcomes than land fragmentation level. This is indicated by greater variability in mean biomass among cattle number scenarios compared to fragmentation levels. We also see that the residual forage biomass is directly correlated with precipitation level, where below average (dry) precipitation level scenarios produce the lowest residual biomass values and above average (wet) precipitation level scenarios produce the highest residual biomass values comparatively.

Cattle performance: The greatest cattle mass at the end of a simulated growing season is correlated with the lowest cattle number (Figure 4.2). Whereas, the influence of land fragmentation on cattle performance depends on the annual precipitation level. For the dry precipitation level, the high land fragmentation level is linked to the scenario resulting greatest cattle mass, and for the average and wet precipitation levels, the high and no fragmentation levels produce the best cattle performance outcome. Interestingly, low and medium fragmentation scenarios, the mid-levels, produced the lowest cattle mass at the end of simulation.

To verify that ECo-Range could be useful in future applications in other contexts, we needed to be confident that the model reasonably reflected reality. Therefore, we calibrated and validated cattle mass model behavior through collaboration with the Lowry Ranch manager (N. Trainor, personal communication). Our results illustrate that cattle weight-gain in ECo-Range occurs at rates comparable to the real system, with 368 kg as the objective in a favorable season. Although there is debate in the literature regarding continuous versus rotational grazing systems (Augustine et al. 2020; Briske et al. 2008; Teague et al. 2013), anecdotal observations from Lowry Ranch indicate that cattle have performed better in a more intensive rotational grazing system. ECo-Range may be used to test this observation. We also noted a larger than expected range of values for mean cow mass across scenarios, a difference in approximately 100 kg from the lowest to highest values. This degree of spread in the data was unpredicted yet offers insight on an important issue for ranch management. It informs us that environmental conditions and management decisions may have broad and variable effects on cattle performance. Implications of this are directly related to ranch profitability and economic sustainability.

Residual vegetation heterogeneity: Land fragmentation level had a more significant effect than cattle number on residual vegetation heterogeneity, as indicated by broader variability among results of fragmentation level options. We observe that the no fragmentation level scenario for all precipitation levels is associated with the lowest vegetation heterogeneity outcomes compared to all other fragmentation levels. Differences in cattle number were not statistically significant for vegetation heterogeneity outcomes (Table 4.1). We can conclude that low to high fragmentation levels, regardless of cattle number, resulted in better outcomes for vegetation heterogeneity.

This direct linkage between low to moderate grazing intensity and vegetation heterogeneity is evident in bird habitat conservation research. Vegetation heterogeneity is an important outcome when considering the co-existence of cattle and wildlife species, like birds (Davis et al. 2020; Derner et al. 2009; Toombs et al. 2010). "Grasslands with more vegetation heterogeneity support a greater number of plant and animal species because they contain additional structural complexity and/or diverse plant communities, which provide added spatial and temporal niches" (Toombs et al. 2010). Research on the effects of grazing intensity on bird habitat concludes that higher grazing intensity is associated with a decrease in bird abundance and richness (Barzan et al. 2021; Kantrud 1981; Willcox et al. 2010). This is likely due to a reduction in the variety of vegetation structure needed to support diverse bird habitat. In other words, a reduction in vegetation heterogeneity due to higher stocking rates and grazing intensity may result in reduced bird habitat and populations. Our model results support previously existing data on the relationship between cattle grazing intensity (in the model represented by higher cattle numbers per unit area) and vegetation heterogeneity.

We can also investigate which management decisions may result in beneficial outcomes under below average, average, or above average annual precipitation. For the dry precipitation scenario, the lowest cattle number produced the highest residual forage biomass, cattle performance, and vegetation heterogeneity. Positive outcomes in this precipitation scenario were tightly coupled with high or medium land fragmentation levels but not with low or no fragmentation levels. The beneficial outcomes for an average precipitation level scenario were also correlated with a lower cattle number. On the other hand, a different land fragmentation level was associated with the highest value for each of the three outcomes. In the wet precipitation scenario, the lowest cattle number was still associated with the highest residual biomass and mean cow mass, but the moderate cattle number was linked to the greatest residual vegetation heterogeneity. The land fragmentation levels correlated with the most beneficial outcomes in this scenario followed the same pattern as observed for the average precipitation scenario.

ECo-Range provides learning opportunities regarding the relationships among environmental conditions, management decisions, and ecological and livestock outcomes. Model results underscore real-world synergies and tradeoffs. For example, while higher cattle numbers and higher fragmentation levels may correlate with better cattle performance, these conditions are less favorable for vegetation heterogeneity and species that depend on that heterogeneity.

Modeling the social-ecological dynamics of highly variable and heterogenous systems like cattle grazing systems requires adaptability and mathematical realism. ECo-Range allows us to test alternative approaches to real-world scenarios without taking risks associated with actual experimentation on working operations. ECo-Range may function as a management planning and learning tool capable of answering a multitude of stakeholder questions, such as: *Can increasing the number of pastures in my rotational grazing schedule result in better cattle weight gain? Could decreasing my stocking rate increase vegetation heterogeneity, providing habitat for wildlife? If we get a wet spring, could decreasing my number of pasture divisions improve the amount of residual biomass at the end of the grazing season?*

When we view grazing systems as social-ecological systems, we are better able to understand the many linkages between human decision-making and the various trophic levels of nature. Further, feedbacks between humans and nature ultimately affect the economic viability of ranching as a livelihood. Therefore, the ability to test multiple hypothetical scenarios in a virtual environment may prevent negative or costly risks and outcomes.

MODEL EVALUATION & NEXT STEPS

In evaluating the efficacy of our model, we reflect on 1) our initial scope and intention, 2) stakeholder participation in model development and calibration 3) model limitations, and 4) user experience and adoptability.

Scope and Intention

The management of grazing systems involves theoretical, practical, and ecological variables, where domestic livestock are the agents of biophysical change. Their agency, however is coupled with and dependent upon human decision-making, as well as interaction with environmental stochasticity. Our objective was to develop a model of human-environment-animal-forage dynamics of rangeland grazing systems and ensure that this model could also be used as an educational tool. While our model was situated in a specific geographical and social context, we incorporated flexibility and adaptability in the model's coding language so that any unique grazing system across the globe may be applied to the model by modification of mathematical coefficients in the coding language.

Stakeholder Participation

Our overall model concept was stakeholder-driven, rooted in the challenges, concerns, and inquiries of real-time, real-scale rangeland cattle management. We developed the model so that it may be used as a knowledge-building tool, where stakeholders can engage in collaborative discovery and social learning by asking questions, posing scenarios, setting goals, using local knowledge, calibrating coefficients, and interpreting results. In this way, stakeholders are promoted from research *subject* to research *partner*, further strengthening the value, applicability, and reach of the science. For example, throughout model development and calibration phases, we consulted with stakeholders, especially the Lowry Ranch manager, who was able to use local knowledge and contextual experience to assist in creating scenarios and verifying mathematical coefficients that most accurately represent the real system.

Model Limitations

Representing the complexities of social-ecological systems is likely one of the biggest challenges in simulation modeling. However, there is sufficient consensus in the scientific community that simulation modeling can be productive in natural resource studies as long as the boundaries and principles of good modeling practice are respected (Jakeman et al. 2006). Canham (2003) playfully makes this point, "For every problem there is a model that is simple, clean, and wrong". In other words, models need to be complex-enough yet simple-enough to make results clear and interpretation compelling (Haraway 2016).

There are two primary areas of complexity in our ABM that we relinquished, which could have resulted in limitations. One is our use of un-manipulated NDVI imagery. NDVI is unable to differentiate vegetation that would be considered forage for cattle grazing and other vegetation that would not be considered forage for cattle, such as tree cover. Therefore, in our model all vegetation is treated as forage, which will create some bias in the model world for tree-covered areas, like riparian zones. A next step toward improving this issue would be to use landcover geospatial data to "mask out" tree cover from the forage biomass calculation in the model interface.

Secondly, cattle grazing behavior in our model is relatively simplistic, as cattle seek out the closest patch of highest forage biomass. This does not reflect cow-to-cow interactions nor herd dynamics such as the influence of "leaders" or "followers" (Jablonski et al. 2018). The model also does not represent different grazing behaviors among groups of cattle, like mature cow versus yearling grazing behavior, which can have diverse effects on landscape variables. A next step toward improving this model component would be to incorporate more realistic cattle or herbivore behavior coding, such as that developed by Jablonski et al. (2018).

User Experience and Adoptability

One of the benefits of our ABM development in NetLogo is its friendly, attractive and easily manipulable user interface. In our model, agents are actually shaped like cattle, water points are blue, and the landscape is illustrated on a green color scale representing a grassy environment. Monitors and plots are intuitively arranged and color-coded so that model outcomes can be easily tracked throughout a simulation. During simulation, the modeled world updates graphically so that the user can observe agent-environment interactions as they evolve. These features create an aesthetically interesting and interactive user experience.

While a trained modeler would be needed to parameterize ECo-Range to different geographical and social-ecological contexts, once the basic components such as geospatial layers are in place, the Netlogo software is accessible and adoptable, even with limited technological experience. First, Netlogo software is cost-free and does not consume excessive amounts of computer memory. Second, the user may adjust model setup options representing environmental conditions and management decisions and run the model for hypothetical scenarios without coding expertise or technical assistance. Thirdly, if the user wanted more flexibility, the modeler could flag certain areas in the code containing coefficients that the user may want to modify or adapt to certain inquiries.

In conclusion, we believe that our novel use of ABM contributes to a growing body of knowledge regarding the power and utility of social-ecological systems modeling. Not only does our model provide a virtual representation of a real variable and heterogenous system of evolving feedbacks and multi-component dynamics, it is a learning tool. We designed an intuitive and user-friendly interface, where linear or multi-faceted questions may be explored through creation of unique scenarios and observation of outcomes. Global challenges of today often encompass seemingly paradoxical endeavors, such as agriculture and conservation. Such objectives are complicated by already highly complex and dynamic systems, like rangelands. It is our hope that this exercise will deepen our undertsanding of how to sustainably manage these social-ecological systems, where humans learn to craft thriving futures in relationship with the natural world.

CHAPTER 5: SYNTHESIS: A TRANSDISCIPLINARY MIXED METHODS STUDY OF GRAZING SYSTEMS

BEGINNINGS

In 2018, with grey strands peeking out from my braids, an infant on my hip, and a burning passion to find solutions to better manage and protect rangeland ecosystems for future generations, I had an idea. This idea was more like a question – *Could we devise a study on collaboratively-managed rangelands that was scientifically rigorous and context-specific enough to mean something to those people who could put the learning into practice?* I imagined a project founded in social-ecological systems theory and ecosystem and sustainability science, yet with a bottom-up systems approach in the research design, where real stakeholders would participate with an active role in the development and intermediary stages of the research.

Why rangelands? Because rangelands are vast, beautiful, and fascinatingly complex ecosystems, which, despite their relevance to life as we know it, remain under-protected and under-funded. Rangelands are also home to large wild and domestic herbivores, who have captivated my mind and heart since I was a child. In addition to the fact that rangelands cover about 54% of the Earth's surface (ILRI 2021), they are vital to global ecological processes and, therefore, human and animal life. Rangelands support global livestock production systems including pastoralists, hunter-gatherers, and ranchers, and provide nearly 70% of total forage for livestock production (Holechek 2013). In the United States, approximately 30% (770 million hectares) of total land cover consists of public and private rangelands (Natural Resource Conservation Service). However, in states like Colorado with expanding human populations, rangeland livestock production increasingly competes for limited space with housing development, crop agriculture, energy production, conservation spaces and recreation.

In this region of the world, the primary agricultural use of native rangelands is cattle ranching. Livestock production is the only way humans may utilize these often non-arable landscapes for sustenance, since ruminant mammals, like cattle, are able to turn fibrous plants that humans cannot digest into a high quality food source in the food chain. But *good* ranching is complex. Rangeland ecosystems, especially those that incorporate partnerships between government agencies and private agricultural operations, are diverse and multifaceted. High environmental variability is further complicated by the human dimension where economics and sociocultural value systems influence decisions and actions. How do today's ranchers navigate their modern world shaped by seemingly paradoxical issues of natural resource management, climate change, food production for growing populations, land use and ownership dynamics, and a global human health and wellness crises?

We wanted to understand the benefits and challenges of collaborative grazing management on government-owned rangelands, which encompass over one-third of the state of Colorado. Were collaborations between these public entities and private ranchers creating mutually beneficial outcomes for natural resource conservation and rancher livelihoods? Did these collaborations incorporate win-win strategies for diverse stakeholder interests? How did these collaborative partnerships navigate decision-making (e.g., grazing plans) when unique human values, needs, and beliefs were present at the negotiating table?

We used the well-known model of sustainability and its three pillars – ecological, social, economic – as a framework for a holistic study (Basiago 1998; Purvis et al. 2019).When conceptualizing our study, it was important that the human socioeconomic dimension of rangeland management was woven into an investigation of the ecological outcomes of such management (Figure 5.1). Our overarching research question was: *Could conceptualizing cattle as partners in conservation be a win-win for the livestock and rangeland conservation sectors, resolving the seemingly paradoxical objectives of food production and natural resource management?*

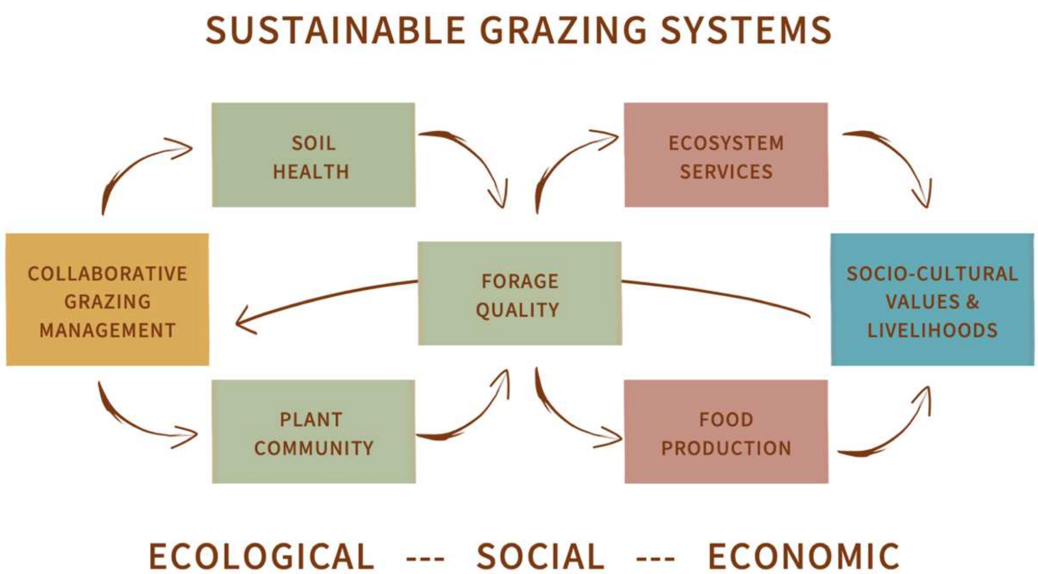


Figure 5.1. A model of sustainable grazing systems incorporating the "three pillars" of sustainability as a framework for a holistic study of collaborative grazing management on Colorado government-owned lands.

We used a lesser-known theoretical model, the head-hands-heart metaphor from the 1927 silent film, *Metropolis*, as a canvas upon which the study would come to life (Lang 1927) (Chapter 1). The *head* refers to the science of the matter, on which we believe that systems ecology, ecocentrism, deep ecology, and social ecology, should take center stage. The *hands* reflect the actions, methods, and initiatives of sustainability science, regenerative ranching, and conservation, which are founded in collaboration and the integration of diverse sources of knowledge and shared responsibility for the human role in the natural world. The *heart* is the bridge between the head and hands … the sense of connection and relationship humans have with nature and with each other, one which also acknowledges the most powerful emotion of all, *love*. Love is something all rangelands managers, scientists, and stakeholders feel, but rarely verbalize publicly, let alone document in published literature and professional correspondence. Some have actually crossed this boundary with music, art, poetry, and scientific research, and their work is inspirational (Bass 1998; Fernández-Giménez et al. 2019; Kimmerer 2013; Provenza 2000; Wallace 2020).

In the end we had incorporated an interdisciplinary methodology to study rangeland ecosystems, while nesting our study of *collaborative* grazing management within a *collaborative* heart-centered approach to research.

SYNTHESIS OF LEARNING & IMPACTS

We soon earned interest and gained support from local, state, and regional industry partners, as well as fellowship programs in research and sustainability science. Our holistic study was launched in 2019 and concluded in 2022. Our skills and knowledge thresholds were stretched by the Coronavirus pandemic, from which new methods and approaches to our research necessarily emerged.

In the ecological component of our study, we investigated soil health (total nitrogen, organic carbon and water infiltration), plant community (plant species composition and diversity), and forage quality (crude protein, acid detergent and neutral detergent fibers) indicators (Chapter 2). We compared these variables in historically grazed and ungrazed areas that were otherwise consistent in soil type, slope, geophysical properties, and reference plant communities.

We learned that areas historically managed by collaborative grazing plans were either no different than ungrazed areas or showed more favorable conditions for land and animal health.

Soil nitrogen and organic carbon content were greater in grazed areas. Forage nutritive quality, indicated by greater percent crude protein and less fiber, was also higher in grazed areas compared to ungrazed areas. Plant community composition, considering functional groups (cool-season & warm-season graminoids, forbs, and shrubs) and species origins (native versus exotic), was not different among grazed and ungrazed areas. In other words, long-term grazing had not significantly altered the plant diversity of these landscapes but rather maintained it without apparent harm, a mutual benefit to livestock and wildlife populations on all trophic levels.

In the socioeconomic component of the study, we explored the human dimension of rangeland ecosystems, where socioeconomic livelihoods and sociocultural values are entwined with land use (Chapter 3). We identified revealing patterns in the values, opinions, and perspectives of stakeholders involved in the management and use of the government-owned rangelands in our study. We used the ecosystem services and Nature's Contributions to People concepts to frame our inquiry and interpretations (Daily 1997; Díaz et al. 2015; Millennium Ecosystem Assessment 2005; Pascual et al. 2017).

We learned that different stakeholder groups--rancher/producers, agency/professionals, and community/recreationers--exhibit distinctive clusters of values and beliefs and noted patterns in how each stakeholder group tended to prioritize certain ecosystem services over others and how this prioritization reflected their value systems. Our study demonstrated that stakeholders involved in the management and use of government-owned rangelands shared more values than not and agreed on more issues than not. For example, stakeholders agreed that the management of government-owned lands inevitably involves some conflict and tradeoffs, but they also agreed that cooperation and collaboration are keys to success. We learned that the inclusion of diverse voices and sources of knowledge around the decision-making table is an auspicious approach and may open doors to solutions, as stakeholder perspectives are likely rooted in overlapping value systems. Stakeholder perspectives and values are directly linked to decision-making and management approaches, and therefore, an in-depth value assessment led to increased awareness and social learning among study participants.

Finally, we combined our knowledge-gained and findings of the ecological and socioeconomic components of our study and created a system dynamics model. We used agent-based modeling to create a virtual grazing system based in contextualized data, and we engaged in scientific inquiry through a series of programmed simulations. The model was designed to explore the overarching question: *How do select cattle management and land use decisions affect grazing system outcomes under various environmental conditions?* The ECo-Range model (Ecological Co-management of Rangelands), is capable of simulating grazing system dynamics in specific ecological and geographical contexts, where the human decision-making dimension and environmental stochasticity are influential in the ecological (animal and land based) outcomes of cattle grazing.

Through a strategic simulation protocol, we learned that environmental conditions like precipitation level and patterns, and management decisions such as cattle number and degree of landscape fragmentation, have significant direct effects on outcomes like residual forage biomass, cattle performance, and residual vegetation heterogeneity. Not only does ECo-Range provide a virtual representation of a real variable and heterogenous system with multi-component dynamics and evolving feedbacks, it can also be used as a learning tool for stakeholders to pose questions, test hypotheses, and investigate theories in a virtual platform prior to making a decision investment on the landscape. We intend that our novel application of agent-based modeling will contribute to a growing body of knowledge regarding the power and utility of social-ecological systems modeling to resolve challenges of today and the future.

COLLABORATIVE CONSERVATION

Grazing management on the Colorado Northern Front Range is highly complex, reflecting an alchemy of social and ecological values, drivers, and perceived outcomes. Our study utilized a combination of ecological field data, sociocultural analyses, geospatial data, and agent-based modeling to explore these complexities, embracing rather than excluding the variability and heterogeneity of these social-ecological systems. This work revealed that collaborative grazing management on government-owned lands can be mutually beneficial for natural resource conservation efforts and sustainable livestock production. In fact, study stakeholders wholeheartedly agreed that cooperative management and collaboration offer a path forward due to the integration of diverse perspectives, sources of knowledge, and experiences.

We believe that the synergies we observed among the ecological, social, and economic components of our study were largely possible due to the collaborative aspect of management. Collaboration was the common thread that united all study sites. Stakeholder demographics varied. Cattle production cycles and breeds varied from site to site, and grazing schedules varied by year and location. The consistent factor was that each of the landscapes we studied incorporated a collaborative approach to management for economic, environmental and social outcomes.

Collaborative conservation is an existing term we can apply to this approach. It is defined as a process that coalesces diverse stakeholders to collectively manage natural resources with the goal of supporting people and the natural world to thrive today and into the future (Margerum 2008). Collaborative conservation can be a tool for reducing conflict and for helping groups achieve common environmental, social, and economic goals (Conley and Moote 2003). In addition to creating community and social accountability, collaboration ensures that a multitude of perspectives are recognized and diverse voices are heard (Ophuls 2011). When diverse public and private stakeholders collaborate on environmental issues, the solutions that emerge can be more impactful, innovative, and enduring (McKinney and Harmon 2004). They are also bound to be more relevant to the people and communities of the space being managed. Over time, collaborative rangeland stewardship may be transformative for social-ecological systems through building relationship among stakeholders, integrating diverse sources of knowledge, co-producing new knowledge, social learning, networking, and implementing action (Reid et al. 2021).

I recommend that our ideas about collaborative conservation also co-involve animals, plants, and ecosystems as contributors at the table of collaboration. If we recognize nature as part of our shared community, and if we are responsive to our observations, the natural world may, in a way, participate in decision-making (Schlosberg 2009). But this is contingent upon human awareness of human-nature relationships and adeptness with systems thinking and ecosystem science so that the role and "voice" of the non-human participants may be understood and integrated. In collaborative groups, this broader level of thinking and intimate understanding of ecological processes and the human role in them is made possible by the presence of diverse stakeholders, each with their own experience, interpretation, perspective, value system, and knowledge base.

CONTRIBUTIONS TO THE RANGELANDS STORY

In the opening chapter of this dissertation, I theorized that we humans need to re-story our relationship with Earth's rangelands, moving from a solely utilitarian perspective to that of community and relationship. Some global rangelands cultures and stewards have been or are already doing this, but in mainstream Western society we have strayed into mentalities and actions that have proved dysfunctional and even detrimental. Our collective use of language and metaphor, traditional ecological knowledge, scientific discoveries, and collaborative actions may all lead to this re-storying. There are five main themes that illustrate our study's contribution to the greater rangelands story: 1) stakeholder integration, 2) climate change conversation, 3) debate resolution, 4) contextualized value, and 5) sustainability.

First, we designed and carried out a study where variables of interest were chosen because of wide interest among local stakeholders. We proceeded to integrate expert assessment with local stakeholder knowledge as we selected study areas. Rancher questions became our questions. Government land agency personnel questions became our questions. We further integrated stakeholders into a social science research component, which explored sociocultural values and perspectives and how those might influence the human decision-making dimension. Stakeholders were again invited to participate in an interactive workshop and focus group where results were presented, stakeholders shared their reflections, and we engaged in discussion to calibrate results against on-the-ground experience. Stakeholders were involved throughout various stages of the research progress, which provided a richness and realness to the study. We observed other outcomes of this approach, including relationship-building, trust development, group cohesion, and social learning. This participatory approach proved to be a powerful tool that impacted the experience of the research team and stakeholders alike. It cemented our relationships and built trust.

Secondly, while we never explicitly focused the study's objectives on the role of rangelands or cattle production in climate change, the processes and variables we considered are very much a part of the climate change conversation. Carbon, nitrogen, hydrology, biodiversity, the livestock agriculture footprint, and collaborative conservation are all climate themes woven throughout this project. While our study lacked the robust sample size or broader spatial and temporal scales for direct extrapolation to climate change-oriented conclusions, we were able to address contextualized dynamics of local grazing systems and design ECo-Range to allow climate-driven variables in the model to be manipulated. We intend that our approach is one that provides both an anecdotal response via a case study, as well as ideas for broader application regarding the utility of grazing as a rangeland management approach for the mitigation of climate change through carbon sequestration, nitrogen retention, and improved or maintained biodiversity.

Thirdly, through this study we were able to respond to an issue of popular debate: Are cattle harming our public lands? We learned that the answer to this question is likely "no," at least not in the case of the places we studied, and potentially more broadly where collaborative management for both environmental and economic outcomes is involved. We learned that strategically-managed cattle grazing may actually improve soil nutrient cycling and forage quality on rangelands. Additionally, considering all variables in our study, we can conclude that long-term grazing has not been harmful to these ecosystems, but rather has sustained them or even improved them in terms of rangeland health.

Fourth, our study made discoveries that are important for the greater rangelands community, while remaining relevant to local producers and stakeholders. Our project was context-based, which produced localized, applicable results and opportunities for learning. We engaged in a collaborative research design where our research questions and variables of interest were co-developed with stakeholders. Because rangeland grazing systems are extremely diverse and variable across social and ecological scales and regions, we believe it was valuable to engage a research study that focused on a specific region and a specific group of rangeland management partnerships. This contextual value contributed to realized interest and direct application of learning and results toward future sustainability efforts. We learned that it is possible to conduct a scientific study that is both context-specific but broadly relevant. In the end, our study may serve as a model for the kind of holistic, systems-oriented scientific inquiry that traverses the boundaries of local landscapes into regional and global relevance.

Lastly, we interwove the socio-cultural aspects of collaborative management into an ecological story. Our project exemplified an innovative approach to sustainability research that was rooted in systems thinking. While the majority of rangeland science studies evaluate ecological dimensions, and others evaluate social dimensions, it is rare for a study to incorporate the intersections of those dimensions. Sustainable management is not only about the ecological underpinnings of a place, but also about supporting the people and communities who hold direct relationships with those landscapes. In that sense, our project upheld a holistic approach that considers all three pillars of sustainability (Basiago 1998; Purvis et al. 2019). This integrated a "whole" story and addressed issues and questions that are too often left unattended in the typical silos of scientific research.

CONTINUING THE RE-IMAGINING

As part of studying and communicating a comprehensive rangelands story, I believe we should engage in the creative process of *re-imagining* rangelands. It is easy for new and seasoned rangeland stewards to follow the examples of the trails most-traveled. From ranchers and producers to scientists and consultants, we tend to follow the lead of our predecessors, our parents, grandparents, teachers, mentors, and supervisors. But in re-imagining, we need to also take those trails less-traveled. We need to elevate our heads, hands, and hearts to envision and reach for new ideas, innovations, and solutions to the challenges of today.

This study was but one brushstroke on the canvas. Every new scientific discovery adds to the body of knowledge upon which a sustainable future on Earth depends. We encountered and worked through challenges like the Coronavirus pandemic, and limitations like sample size and operating resources. Yet we forged forth, completed the journey, and have insight to share with the larger rangelands community. This required stepping out of the box, utilizing creative thinking, and recruiting transdisciplinary efforts.

To re-story our relationship with rangelands, we must first re-imagine them. What were they like before the Anthropocene, and what could they be in the next epoch of life on Earth? How might climate change shift rangeland conditions? If we can clearly imagine what rangelands could be, then we should be able to imagine a path transitioning us toward that state. This re-imaging may benefit from embodying an ecocentric point of view, where all aspects of nature: animal, land, water, and soil, have a vital role in the story. As we have identified, collaborative efforts across various spatial and temporal scales are likely key to this process.

I reiterate the call for more holistic research, that which braids the ecological, social, and economic dimensions of sustainability, so that we may learn more about the intersections of worlds and processes. A de-coupling of humans and nature is unlikely to yield applicable results. I reiterate the call for more transdisciplinary research, that which integrates the public and private sectors, crosses institutional and cultural boundaries, as well as welds collaboration among diverse fields of study and sources of knowledge and expertise. We have learned that sustainable food production can co-exist with natural resource management, that agriculture and conservation can be compatible ventures. However, future research endeavors need to be solution-focused, discovering win-win paths forward.

Lastly, I reiterate the call for love, that we work diligently with passion. We are emotional beings, and unless we lead our work with the heart to mediate the head and the hands, we may be misled or misinterpreted. We should let our language and our metaphors be reflections of our love for science, for nature, for the life we wish to create. Feelings and love should not be something set aside from how we write about and talk about science. They should be a visible force that unites all that we do, a community of people near and far who are working to identify ways in which humans and nature may proceed harmoniously and with awareness that our values and actions have consequences. The infinite feedback cycles which sustain and perpetuate a planet of life should be at the forefront of imaginings and storyings, in true recognition of the greater-than-human web. It is one of humility, reciprocity, respect, response-ability, and … love. So, let the re-imagining begin.

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APPENDIX A

Soil Units within which transects were located and field data was collected (Soil Survey Staff 2017).

Study Site	Treatment	Map Unit Symbol	Soil Unit Name
Coyote Ridge Natural Area	Grazed	47	Harlan fine sandy loam
		57	Kirtley loam
		205	Potts-Harlan complex
		85	Purner fine sandy loam
		74	Nunn clay loam
	Ungrazed	47	Harlan fine sandy loam
		57	Kirtley loam
		205	Potts-Harlan complex
Coalton Trail Open Space	Grazed	NuB	Nunn clay loam
		VcC	Valmont cobly clay loam
		MdB	Manter sandy loam
		KuD	Kutch clay loam
		CaB	Calkins sandy loam
	Ungrazed	VcC	Valmont cobly clay loam
Lowry Ranch	Grazed	NrB	Nunn-Bresser-Ascalon complex
		BvE	Bresser tructin sandy loam
		Lv	Loamy alluvial land
	Ungrazed	BvE	Bresser tructin sandy loam
		Lv	Loamy alluvial land
Soapstone Prairie Natural Area	Grazed	1, 2	Altvan loam
		10	Bainville-Keith complex
		65	Midway clay loam
	Ungrazed	65	Midway clay loam
		91	Renohill-Midway clay loam

APPENDIX B

Plant species identified across four Northern Colorado Front Range study sites and integrated in statistical analysis.

#	Species Code	Scientific Name	Common Name
1	ACHY	*Achnatherum hymenoides*	Indian ricegrass
2	ACMI2	Achillea millefolium	common yarrow
3	AGCR	*Agropyron cristatum*	crested wheatgrass
4	ALSI	*Alyssum simplex*	wild allysum/madwort
5	ALTE	*Allium textile*	textile onion
6	AMPS	*Ambrosia psilostachya*	western ragweed
7	ANGE	*Andropogon gerardii*	big bluestem
8	ANTEN	Antennaria Gaertn.	pussytoes
9	ANRO2	*Antennaria rosea*	rosy pussytoes
10	ARCA12	*Artemisia campestris*	field sagewort/wormwood
11	ARDR	*Artemisia dracunculus*	tarragon
12	ARFI	*Artemisia filifolia*	sand sagebrush
13	ARFR	*Artemisia frigida*	fringed sage/prairie sagewort
14	ARLU	*Artemisia ludoviciana*	white sagebrush
15	ARPO2	*Argemone polyanthemos*	prickly poppy
16	ARPU9	*Aristida purpurea*	purple threeawn
17	ASPU	*Asclepias pumila*	plains milkweed
18	ASMI10	*Astragalus missouriensis*	Missouri milkvetch
19	ASPE5	*Astragalus pectinatus*	narrowleaf milkvetch
20	ASTR7	*Astragalus tridactylicus*	foothill milkvetch
21	BOGR	*Bouteloua gracilis*	blue grama
22	BRIN	*Bromus inermis*	smooth brome
23	BRAR	*Bromus arvensis*	field brome
24	BRTE	*Bromus tectorum*	heatgrass
25	BUDA	*Bouteloua dactyloides*	buffalo grass
26	CALO	*Calamovilfa longifolia*	prairie sandreed
27	CAINH2	*Carex inops*	sun sedge
28	CAMI2	*Camelina microcarpa*	false flax
29	CANU4	*Carduus nutans*	plumeless thistle
30	CEDI3	*Centaurea diffusa*	diffuse knapweed
31	CHPR5	*Chenopodium pratericola*	desert goosfoot
32	CIOC2	*Cirsium ochrocentrum*	yellowspine thistle
33	CIUN	*Cirsium undulatum*	wavyleaf thistle
34	COAR4	*Convolvulus arvensis*	field bindweed
35	COBO	*Conyza bonariensis*	hairy fleabane
36	COUM	*Comandra umbellata*	bastard toadflax
37	COVI	*Coryphantha vivipara*	spinystar cactus
38	DAGL	*Dactylis glomerata*	orchardgrass
39	DAPU	*Dalea purpurea*	purple prairie clover
40	DESO2	*Descurania sophia*	tansy mustard
41	ELEL5	*Elymus elymoides*	bottlebrush squirreltail
42	ELCA4	*Elymus canadensis*	Canada wildrye
43	ERPU2	*Erigeron pumilus*	shaggy fleabane
44	ERBR5	*Eriogonum brevicaule*	shortstem buckwheat
45	ERCI6	*Erodium cicutarium*	redstem stork's bill
46	EREF	*Eriogonum effusum*	spreading buckwheat
47	ERUM	Eriogonum umbellatum	sulphur-flower buckwheat
48	ERDI4	*Erigeron divergens*	spreading fleabane
49	ERNA	*Ericameria nauseosa*	rubber rabbitbrush
50	EUBR	*Euphorbia brachycera*	horned spurge
51	EUES	*Euphorbia esula*	leafy spurge
52	EUSE4	*Euphorbia serpens*	creeping spurge
53	FEID	*Festuca idahoensis*	Idaho fescue
54	GECA3	*Geranium caespitosum*	Pineywoods geranium
55	GRSQ	*Grindelia squarrosa*	curlycup gumweed
56	GUSA2	*Gutierrezia sarothrae*	broom snakeweed
57	HECO	*Hesperostipa comata*	needle and thread
58	HEPU3	*Helianthus pumilus*	little sunflower
59	HEVI4	*Heterotheca villosa*	hairy golden aster
60	HYFI	*Hymenopappus filifolius*	fineleaf hymenopappus
61	IPLE	*Ipomoea leptophylla*	bush morning-glory

62	KRLA2	*Krascheninnikovia lanata*	winterfat
63	KOMA	*Koeleria macrantha (Koeleria cristata)*	priaire Junegrass
64	LAOC3	*Lappula occidentalis*	flatspine stickweed
65	LASE	*Lactuca serriola*	prickly lettuce
66	LIDA	*Linaria dalmatica*	dalmatian toadflax
67	LIIN2	Lithospermum incisum	narrowleaf stoneseed
68	LIPU	*Liatris punctata*	dotted gayfeather
69	LUAR	*Lupinus argenteus*	silvery lupine
70	LYJU	*Lygodesmia juncea*	rush skeletonplant
71	MAPI	*Machaeranthera pinnatifida (Xanthisma spinulosum*)	lacy tansyaster
72	MELU	*Medico lupolina*	black medick
73	MESA	*Medicago sativa*	alfalfa
74	MILI3	*Mirabilis linearis*	narrowleaf four-o'clock
75	NAVI4	*Nassella viridula*	green needlegrass
76	OESU3	*Oenothera suffrutescens*	scarlet beeblossom
77	ONAC	*Onopordum acanthium*	scotch thistle
78	OPPO	*Opuntia polyacantha*	plains pricklypear
79	PASM	*Pascopyrum smithii*	western wheatgrass
80	PIOP	*Picradeniopsis oppositifolia*	oppositeleaf bahia
81	PLPA2	*Plantago patagonica*	wooly plantain
82	POAN	Poa annua	annual bluegrass
83	POCO	*Poa compressa*	Canada bluegrass
84	POAR5	*Polygonum argyrocoleon*	silversheath knotweed
85	PSTE	*Psoralidium tenuiflorum*	slimflower scurfpea
86	ROWO	*Rosa woodsia*	woods' (American) rose
87	SATR12	*Salsola tragus*	Russian thistle
88	SECE	*Secale cereale*	cereal rye
89	SIAL2	*Sisymbrium altissimum*	tall tumbleweed
90	SIAN2	*Silene antirrhina*	sleepy silene
91	SPCO	*Sphaeralcea coccinea*	scarlet globemallow
92	SPCR	*Sporobolus cryptandrus*	sand dropseed
93	STRU3	*Stephanomeria runcinate*	desert wirelettuce
94	SYER	*Symphyotrichum ericoides*	white heath aster
95	SYFA	*Symphyotrichum falcatum*	white prairie aster
96	SYPO4	*Symphyotrichum porteri*	smooth white aster
97	TAOF	*Taraxacum officinale*	common dandelion
98	TEAC	*Tetraneuris acaulis*	stemless 4-nerved daisy
99	THME	*Thelesperma megapotamicum*	Hopi tea greenthread
100	TRDU	*Tragopogon dubius*	yellow salsify
101	TRPR	*Tragopogon pratensis*	Jack-go-to-bed-at-noon
102	TROC	*Tradescantia occidentalis*	prairie spiderwort
103	VEBR	Verbena bracteata	bigbract verbena
104	VETH	*Verbascum thapsus*	commmon mullein
105	VEBR	*Verbena bracteate*	bigbract vervain
106	VIAM	*Vicia Americana*	American vetch
107	VINU	*Viola nuttallii*	Nuttali's violet
108	VUOC	*Vulpia octoflora*	sixweeks fescue
109	YUGL	*Yucca glauca*	soapweed yucca
110	ZIPA2	*Zigadenus paniculatus*	foothill deathcamas

APPENDIX C

Soil health data summary, including % total nitrogen at a 0-10 cm depth (N_up) and at a 10-20 cm depth (N_low), % organic carbon at a 0-10 cm depth (OC_up) and at a 10-20 cm depth (OC_low), and water infiltration rates (Infil), in minutes, for each grazed and ungrazed transect across 4 study sites.

Site	Treatment	Year	N_up	N_low	OC_up	OC_low	Infil
CRN	Grazed	2020	0.23	0.16	2.59	1.70	0.71
CRN	Ungrazed	2020	0.10	0.09	1.07	0.79	5.22
CRN	Grazed	2020	0.13	0.16	1.22	1.29	9.18
CRN	Ungrazed	2020	0.13	0.12	1.19	1.01	2.59
CRN	Grazed	2020	0.14	0.12	1.30	1.08	10.14
CRN	Grazed	2020	0.12	0.12	1.16	0.92	14.97
CTO	Grazed	2020	0.22	0.17	2.33	1.70	2.71
CTO	Ungrazed	2020	0.15	0.13	1.76	1.23	7.65
CTO	Grazed	2020	0.26	0.21	2.99	2.22	3.70
CTO	Ungrazed	2020	0.16	0.13	1.97	1.36	6.48
CTO	Grazed	2020	0.21	0.14	2.07	1.38	0.15
CTO	Grazed	2020	0.24	0.13	2.46	1.28	0.17
LRR	Grazed	2020	0.11	0.05	1.18	0.55	1.50
LRR	Ungrazed	2020	0.08	0.07	0.83	0.69	0.96
LRR	Grazed	2020	0.12	0.08	1.39	0.81	0.91
LRR	Ungrazed	2020	0.10	0.08	1.02	0.74	1.42
LRR	Grazed	2020	0.10	0.05	1.03	0.46	4.98
LRR	Grazed	2020	0.13	0.07	1.44	0.70	1.78
SSN	Grazed	2020	0.31	0.24	3.02	2.20	10.38
SSN	Ungrazed	2020	0.13	0.11	1.04	0.71	7.05
SSN	Grazed	2020	0.37	0.18	3.62	1.61	6.79
SSN	Ungrazed	2020	0.18	0.11	1.71	0.90	6.48
SSN	Grazed	2020	0.21	0.14	2.14	1.32	19.43
SSN	Grazed	2020	0.19	0.14	1.87	1.24	20.90
CRN	Grazed	2021	0.27	0.20	2.88	2.08	1.44
CRN	Ungrazed	2021	0.11	0.09	1.18	1.01	1.45
CRN	Grazed	2021	0.14	0.13	1.38	1.08	4.09
CRN	Ungrazed	2021	0.11	0.10	1.25	1.08	2.19
CRN	Grazed	2021	0.16	0.14	1.57	1.21	3.08
CRN	Grazed	2021	0.15	0.12	1.30	1.05	2.21

CTO	Grazed	2021	0.21	0.16	2.47	1.82	6.47
CTO	Ungrazed	2021	0.17	0.13	1.83	1.31	0.42
CTO	Grazed	2021	0.25	0.22	2.94	2.51	5.69
CTO	Ungrazed	2021	0.16	0.12	1.70	1.23	0.43
CTO	Grazed	2021	0.34	0.14	2.04	1.31	0.14
CTO	Grazed	2021	0.21	0.14	2.09	1.37	0.16
LRR	Grazed	2021	0.11	0.07	1.15	0.79	2.06
LRR	Ungrazed	2021	0.07	0.07	0.80	0.72	2.49
LRR	Grazed	2021	0.10	0.10	1.23	1.06	3.01
LRR	Ungrazed	2021	0.09	0.06	1.04	0.59	1.47
LRR	Grazed	2021	0.12	0.09	1.34	0.89	4.70
LRR	Grazed	2021	0.16	0.09	1.74	0.97	2.12
SSN	Grazed	2021	0.26	0.23	2.51	2.07	5.75
SSN	Ungrazed	2021	0.14	0.11	1.08	0.72	6.26
SSN	Grazed	2021	0.33	0.21	3.19	1.91	6.80
SSN	Ungrazed	2021	0.19	0.14	1.54	0.92	2.20
SSN	Grazed	2021	0.20	0.16	2.01	1.45	6.24
SSN	Grazed	2021	0.20	0.15	1.92	1.38	8.23

APPENDIX D

Stakeholder questionnaire that functioned as Step 1 of Q methodology, which gathered initial perspectives and opinions for creation of Q concourse.

Q Method: Part 1 Questionnaire
Creating a List of Values and Perspectives

Please take the time to complete the following form to the best of your ability.

* For the purposes of this questionnaire, rangeland is defined as: landscapes dominated by grasses that are used by wild and/or domestic animals for foraging.

Date: Name:

Title/Role and Affiliation (if retired, most recent):

Total time spent in above position (months/years):

Total time spent working in your area of practice (months/years):

1. When you think of public or government-owned rangelands, what things immediately come to mind? Please list. Order of importance is not necessary.
2. What "material" benefits (things that sustain our physical existence or assets) do we receive from rangeland landscapes/ecosystems?
3. What "non-material" benefits (things that affect us emotionally, psychologically, or our quality of life) do we receive from rangeland landscapes/ecosystems?
4. In what ways are rangelands important for nature itself or our greater environment?
5. What do you value about public or government-owned rangelands?
6. What management activities do you think support the health of public or government-owned rangelands?
7. What management activities do you think could potentially harm the health of public or government-owned rangelands?

Thank you for your time and participation in this study!

APPENDIX E

Q sample consisting of 36 statements derived from initial stakeholder questionnaire. Each statement was allocated to an ES (ES) category (Díaz et al. 2018).

ES Category	Q Sample Statements (GOL = Government-owned lands)
Material	1. It is important that GOL continue partnerships with local private agriculture operations via leases.
	2. GOL should be maintained as multi-use, working landscapes.
	3. I believe ranchers need to be able to make a profit from leasing GOL.
	4. GOL should be used for research and educational purposes.
	5. Beef is an important product that comes from GOL.
	6. GOL should continue to be spaces for the production of food/meat and fiber/wool.
	7. GOL should also be used for the production of timber.
	8. I believe that GOL should also be used for oil & gas extraction.
	9. The balance between underuse and overuse of grazing areas should be a major focus of GOL management.
	10. GOL should continue to be used for crop agriculture.
	11. I believe that GOL should also be used for renewable energy production (i.e. wind, solar, and hydro power).
	12. Livestock grazing plays an important role in the maintenance of GOL.
Non-Material	1. We have a moral and ethical duty to preserve America's prairie and grassland ecosystems.
	2. I support public access of GOL for recreation opportunities like hiking, camping, and hunting.
	3. I value GOL for providing buffers to urban development & industrialization.
	4. Beauty and undisturbed open space are qualities that attract me to GOL.
	5. A benefit of GOL is public access to connect with nature for peace, renewal, solitude, and relaxation.
	6. GOL are important places for the public to exercise outdoors.
	7. GOL are important for preserving history and cultural heritage (i.e. ranching heritage).
	8. GOL should be managed for long-term sustainability goals with future generations in mind.
	9. There is spiritual value in GOL.
	10. GOL play a significant role in preserving wilderness and wild spaces.
Regulating	1. GOL provide essential wildlife habitat and migration corridors.
	2. Increasing carbon sequestration through grazing management should be a focus of GOL.
	3. Control of noxious and invasive species is a joint responsibility of GOL staff and ranchers.
	4. The top priority of GOL should be protecting natural resources.
	5. GOL are places for diverse plant species (i.e. native, rare, endangered) to thrive and be protected.
	6. Managing water quality and riparian areas should be a priority of GOL.
	7. GOL management should focus on maintaining natural ecosystem functions and processes.
	8. We need GOL for pollination and pollinator habitat.
	9. GOL should provide public access to clean air, natural, "green", and unpolluted landscapes.
	10. Soil health (stability and structure) is of major importance to GOL management.
	11. GOL can be used to help mitigate the effects of climate change.
	12. Maintaining plant and animal biodiversity is important to GOL management.
	13. Pesticides and herbicides should play a role in GOL management.
	14. Fire management should be a focus of GOL.

APPENDIX F

Management survey regarding management approaches that was provided to stakeholders in tandem with the Q sort exercise.

Q Method: Part 2 Management Survey

Please take the time to complete the following form to the best of your ability. Circle the answer that most represents your belief or opinion. Please complete every item and feel free to add a comment if you would like to clarify your response.
Date: **Participant ID:**

1. Management decisions on government-owned lands should be based on science (education & knowledge).

Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**

Comment:

2. Management decisions on government-owned lands should be based on research (surveying and monitoring).

Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**

Comment:

3. Management decisions on government-owned lands should be based on local knowledge (rancher experience and knowledge, intergenerational wisdom).

Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**

Comment:

4. Government-owned lands management should be holistic, incorporating ecological, social, and economic drivers and outcomes.

Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**

Comment:

5. Government-owned lands management should be flexible, and adaptive.

Strongly disagree	**Disagree**	**Neither agree nor disagree**	**Agree**	**Strongly agree**

Comment:

6. Enforcing rules and strict oversight of government-owned lands is important in their preservation.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Comment:

7. Setting goals and objectives is important for government-owned lands management.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Comment:

8. A hands-off approach, allowing unlimited use by grazing livestock would be detrimental to government-owned lands.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Comment:

9. A hands-off approach, allowing unlimited use for recreation would be detrimental to government-owned lands.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Comment:

10. I believe that the management of government-owned lands also entails dealing with conflicting interests.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Comment:

11. Government-owned lands should be places of collaborative and cooperative management, as opposed to prescriptive management.

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree

Comment:

Thank you for your time and participation in this study!

APPENDIX G

Annual precipitation and water-year precipitation data for Lowry Ranch, Arapaho County, Colorado, derived from the Byers station of the Colorado Climate Center and the Cocorah's Station ID CO-AR-314 on Lowry Ranch headquarters. Precipitation totals for each were compared to a 45-year average and classified accordingly as "wet," "average," or "dry."

Year	Annual Precip (in)	Annual Precip (cm)	Water Yr (in)	Water Yr (cm)	% of Normal	Class
2010	14.88	37.79	17.23	43.76	106	**wet**
2011	14.52	36.88	12.94	32.86	79	**dry**
2012	11.64	29.56	12.38	31.44	76	**dry**
2013	18.02	45.77	18.54	47.09	114	**wet**
2014	19.88	50.49	19.66	49.93	121	**wet**
2015	24.37	61.89	21.67	55.04	133	**wet**
2016	16.9	42.9	13.65	34.67	84	**average**
2017	11.85	30.09	11.2	28.44	69	**dry**
2018	12.54	31.85	9.69	24.61	59	**dry**
2019	20.17	51.23	16.8	42.67	103	**average**

APPENDIX H

Agent-Based Model grazing systems code from Netlogo 6.2.0.

```
; *********************************
; *** VARIABLES AND GLOBAL SETUP ***
; *********************************

extensions [ gis ]

; Variables available throughout the model
globals [
	NDVI10-layer
	NDVI11-layer
	NDVI12-layer
	NDVI13-layer
	NDVI14-layer
	NDVI15-layer
	NDVI16-layer
	NDVI17-layer
	NDVI18-layer
	NDVI19-layer
	NDVI20-layer
	rain-per-day
	base-rain-per-day
	ndvi-root
	correction
	init-all-mean-biomass
	mass-loss
	mass-gain1
	mass-gain2
	mass-gain3
	rain-per-season
	base-rain-per-season
	parcel_biomass

]

;Establishes a "breed" of agent that NetLogo can recognize; a plural term (cattle) and a singular term (cow)
breed [
	cattle
	cow
]

;Variables ascribed to each cattle/agent
cattle-own [
	mass
	current-parcel
]

;Variables ascribed to each individual patch
patches-own [
	NDVI
	biomass
	parcel-id
	biomass-on-patch
	ranch?
	parcels
```

```
        fence?
        k-of-r-coef
]

; ******************************
; *** DISPLAY AND AGENT SETUP ***
; ******************************
to setup
  ;Insert path to the location where the relevant pngs are stored
  set-current-directory "C:/Users/annaclar/Documents"

  ;Reset display to account for subsequent runs
  clear-all

  ;Make display invisible during setup phase
  no-display

  ;Initialize values to some important variables
  setup-parms

  ;Setup landscape from GIS landscape data
  setup-patches

  ;Import relevant parcel/fragmentation image
if Fragmentation-Level = "High Fragmentation" [
  import-pcolors "/LRR_pngs/LRR_High_Frag.png"
  ]
if Fragmentation-Level = "Medium Fragmentation" [
  import-pcolors "/LRR_pngs/LRR_Med_Frag.png"
  ]
if Fragmentation-Level = "Low Fragmentation" [
  import-pcolors "/LRR_pngs/LRR_Low_Frag.png"
  ]
if Fragmentation-Level = "No Fragmentation" [
  import-pcolors "/LRR_pngs/LRR_No_Frag.png"
  ]

  ;Identifies ranch from non-ranch patches using the imported fragmentation image
  find-parcels

  ;Stores a unique ID representing a given parcel into each patch. Patches in the same parcel will share a parcel id. This ID is
derived from the unique colors on the fragmentation map.
  save-parcels

  ;Identifies the boundary between parcels by finding areas where parcel-id/color changes between two adjacent patches. Draws
fence between parcels.
  save-edges

  ;Make display visible
  display

  ;Draws fence between parcels. Draws ranch patches on a scale of green according to NDVI
  redraw

  ;Initialize cattle properties and place herd in parcel with highest average biomass
  setup-cattle

  ;Reset ticks to zero to account for subsequent runs
  reset-ticks

  ;Calculate and print initial ranch biomass
  set init-all-mean-biomass mean [biomass] of patches with [ranch? = TRUE]
```

```
  type "Initial mean ranch biomass:" print init-all-mean-biomass

end

; *******************
; *** SETUP-PARMS ***
; *******************
;Global parameters relevant to cattle mass gain and forage regrowth
to setup-parms
  let K-of-R 0                    ; Used to calculate forage production for a given amount of rainfall
  set mass-gain1 1.00030          ;Coefficient for optimal weight gain of 0.30% of body mass, divided by ten to account for the 10
hours in each loop, reduced to account for external grazing variability (weather events),
https://extension.oregonstate.edu/animals-livestock/beef/grass-or-not-grass-calf-question
  set mass-gain2 1.00015          ;Coefficient for moderate weight gain of 0.15% of body mass
  set mass-gain3 1.00             ;Coefficient of 1 for maintanence level feeding
  set mass-loss  0.99967          ;Proportion of body mass retained upon weight loss, 0.33% lost per day:
https://franklin.tennessee.edu/wp-content/uploads/sites/54/2020/01/SP777-Managing-Malnourished-Beef-Cattle.pdf

  ;Historic weather values from the Colorado Climate Center
  if Precipitation-Level = "Wet" [set base-rain-per-day 1.341 ]    ;mm/day  ;average cumulative rainfall values from 2010-2020,
divided by 365 to find daily rainfall
  if Precipitation-Level = "Average" [set base-rain-per-day 1.059]  ;mm/day  ;average cumulative rainfall values from 2010-2020,
divided by 365 to find daily rainfall
  if Precipitation-Level = "Dry" [set base-rain-per-day 0.841] ;mm/day  ;average cumulative rainfall values from 2010-2020,
divided by 365 to find daily rainfall
end

; *********************
; *** SETUP-PATCHES ***
; *********************

to setup-patches

;Establish three precipitation levels and their corresponding NDVI years, select a random year from relevant precipitation level
category
  set ndvi-root ""
  if Precipitation-Level = "Wet" [
    set ndvi-root one-of [ "NDVI10" "NDVI13" "NDVI14" ]
  ]
  if Precipitation-Level = "Average" [
    set ndvi-root one-of [  "NDVI16" "NDVI19" ]
  ]
  if Precipitation-Level = "Dry" [
    set ndvi-root one-of [ "NDVI12" "NDVI17" "NDVI18" "NDVI20" ]
  ]

;Import the selected NDVI image, save NDVI value of each pixel to the corresponding patch in the model
  if Fragmentation-Level = "No Fragmentation" [
    let file-name ( word "/LRR_pngs/LRR_Less_Pastures_" ndvi-root ".png" )
    import-pcolors file-name
    ask patches [
      set NDVI pcolor ;saves the NDVI pcolor as "NDVI"
      set k-of-r-coef NDVI * 8 ;does not edit initial biomass... edits peak of curves for growing forage
    ]
  ]
  if Fragmentation-Level = "Low Fragmentation" [
    let file-name ( word "/LRR_pngs/LRR_Less_Pastures_" ndvi-root ".png" )
    import-pcolors file-name
    ask patches [
      set NDVI pcolor ;saves the NDVI pcolor as "NDVI"
      set k-of-r-coef NDVI * 8 ;does not edit initial biomass... edits peak of curves for growing forage
    ]
```

```
  ]
  if Fragmentation-Level = "Medium Fragmentation" [
    let file-name ( word "/LRR_pngs/LRR_Less_Pastures_" ndvi-root ".png" )
    import-pcolors file-name
    ask patches [
      set NDVI pcolor ;saves the NDVI pcolor as "NDVI"
      set k-of-r-coef NDVI * 8 ;does not edit initial biomass... edits peak of curves for growing forage
    ]
  ]
  if Fragmentation-Level = "High Fragmentation" [
    let file-name ( word "/LRR_pngs/LRR_More_Pastures_" ndvi-root ".png" )
    import-pcolors file-name
    ask patches [
      set NDVI pcolor ;saves the NDVI pcolor as "NDVI"
      set k-of-r-coef NDVI * 8 ;does not edit initial biomass... edits peak of curves for growing forage
    ]
  ]

 ;Establish local variables, coefficients from Fryxell and Boone
 let t1 0
 let t2 0
 let K-of-R 0
 let dV 0
 let Fmax 0.039   ; Fmax from Fryxell et al. (2005)

 ;Calculate biomass with formula 3 from Fryxell et al. (2005)
  ask patches [
    set K-of-R ( k-of-r-coef * base-rain-per-day )                           ; can use also Coefficient from Fryxell et al. (2005) = 80.872
    set t1 ( 1.0 - ( ( biomass + K-of-R ) / ( ( 2.0 * K-of-R ) + 0.001 ) ) )  ; The right side of formula 3 of Fryxell et al. (2005)
    set t2 ( biomass + K-of-R )
    set dV ( Fmax * t1 * t2 )
    set biomass dV * 40 ; simulates number of days passed before livestock put on system / NDVI values; indicates the start of the
biomass model
  ]

end

; **********************
; *** TO FIND PARCELS ***
; **********************
;Identifies ranch from non-ranch patches using the imported fragmentation image
to find-parcels
  ask patches with [pcolor != black] [
      set ranch? TRUE
  ]
  ask patches with [pcolor = black] [
      set ranch? FALSE
  ]

end

; ********************
; *** TO SAVE-EDGES ***
; ********************
  ;Identifies the boundary between parcels by finding areas where parcel-id/color changes between two adjacent patches.
to save-edges
  ask patches [
      let c pcolor
  ask neighbors [
      if pcolor != c [
        set fence? TRUE
      ]
```

```
    ]
  ]
end

; **********************
; *** TO SAVE-PARCELS ***
; **********************
;Stores a unique ID representing a given parcel into each patch. Patches in the same parcel will share a parcel id. This ID is
derived from the unique colors on the fragmentation map.
to save-parcels
  ask patches [
      set parcel-id pcolor
  ]
end

; *******************************
; *** TO REDRAW RANCH AND WATER ***
; *******************************
 ;Draws fence between parcels. Draws ranch patches on a scale of green according to NDVI
to redraw
  ;paint parcels and fence
      ask patches  [                    ;if a patch is a fence, it will be grey. if it's not a fence, it will be NDVI.
       ifelse fence? = TRUE [
          set pcolor 5] [
       ifelse Draw-Biomass? = FALSE
          [ set pcolor scale-color 56 NDVI 8.5 0 ]
          [ set pcolor scale-color 56 biomass 90 0 ]
     ]
    ]

; ********************
; *** TO DRAW WATER ***
; ********************
   ;Water points will be drawn centered on the coordinate pairs below. There are four lists for four fragmentation levels.
  let pairlist []
    if Fragmentation-Level = "No Fragmentation" [
    set pairlist [[251 194][117 319][121 414][253 51]]]

    if Fragmentation-Level = "Low Fragmentation" [
    set pairlist [[105 251][147 109][219 232][245 70][336 125][336 240][116 318]]]

    if Fragmentation-Level = "Medium Fragmentation" [
    set pairlist [[219 232][245 70][338 125][336 240][116 318][37 372][87 386][93 246][183 250][166 88][271 44][361 185][244
138]]]

    if Fragmentation-Level = "High Fragmentation" [
    set pairlist [[153 376][69 330][133 291][161 45][172 143][120 219][251 272][247 224][245 70][306 165][102 130][126
59][140 116][349 92][358 35][336 238][116 325][37 372][87 386][93 246][183 250][166 88][271 44][377 234][244 138][358
147]]]

  ;Draw water points using list of coordinate pairs
    let looplimit length pairlist - 1                          ;upper limit of the number of while loop iterations, reduced by
one because the first indexing position for a list is 0
    let index 0                                                ;index for the while loop
    while [index <= looplimit][                                ;"while the index is less than or equal to the number of
coordinate pairs"
      let currentpair item index pairlist                      ;assign currentpair variable to item number [index] from the
list of coordinate pairs
      let a item 0 currentpair                                 ;assign a to x coordinate (item 0 currentpair)
      let b item 1 currentpair                                 ;assign b to y coordinate
      let xcordupper (a) + 1                                   ;variables are created around the coordinates so that a 3x3 box
may be drawn around the center coordinate point
```

```
    let xcordlower (a) - 1
    let ycordupper (b) + 1
    let ycordlower (b) - 1

    ask patches with [pxcor >= xcordlower and pxcor <= xcordupper and pycor >= ycordlower and pycor <=
ycordupper]            ;Water source is painted blue in a square using the above cornerpoints
        [
        set pcolor sky + 1
        ask neighbors4                              ;Makes watersource even larger by accessing neighbors4, before
looping to the next coordinate pair
            [
            set pcolor sky + 1
    ]]
    set index index + 1                             ;increment index
  ]

end

; **********************
; *** TO-SETUP-CATTLE ***
; **********************

to setup-cattle
  ;Initialize local variables used in this section
  let a-water-patch 0
  let water-parcel-id 0
  let frag-level 0
  let water-list []

  ;Set a-water-patch variable to a list of all patches with water ([ pcolor = sky + 1 ])
  set a-water-patch patches with [ pcolor = sky + 1 ]

  ;Find the parcel with the highest average NDVI to place the cows in

  ;Create a list of all parcels by cycling through water patches and recording their parcel ID
  ask a-water-patch [
      set frag-level parcel-id              ;Set frag-level variable to the parcel ID of the looped water patch
      set water-list lput frag-level water-list  ;Append frag-level to water-list
    ]

  ;Remove duplicates from the list
  type "Dups   : " print length water-list  ; Print the contents of water list
  ;type "printing waterlist with duplicates" print water-list
  set water-list remove-duplicates water-list ; Removes duplicates from water list
  type "No dups: " print length water-list ; Confirm the removal of duplicates
  ;type "printing waterlist w/o duplicates" print water-list

  ; Step through the parcel IDs, calculating the average biomass of each, and outputting parcel ID of the parcel with highest
average biomass
  let best-parcel-id 0          ;Initialize best-parcel-id
  let high-parcel-biomass -999   ;Set arbitrary low value to compare real value against
  let i 0

  while [ i < length water-list ] [                     ;Step through the water list using iterator i
    let p-id item i water-list                         ;"item" operator requests entry number "i" from a list, water-list
    let avg 0                                     ;Initialize empty variable avg for use later
    set avg mean [ biomass ] of patches with [ parcel-id = p-id ]   ;Set avg to the average biomass of the currently looped parcel

    if avg > high-parcel-biomass [                     ;If the current average is higher than the current maximum, it replaces the
maximum and its ID is saved
      set best-parcel-id p-id                          ;Saves the ID of the current parcel to best-parcel-id, only if the current parcel
is replacing the best parcel
```

```
      set high-parcel-biomass avg                              ;Saves the new maximum value for further comparison
     ]
     set i i + 1                                       ;Increment iterator
    ]

  ;Directs cattle to start in parcel with highest NDVI
  set a-water-patch one-of a-water-patch with [ parcel-id = best-parcel-id ]

    set water-parcel-id [parcel-id] of a-water-patch                         ;Assigns variable to the desired parcel ID so that it may be
printed in console
    type "  water-parcel-id   " print water-parcel-id                        ;Prints ID in console
    display

  ;ask a-water-patch [ask patches in-radius 20[set pcolor yellow]]
  create-cattle Cattle-Number [ ;; create the cattle, then initialize their variables
    set mass 250 ; set a starting mass variable, kg or 550 lbs
    set color 34 ;set color of cattle
    set size 7  ; set size of cattle
    set shape "cow"

 let d distance a-water-patch ;set's d as distnce between cow and water patch
    set current-parcel parcel-id

 while [ d > 20 or current-parcel != water-parcel-id ] [  ;if distance to water is greater than 20 or if cow's patch outside the parcel,
then keep cycling for new setup spot
    setxy random-xcor random-ycor ;set a cow randomly
    set current-parcel parcel-id

      set d distance a-water-patch
      ]
    ]
end

; **********************
; *** TO-SHIFT-CATTLE ***
; **********************

to shift-cattle
   ;Initialize local variables used in this section
  let c-parcel [current-parcel] of one-of cattle ; store  id of current parcel with cattle
  let a-water-patch 0
  let water-parcel-id c-parcel ;Set water-parcel-id

  let frag-level 0
  let current-frag-level 0

  print c-parcel
  while [water-parcel-id = c-parcel] [ ;runs shift-cattle to select parcel that's not the current parcel

  set a-water-patch patches with [ pcolor = sky + 1 ] ;sets a-water-patch variable to all of patches with pcolor sky + 1
  set current-frag-level parcel-id

  ;Find the parcel with the highest average NDVI to place the cows in

  let water-list []  ; Create an empty list to fill with water patches
  ;Create a list of all parcels by cycling through water patches and recording their parcel ID
  ask a-water-patch [
      set frag-level parcel-id                  ;Set frag-level variable to the parcel ID of the looped water patch
      set water-list lput frag-level water-list  ;Append frag-level to water-list
    ]

  ;Remove duplicates from the list
```

```
 type "Dups   : " print length water-list  ; Print the contents of water list
 ;type "printing waterlist with duplicates" print water-list
 set water-list remove-duplicates water-list ; Removes duplicates from water list
 type "No dups: " print length water-list ; Confirm the removal of duplicates
 ;type "printing waterlist w/o duplicates" print water-list

 ; Step through the parcel IDs, calculating the average biomass of each, and outputting parcel ID of the parcel with highest
average biomass
 let best-parcel-id 0
 let high-parcel-biomass -999
 let i 0
 while [ i < length water-list ] [                              ;Step through the water list using iterator i
    let p-id item i water-list                                  ;"item" operator requests entry number "i" from a list, water-list
    let avg 0                                                   ;Initialize empty variable avg for use later
    set avg mean [ biomass ] of patches with [ parcel-id = p-id ]   ;Set avg to the average biomass of the currently looped parcel

    if avg > high-parcel-biomass [                              ;If the current average is higher than the current maximum, it replaces the
maximum and its ID is saved
      set best-parcel-id p-id                                   ;Saves the ID of the current parcel to best-parcel-id, only if the current parcel
is replacing the best parcel
      set high-parcel-biomass avg                               ;Saves the new maximum value for further comparison
    ]
    set i i + 1                                                 ;Increment iterator
   ]

    set a-water-patch one-of a-water-patch with [ parcel-id = best-parcel-id ]   ;Assign a-water-patch to one of the water patches in
the desired parcel that was selected above
    set water-parcel-id [parcel-id] of a-water-patch                            ;Assigns variable to the desired parcel ID so that it may be
printed in console
    type "  water-parcel-id   " print water-parcel-id                            ;Prints ID in console
    display
 ]

 ask cattle [

 let d distance a-water-patch ;set's d as distnce between cow and water patch
    set current-parcel parcel-id

 while [ d > 20 or current-parcel != water-parcel-id ] [  ; if distance to water is greater than 20 or if cow's patch outside the parcel,
then keep cycling for new setup spot
    setxy random-xcor random-ycor ;set a cow randomly
    set current-parcel parcel-id

    set d distance a-water-patch
      ]
    ]
end

; *************
; *** TO-GO ***
; *************

to go
 if not any? turtles [ stop ]
 grow-forage ;Tells the landscape forage to grow according to precipitation
 let first-hour? TRUE
 let all-mean-biomass mean [biomass] of patches with [ranch? = TRUE]
 repeat 10 [ ;hourly loop to represent 10 hours a day that cows eat-forage, with each tick, cows move and eat-forage 10x
    move-cattle ;; cattle move randomly through the entire world
    eat-forage all-mean-biomass first-hour? ;; cattle gain mass from forage
    set first-hour? FALSE
    ]
```

```
  tick
  ;update-plots
  check-table
  redraw
  if ticks >= 150 [stop]
end

; ******************
; *** MOVE-CATTLE ***
; ******************

to move-cattle
  let parcel-patches 0
  let temp-parcel-ID [current-parcel] of one-of cattle ;Identifies the current parcel of the herd
  set parcel-patches patches with [parcel-id = temp-parcel-ID] ;Creates a list of patches in this parcel

  ask cattle [
    move-to patch-here  ;; go to patch center

  let p 0
  set p one-of parcel-patches ;selecting one patch from the parcel and name it p
  if [biomass] of p > biomass [ ;if biomass of newly identified patch > than current patch, then cow moves to new patch
    face p
    move-to p
    ]
   ]

end

; ******************
; *** CHECK-TABLE ***
; ******************

to check-table
  let parcel-mean-biomass 0
  let heterogeneity 0
  let all-mean-biomass mean [biomass] of patches with [ranch? = TRUE] ; mean of entire landscape
  ask one-of cattle [
       set parcel-mean-biomass mean [ biomass ] of patches with [ parcel-id = [ current-parcel ] of myself ]
       let cattle_mean mean [mass] of cattle
       ifelse ( mean [ biomass ] of patches with [ ranch? = true ] ) > 0
         [ set heterogeneity ((standard-deviation [ biomass ] of patches with [ ranch? = true ] * standard-deviation [ biomass ] of
patches with [ ranch? = true ] ) / ( mean [ biomass ] of patches with [ ranch? = true ] ) )]
         [ set heterogeneity 0 ]
       type " All mean biomass: " type precision all-mean-biomass 3 type " Parcel mean biomass: " type precision parcel-mean-
biomass 3 type " Shift threshold: " print precision (all-mean-biomass * 0.3) 3 type " Average cattle mass: " type precision
cattle_mean 3 type " Vegetation heterogeneity:" type precision heterogeneity 3
       ;Calculates the average biomass of the whole landscape and compares it to the current parcel; If the current parcel is below a
certain quality threshold, the herd moves to a different parcel

     if parcel-mean-biomass < all-mean-biomass * 0.5 ;when mean biomass of current patch falls below 50% of landscape mean
biomass, then shift cattle.

       [shift-cattle
        print "shifting cattle"
    ]
  ]
end


; *****************
; *** EAT-FORAGE ***
```

```
; ******************

;each tick is 1 day with 10 hours grazing, take 2% (daily intake) convert to grams, divide by number of hours grazed, then subtract from biomass (which is set in grow-forage)

to eat-forage [ all-mean-biomass first-hour? ]
    let hourly-intake-g 625 ;a 250kg cow's intake for approx 10 hours per day at 2.5% of body weight (total biomass, not only dry matter), 6250 grams/day (625 g/grazing hour) over 10 hours.
    if first-hour? = TRUE [
   ask patches [
      set biomass-on-patch biomass * 29.3 * 29.3 * 0.2  ;how much biomass is available per 30 x 30 m (NDVI pixel) COMBINED WITH (rbb/08/22):  ;common value used (several of Randy's projects), to represent proportion of NPP available to livestock, based on utilization of about 30% on rangelands. This is a measure for conservation/invasive species/etc, reasons why utilization is only 30%
     ]
      set parcel_biomass mean [ biomass ] of patches with [ parcel-id = item 1 [ current-parcel ] of cattle ]      ; Updating parcel_biomas just once per day, and stored as a global
   ]

   let all_mean_biomass_high (init-all-mean-biomass * 0.90) ;When current pasture biomass is 90% or greater than ranch average biomass, cattle gain weight at the "high" rate
   let all_mean_biomass_med (init-all-mean-biomass * 0.70) ;When current pasture biomass is between 70% and 90% of ranch average biomass, cattle gain weight at the "medium" rate
   let all_mean_biomass_low (init-all-mean-biomass * 0.525) ;When current pasture biomass is between 5.25% and 70% of ranch average biomass, cattle maintain their weight
   let all_mean_biomass_under (init-all-mean-biomass * 0.5) ;When current pasture biomass is between 50% and 5.25% of ranch average biomass, cattle lose weight at the "weight loss" rate

    ask cattle [
      ifelse biomass-on-patch > hourly-intake-g
        [
         set biomass-on-patch biomass-on-patch - hourly-intake-g
         set biomass (biomass-on-patch / 0.2) / (29.3 * 29.3) ; get back to square m scale value so interface shows patch color change based on consumption
        ]
        [
         set biomass-on-patch 0
         set biomass 0
        ]
      if mass < 375 [ ;This section adds or subtracts varying quanities of mass to the cattle determined by their location in a set of intervals representing parcel forage quality and quantity
        if parcel_biomass > all_mean_biomass_high
         [set mass ( mass * mass-gain1 )]
        if parcel_biomass >= all_mean_biomass_med and parcel_biomass < all_mean_biomass_high
         [set mass ( mass * mass-gain2 )]
        if parcel_biomass >= all_mean_biomass_low and parcel_biomass < all_mean_biomass_med
         [set mass ( mass * mass-gain3 )]
        if parcel_biomass >= all_mean_biomass_under and parcel_biomass < all_mean_biomass_low
         [set mass ( mass * mass-loss )]
      ]
    ]


end

; ******************
; *** GROW-FORAGE ***
; ******************

to grow-forage
 ;Establish useful local variables
 let t1 0
```

```
 let t2 0
 let K-of-R 0
 let dV 0
 let Fmax 0.039 ; rmax from Fryxell et al. (2005)

 decide-dekade ; sets the 'correction' vartiable to the idex of the current decade

 correct-precip ;Converts base-rain-per-day to corrected rain-per-day
 set base-rain-per-season base-rain-per-season + base-rain-per-day ;Adds daily uncorrected rain value to seasonal sum
 set rain-per-season rain-per-season + rain-per-day ;Adds daily corrected rain value to seasonal sum

  ;Calculate biomass growth with formula 3 from Fryxell et al. (2005)
 ask patches [
    set K-of-R ( k-of-r-coef * rain-per-day ) ; k-of-r-coef derived from NDVI,
    ; (can use also K of R Coefficient from Fryxell et al. (2005) = 80.872, if another metric such as NDVI is unavailable)
    set t1 ( 1.0 - ( ( biomass + K-of-R ) / ( ( 2.0 * K-of-R ) + 0.001 ) ) ) ; The right side of formula 3 of Fryxell et al. (2005)
    set t2 ( biomass + K-of-R )
    set dV ( Fmax * t1 * t2 )
    if dV < 0 [ set dV 0 ] ; if rate of growth in the landscape drops below zero, then the rate is corrected to 0 so that growth does
not occur until conditions change in the next tick
    set biomass biomass + dV
  ]
end

to constant
  set Dek1-10 5
  set Dek11-20 5
  set Dek21-30 5
  set Dek31-40 5
  set Dek41-50 5
  set Dek51-60 5
  set Dek61-70 5
  set Dek71-80 5
  set Dek81-90 5
  set Dek91-100 5
  set Dek101-110 5
  set Dek111-120 5
  set Dek121-130 5
  set Dek131-140 5
  set Dek141-150 5
end

to observed
  set Dek1-10 4
  set Dek11-20 5
  set Dek21-30 6
  set Dek31-40 6
  set Dek41-50 5
  set Dek51-60 9
  set Dek61-70 3
  set Dek71-80 3
  set Dek81-90 3
  set Dek91-100 8
  set Dek101-110 8
  set Dek111-120 3
  set Dek121-130 5
  set Dek131-140 9
  set Dek141-150 5
end

to dry-spring
  set Dek1-10 1
```

```
  set Dek11-20 0
  set Dek21-30 0
  set Dek31-40 1
  set Dek41-50 2
  set Dek51-60 3
  set Dek61-70 4
  set Dek71-80 6
  set Dek81-90 6
  set Dek91-100 7
  set Dek101-110 8
  set Dek111-120 8
  set Dek121-130 9
  set Dek131-140 10
  set Dek141-150 8
end

to wet-spring
  set Dek1-10 10
  set Dek11-20 9
  set Dek21-30 8
  set Dek31-40 9
  set Dek41-50 7
  set Dek51-60 6
  set Dek61-70 0
  set Dek71-80 0
  set Dek81-90 1
  set Dek91-100 3
  set Dek101-110 2
  set Dek111-120 4
  set Dek121-130 4
  set Dek131-140 5
  set Dek141-150 6
end

to monsoon
  set Dek1-10 6
  set Dek11-20 5
  set Dek21-30 5
  set Dek31-40 3
  set Dek41-50 1
  set Dek51-60 0
  set Dek61-70 0
  set Dek71-80 5
  set Dek81-90 7
  set Dek91-100 8
  set Dek101-110 9
  set Dek111-120 8
  set Dek121-130 7
  set Dek131-140 5
  set Dek141-150 4
end

to variable
  set Dek1-10 8
  set Dek11-20 4
  set Dek21-30 2
  set Dek31-40 1
  set Dek41-50 7
  set Dek51-60 3
  set Dek61-70 3
  set Dek71-80 9
  set Dek81-90 4
```

```
  set Dek91-100 2
  set Dek101-110 0
  set Dek111-120 3
  set Dek121-130 4
  set Dek131-140 6
  set Dek141-150 10
end

to decide-dekade
  set correction 0
  if ticks > 0 and ticks <= 10 [ set correction Dek1-10 ]
  if ticks > 10 and ticks <= 20 [ set correction Dek11-20 ]
  if ticks > 20 and ticks <= 30 [ set correction Dek21-30 ]
  if ticks > 30 and ticks <= 40 [ set correction Dek31-40 ]
  if ticks > 40 and ticks <= 50 [ set correction Dek41-50 ]
  if ticks > 50 and ticks <= 60 [ set correction Dek51-60 ]
  if ticks > 60 and ticks <= 70 [ set correction Dek61-70 ]
  if ticks > 70 and ticks <= 80 [ set correction Dek71-80 ]
  if ticks > 80 and ticks <= 90 [ set correction Dek81-90 ]
  if ticks > 90 and ticks <= 100 [ set correction Dek91-100 ]
  if ticks > 100 and ticks <= 110 [ set correction Dek101-110 ]
  if ticks > 110 and ticks <= 120 [ set correction Dek111-120 ]
  if ticks > 120 and ticks <= 130 [ set correction Dek121-130 ]
  if ticks > 130 and ticks <= 140 [ set correction Dek131-140 ]
  if ticks > 140 and ticks <= 150 [ set correction Dek141-150 ]
end

to correct-precip
  if correction = 0 [set rain-per-day 0.0]
  if correction = 1 [set rain-per-day base-rain-per-day * 0.2]
  if correction = 2 [set rain-per-day base-rain-per-day * 0.4]
  if correction = 3 [set rain-per-day base-rain-per-day * 0.6]
  if correction = 4 [set rain-per-day base-rain-per-day * 0.8]
  if correction = 5 [set rain-per-day base-rain-per-day * 1.0]
  if correction = 6 [set rain-per-day base-rain-per-day * 1.2]
  if correction = 7 [set rain-per-day base-rain-per-day * 1.4]
  if correction = 8 [set rain-per-day base-rain-per-day * 1.6]
  if correction = 9 [set rain-per-day base-rain-per-day * 1.8]
  if correction = 10 [set rain-per-day base-rain-per-day * 2.00]
end
```