THESIS

CATTLE AS PARTNERS IN CONSERVATION:

THE EFFECTS OF GRAZING ON INDICATORS OF RANGELAND HEALTH

Submitted by

Anna Clare Monlezun

Department of Animal Sciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2018

Master's Committee:

Advisor: Ryan Rhoades
Co-Advisor: Jason Ahola

Joe Brummer
Paul Meiman
Phillip Turk

ABSTRACT

CATTLE AS PARTNERS IN CONSERVATION:

THE EFFECTS OF GRAZING ON INDICATORS OF RANGELAND HEALTH

For centuries, the natural ecology of rangelands has supported large herds of herbivores. The partnership between these herbivores and the land has usually been, and can continue to be a sustainable one. However, the debate over the use of public lands for cattle grazing continues to intensify. Scientific literature and corresponding recommendations regarding cattle management on rangelands are conflictual. This thesis proposes that the resolution is not to remove grazing from rangelands, but to effectively manage grazing for specific landscapes and ecosystem types. Grassland ecosystems are highly dynamic and maintained by continuous adaptation to biotic and abiotic events. Therefore, strategic grazing management that also incorporates dynamic adaptation to environmental conditions may produce successful outcomes with respect to cattle grazing and sustainable land management.

The objective of this study was to compare selected indicators of rangeland health in ungrazed areas to adjacent areas where strategic grazing management had been implemented. It was hypothesized that compared to areas excluded from grazing, areas where strategic grazing was implemented would exhibit: increased nutrient cycling by integration of organic carbon and nitrogen into the soil, increased abundance of native graminoids and native forbs, and reduced abundance of noxious weeds. It was hypothesized that forage quality would follow a particular pattern because of grazing: a decrease in forage quality shortly following grazing, an increase in forage quality with a period of rest, and a decrease in forage quality with continued absence of grazing.

Paired grazed and ungrazed areas were established in 6 pastures across a grassland valley on Colorado’s Front Range, which had not been grazed for at least 10 years. In 2016, baseline data were collected from both grazed and ungrazed areas prior to grazing. Subsequent data were collected in 2017, following strategic grazing management and adequate rest. Linear mixed models were used to compare differences between grazed and ungrazed areas. Results indicated no significant differences in soil organic carbon ($P = 0.97$), total nitrogen ($P = 0.64$), relative abundance of native graminoids ($P = 0.15$) or relative abundance of forbs/subshrubs ($P = 0.74$) between grazed and ungrazed areas. In regards to forage quality, crude protein was lower ($P = <0.01$) and neutral detergent fiber was higher ($P = 0.05$) at the conclusion of the grazing period, but acid detergent fiber did not differ ($P = 0.51$) in grazed versus ungrazed areas. Additionally, areas that were grazed in the spring and received 2-3 months of rest demonstrated higher forage quality than areas that were grazed in the fall and received 9-10 months of rest as indicated by higher crude protein ($P = 0.03$), and a tendency for lower neutral detergent fiber ($P = 0.06$), but no difference in acid detergent fiber ($P = 0.97$). Chi-square tests for soil and vegetation variables detected no variation between pairs of grazed and ungrazed areas across the landscape. This suggested that the biological variability within and between grazed and ungrazed areas was minimal, and that the strategic grazing regime, which incorporated flexibility in grazing intensity, stocking density, and season of grazing, produced homogeneous effects across all pastures.

The results of this study indicated that one year of strategic grazing does not significantly affect select soil and vegetation variables and that further study is needed in order to inform

application. As part of a long-term project, this collection of data and analysis was important for the initiation of a collaborative monitoring process, which will eventually determine if strategic grazing management proves to be helpful or harmful for land management goals. Continued research will aid ranchers and land managers in developing collaborations so that cattle might serve as partners in the conservation of rangelands, while maintaining animal performance and beef production objectives. Effective livestock management is key. Therefore, the human decision-making dimension is imperative to incorporate in future grazing studies.

ACKNOWLEDGEMENTS

I would like to first and foremost thank my family, especially my husband, Giovanni, and my parents, Malcolm and Ursula, for their never ending support of my dreams. I could not have attempted this endeavor if it was not for their care and sustenance, both morally and practically.

Secondly, I would like to thank my graduate advisors, committee members, and Jim Self of the soils testing lab for believing in me and challenging me to do better, when I thought I was already doing my best. Thank you for your patience and willingness to accompany me on this project, and for your contribution to my experience of learning and discovery.

This study would not have been possible without the committed collaboration of Sylvan Dale Ranch owner, David Jessup, and cattle manager, Greg Boylan. Thank you for putting in extra long days for the sake of managing cattle under the constraints of scientific study. Thank you for countless communication threads and days ending in dirty boots and sweaty hats. Thank you for believing in restorative ranching and the sustainable use of cattle on conservation lands.

Much respect and gratitude goes to the City of Fort Collins' Natural Areas Department for stepping out on a limb and joining us in this new territory of strategic grazing management. Thank you for believing in the potential of domestic herbivores to play a positive role in rangeland management. Thank you for all of the time you dedicated to meetings, fieldwork, and logistical needs of this study. Your team is truly a force of innovation, passion, and service.

Lastly, I would like to dedicate this thesis to my son, Gavino Malcolm Taormina, who was born during the heart of this project, and who inspires me every day to continue to plant firm roots while sprouting fearless wings.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

According to the Association of Public and Land Grant Universities, the mission of a land grant university is to teach agriculture. This includes the cultivation of land and soil to rear animals for food production. As a student at Colorado State University, one cannot help but be inspired by the beauty of the state's natural resources and natural heritage. However, due to society's choices in land use, it is apparent that some of Colorado's forests and grasslands have succumbed to a substantial amount of degradation or have been permanently modified. The answer to past mistakes in overgrazing, to which Colorado has not been immune, is not to remove cattle from the land entirely, but rather to appropriately and effectively manage cattle for various land and ecosystem types. According to the 2012 Agriculture Census, Colorado livestock products totaled $3.7 billion in cash receipts, of which cattle made up 75%. Colorado was ranked 10th in the country for total cattle on inventory and 4th for the largest exporter of beef.[1] Therefore, a large portion of this region's local economy and culture depend upon the cattle industry.

The continuous debate between ranchers and conservationists could be resolved if leaders and scientists on both sides were to find a solution that benefited all. This research project intends to contribute to that body of scientific knowledge, so that managers may develop ways in which cattle aid in the resiliency and sustainability of our rangelands, while maintaining optimal animal performance and beef production objectives.

It is this author's belief that the world's rangelands, and especially those in the state of Colorado, are natural treasures. They are home to some of the largest herds of animals on the

[1] United States Department of Agriculture. 2012 Census of Agriculture. AC-12-A-6.

planet and provide respite and inspiration for individuals who wish to reconnect with their own primitive roots in the wild. By human error, many rangelands are in poor condition, but are not irrevocably altered. Furthermore, humans, as inhabitants of this earth, have the obligation to facilitate the restoration of these lands as carefully as they tend their own gardens and lawns. It is the combination of wisdom and experience along with knowledge and science that will provide the tools with which to embark on this journey of restorative ranching, a necessary shift in the land management paradigm.

CHAPTER 1: LITERATURE REVIEW

INTRODUCTION

This review of the literature begins by the presentation of the history behind current conflicts of interest between land use and land conservation on North America's rangelands. In terms of research methods and outcomes, key indicators of rangeland health such as soil, vegetation, and forage quality are discussed. The challenges of designing research around land use for cattle grazing are then delineated. This is followed by highlighting the human decision-making dimension and the role of management in livestock grazing. In conclusion, suggestions as well as questions for future research endeavors are proposed as a segue to Chapter 2, which has been formatted for submission to peer-reviewed journals.

THE EVOLUTION OF A DEBATE

As our world's private farm and ranch land is sold to urban and non-agriculture development at an extraordinary pace, it has become more important than ever that we carefully and optimally manage our remaining open space and rangelands.[1; 2] The livestock industry, especially the cattle industry, has had a longstanding relationship with United States government public land management, including the Bureau of Land Management and the United States Forest Service, to for livestock grazing. However, over the last 30 years, the debate over the use of public lands has intensified.[3]

The debate over private grazing on public lands is an issue of "land-sparing" versus "land-sharing." As indicated by the United Nation's project, *Sustainable Development in the 21st Century*, "For the first time at a global level, food production faces multiple limiting factors for key resources such as land, water, energy, and inputs. We must use this challenge to stimulate creative innovation."[4] The growing global population's rising demands for livestock products and by-products will continue to instigate competition for land and water between food production, feed production, bioenergy sources, development, and recreation. In turn scarcities in land and water will require that livestock management be more efficient in its use of these and other natural resources to avoid negative outcomes on sustainability.[5] It is here that large herbivores, specifically ruminants with their plant-based diets, may become allies, not foes. By consuming highly fibrous plants and dry roughage from non-arable landscapes and transforming them into nutritious meat and dairy food products for human consumption, ruminants can produce food products and by-products from locations that could never sustain traditional crop agriculture.[6] The challenge, however, is doing so without compromising environmental sustainability. It is known that over half of the world's "usable" land is already occupied by agriculture, but what if it were possible to increase that total amount of usable land simply by modifying the methods with which it is used?[7]

Therefore, what does the future hold for the management of these rangelands and what will be the effect on livestock and ranching industries? How do we determine the most effective way to maintain healthy rangelands, including public lands, as working landscapes? It seems that even with all of our advances in bovine genetics and nutrition, meat science and disease control; there may be wisdom in looking back. Looking back to the way large herbivores thrived on the land before man's intervention could provide insight. After all, before man, the dynamics of the natural world forced balance upon the land and its inhabitants. Therefore, if the goal is sustainable management of cattle on the land, then perhaps a valid strategy would be to mimic what we observe of other ruminant species in nature. Because our modern day bovine, or cattle (*Bos indicus* and *Bos taurus*), are no longer observable in their natural habitat, one must reach back to previous eras and the movement of large ungulates across the earth, in order to understand this balance.[8]

THE LARGE HERBIVORE ROLE IN RANGELAND BALANCE

To take this discussion to its origin, one must examine the work done in the late 1950's, when the first ecological research was conducted in Serengeti National Park, the home of more than half a million wild animals, living much the same way they had lived for thousands of years. Specifically, the work of Richard Bell brought to light the intricacies of the relationship between large herbivores, the vegetation that fed them, and their migratory patterns.[9] Bell claimed that the most important relationship in the Serengeti ecosystem was the use of graminoids, herbaceous plants with grass-like morphology, and forbs, herbaceous flowering plants, by grazing ungulates, hooved animals, who comprised an impressive 90% of the mammalian biomass in this region.[9]

It is a particular ability of ruminant ungulates to survive on plants containing high proportions of cell wall (fiber). Actually, the larger the animal, the more adaptive it is to both tolerate and thrive off such plants. However, this is not merely a discussion of survival, but a discussion about how these ruminant herbivores and their grazing habits actually filled a necessary role in the balance of their ecosystem.

Due to their movement in herds across the landscape, large herbivores had less opportunity to be selective than their smaller herbivore counterparts, so they grazed the taller fibrous grasses and upper canopy of forage. This grazing and trampling in turn, cleared a path in the dense vegetation to expose the lower canopy, filled with more concentrated, nutrient dense herbs and forbs for those smaller, more selective grazers to follow.[9] In effect, the ideal heterogeneity of the plant communities was maintained, since various groups of species moved across the landscape by the influence of forage presence and seasonal weather conditions.[9; 10] In the Serengeti, this succession of grazing behavior can be observed in the wildebeest (*Connochaetes taurinus*) and gazelle (*Gazella thomsoni*) relationship.[9] Even in the present day American West, the same can be observed between domestic cattle (*Bos taurus*) and wild elk (*Cervus canadensis*). Research on strategic cattle grazing suggests that elk tend to graze in areas that overlap with areas where cattle had previously grazed.[11-13] Furthermore, the addition of cattle to rangeland of low forage quality has been shown to improve winter forage for elk thereby increasing herd numbers over time.[14] This mirrors the natural migratory succession and cohabitation of diverse species that Bell observed in Africa.

In a similar fashion, the American Bison (*Bison bison*) was previously an essential member of our grassland ecosystems of the central and western United States.[10] It was only 160 years ago that our grasslands were inhabited by free-ranging herds of these large ruminants.[15] Paradoxical to claims that contest the sustainability of grazing, these grasslands were able to sustainably support an even greater amount of herbivore biomass than any other land-based ecosystem.[10; 15] Today, our rangelands not only lack the massive herds of bison, but also the vital disturbance and defoliation they brought to the ecosystem by their migratory behavior.[10]

Natural reserves such as the Serengeti and Yellowstone National Park provide an indication of what natural relationships between large landscapes and large herds of herbivores might have been.[16]

On the Konza Prairie Research Institute in Kansas, a group of 30 bison was reintroduced in 1987.[15] They were allowed to freely roam and procreate to a certain limit so that their numbers did not overpopulate the allotted grazing lands.[15] This allowed scientists and researchers to study the impact of these large herbivores in their natural habitat.[15] After nearly ten years of data collection, it was concluded that grazing activity of bison improved the overall biodiversity of the ecosystem, both at the plant and soil levels.[15] Furthermore, it was stressed that the large herbivore's role in grassland ecosystems is a vital one.[15] Due to major similarities in foraging behavior, cattle may be the obvious solution for lands on which it would be difficult or impossible to manage bison.[15]

Moreover, domesticated cattle in pastoral systems controlled by man could potentially play the role of the wildebeest or the bison, if only they were allowed to mimic their wild counterparts. The natural grazing behavior of cattle and their selection of graminoids over forbs is very similar to that of the plains bison or the savannah wildebeest. In fact, the grazing of domesticated herbivores is also an ancient lifestyle. It has been practiced harmoniously in shared grazing areas of migratory wild herbivores for centuries. It has been observed that these pastoral effects can maintain ecosystem balance, instead of being in conflict with it.[9] It appears that the strategy in managing these domesticated species is the key to achieving ecologically equivalent impacts as their wild counterparts.

ORIGINS OF CONSERVATIONISM

Unfortunately, not all pastoral efforts have created such positive effects on Earth's landscapes. While some long-term grazing strategies have maintained ecosystem balance, others have created ecosystem destruction. As a result, conservation laws have filled the role of reversing the ill effects of poorly managed lands. However, this is not a modern concept. Remarkably, the earliest record of conservationist sentiments can be found in a piece of literature from the 4th millennium B.C., *The Epic of Gilgamesh* .[17] It told of the effects of uncontrolled deforestation in the Middle East. It was well known by this time that deforestation led to soil erosion, and that empires founded on hydraulic and agricultural advances already had to import timber, since their own resources were irreparably exploited.[17]

A couple thousand years later in Greece, Aristotle's biographer, Theophrastus, correlated deforestation with a decrease in rainfall, a form of manufactured climate change.[17] Finally, by the 13th Century A.D., so much of Europe's forests had been cleared for timber due to agricultural, industrial, and military motives, environmentalist attitudes were born.[17] Particularly in Germany, we find the first conservation law, where forests were protected from clearing except by special permission.[17] Furthermore, in the 14th Century A.D., Henry VII ruled that deforested lands, converted into agriculture, be returned to forests.[17]

Then came Christopher Columbus and post-classical colonialism, where he observed climate change occurring on tropical islands. Similar to Theophrastus, Columbus documented the steep decline of rainfall and mist after aggressive deforestation activity in new territories.[17] He concluded that future colonial expansion and human survival depended on environmentalism and a conservationist mentality.[17] His efforts to disseminate this important knowledge were in vain, however, as any modern citizen is aware of the catastrophic results of European expansion into the Americas: deforestation, erosion, natural resource exploitation, and desertification.

Due primarily to westward expansion and the Homestead Act of 1862, public grasslands were allocated to pioneers for growing crops.[18] However, with a growing western population came a greater demand for meat products. By 1880, unlimited livestock grazing on homesteaded land caused a devastating decrease in the stocking capacity of rangelands.[18]

Fast-forward to the 21st century, where man and nature continue their endemic battle. While today there are over 150 registered environmental and conservation organizations in the United States, the "fountainhead of the North American conservation movement" is G. P. Marsh and his publication in 1864, *Man and Nature*.[17] In the early 1900's, Theodore Roosevelt launched the first nationwide conservation effort in U.S. history, and he was accompanied by Henry David Thoreau, John Muir, Aldo Leopold and others in an effort to shift the paradigm from anthropocentrism to ecocentrism.[19]

Finally, in 1934, the Taylor Grazing Act initiated much needed control over North America's grazing lands.[18] Overall, there have been three distinct conservation periods in the United States, Conservationist/Preservationist, Ecocentrist, and Political/Deep Ecology.[20] It wasn't until the 1970's that Congress passed environmental legislation, marked today by Earth Day, where suddenly conservationism became intertwined in an institutional, bureaucratic web.[19] More than two decades later, society is still grappling with how to harmoniously manage economy and conservation.

RANCHING AND CONSERVATION

It has taken nearly 200 years for the ecological pendulum to reach the opposing extremes of ranching and conservation and finally rest somewhere in the middle. It is here and now where the wisdom of experience and science may finally work together for the benefit of all. If conservation means protection, guardianship, repair, upkeep, maintenance, and restoration, then we cannot ignore the fact that herbivores have evolved to accomplish this for our rangeland ecosystems.[10; 21] They are nourished by the grass, and by their grazing and trampling, in turn, maintain the grass.[21] This is done through defoliation and nutrient cycling. For centuries, the natural production of rangelands has supported generation after generation of large herds of herbivorous animals, and the partnership between grazing animals and the land has been and can continue to be a sustainable one.[10; 22]

Today, we no longer have the massive herbivore herds of centuries past. We have already established that the interference of humans and civilization brought irrevocable change to the balance of certain ecosystems. However, the tools maintain balance in remaining intact ecosystems are still available to us. Good ranchers are land managers, land stewards, and land preservationists.[22; 23] They strive to manage their domestic herds in ways that sustains long-term operational capacity.[23] In short, ranching must to be sustainable or the operation is self-defeating.[23] The key is effective management.

Especially in the case of public lands, the rancher must first form an effective collaborative relationship with the agency that owns the land. The rancher should be transparent, allowing anyone to observe first hand, the immediate, seasonal, or long-term effects of his/her cattle management.[22] The rancher should be just as much of a resource manager as the landowner, taking into careful consideration soil health, plant composition and viability, water health, and wildlife interaction.[22] Openness to new knowledge, discussion, and change is also a vital attribute. The two parties should be on the same team, not opposing sides struggling to negotiate one's rights over another. Unfortunately, in reality, this collaboration has not always been without conflict.[22]

The breadth of literature advocating for the use of livestock on public lands is quite limited compared to the literature aimed at removing or at least limiting the grazing of domestic livestock on public lands. Subsequent recommendations are also conflictual. A study authored by the Department of Conservation in New Zealand goes so far as to recommend that livestock only be grazed on areas which are already degraded so as to minimize further impact.[24] Another publication exclaims that rangelands should have never been used for domestic livestock grazing in the first place.[3] By remaining on the surface, one can easily become lost in the conundrum of anti-grazing sentiments.

Yet digging deeper into the discourse, ranching and the grazing of large herbivores can be seen as part of the recipe for conservation. In Kansas, extensive research concluded that large herbivores are key to maintaining grassland vegetative health and preventing it from succeeding to shrub or woodland.[15] Studies in Europe have confirmed that with special attention to habitat, domestic ruminants can play an important role in habitat management and conservation objectives.[25] In studies conducted in California and Mexico, the leasing of public lands by ranchers is saving it from urban sprawl and sub-division development.[26; 27] The concept of "working landscapes" can also be found in the literature, referring to the capacity for ranchers to protect public lands by maintaining use of them through grazing leases.[28] In addition, the use of livestock grazing on "marginal lands" might be the only way such lands are capable of being biologically productive and not succumbing to modern development.[21]

So, where does the truth lie? A logical step would be to look to science for the answer to this question. However, the conundrum in the scientific study of ranching and grazing is the extreme sensitivity to space and time. In some regions, it can take decades for the land to regenerate from overgrazing, and therefore, the ranchers of today cannot be blamed for the mistakes of the past.[26] A single grazing study is inherently specific to its own microcosmic location on an ecological site, episodic events in weather, climate patterns, and especially the specific style of grazing management.[8] For example, a study conducted in a forested region might see the trampling effect of grazing as detrimental to desirable young saplings,[24] while another study might find that trampling prevents the invasion of unwanted sagebrush and other woody species over desirable perennial grassland species.[15] The site-specific aspect of rangeland research makes it even more difficult for land managers to apply results and implement recommendations. In fact, without site-specific knowledge, grazing management strategies can be difficult adequately formulate to avoid undesirable effects, let alone attempt to meet conservation or restoration goals.[25]

The spatial-temporal nature of rangeland research is unavoidably confounding. The results of one study are difficult to replicate on another site due to biological and climatic variabilities. For instance, the management of grazing on public lands on the lush Pacific coasts of California cannot be equivalent to the management of cattle in the desert grasslands of Arizona, nor can they be compared to management strategies on irrigated pasture seeded with exotic plant species. However, what we cannot ignore is the fact that these types of ecosystems used to thrive on the movement of large herds of herbivores. It would make sense then, that instead of making these delicate areas void of domestic herbivore activity, we should attempt to mimic the patterns of their ungulate ancestors. Justin Derner, a rangeland scientist with the United States Department of Agriculture, explains that across the American West, ungrazed range is some of the unhealthiest land we have, and that on the level of evolution, grasslands depended on the activity of grazing to maintain balance.[23] The solution, therefore, is not to remove grazing from the picture, but to insist on effective, strategic grazing for the respective landscapes.[23]

A CONFLICTING BODY OF LITERATURE

Some observational research suggests that herbivore activity is associated with modern rangeland problems.[29] However, experimental manipulation and empirical data are lacking.[29] Thus, cause and effect relationships cannot be made. Furthermore, the confounding effects of biological variability from season-to-season, year-to-year, site-to-site, and herd-to-herd can be so extreme that grazing studies are difficult to replicate. There is also a lack of experimental controls needed to account for these confounding sources of variation in most studies.[29] As a result, the body of literature on the subject of the effects of livestock grazing on rangeland is extremely conflictual. How then, can one design a new study that effectively takes into account the methodological challenges just described? It behooves us to examine the methods with which such research has already been conducted. For this discussion, 3 categories of variables, soil, vegetation, and forage quality that are known to be affected by grazing, will be examined.

SOIL HEALTH

Agricultural research on important soil nutrients, such as nitrogen and organic carbon, includes an array of data collection and analysis methods.[30] First, soil samples can be collected at multiple depths, 0-5 cm, 0-10 cm, etc. Next, varying laboratory methods including combustion or wet oxidation, for example, can be used to oxidize soil carbon.[30; 31] Analysis can then be performed by either titration, conductivity, or chromatography.[30; 31] These different forms of measurement and reporting make it difficult to compare results from various studies. While an overall conclusion from such studies indicates that an increase in forage production is associated with an increase in soil organic carbon, there is variation in the details.[31] Precipitation, temperature, grazing management, and the seeding of certain grasses or legumes can all be factors that influence soil organic carbon.[10; 31] Any of these applications or combination of them may constitute a given rangeland study.

Other soil properties, such as nitrogen content, are susceptible to spatial scales.[32] A study conducted in Yellowstone National Park, utilizing 36+ year exclosures, attempted to observe the effects of large herbivore activity on soil nitrogen. [32] Taking into account the interdependent spatial patterns of plants, nutrients, and animals, data had to be collected at both large and small spatial scales, in other words, at the individual plant level and the greater landscape level. [32] It was concluded that animals influence nitrogen deposition at both scales, but by various means including grazing selectivity, manure and urine deposition, and plant litter inputs.[32]

It is also problematic that many grazing studies have failed to take into account differences in soil type from one treatment plot to the next.[8; 31] Especially on rangelands, soil variability is high, and a significant source of confounding data.[10] Moreover, forage quality is directly linked to soil fertility, and therefore an important relationship to consider in any grazing study.[16] Therefore, if soil type was not reported or considered in the experimental design, it is probable that inaccurate conclusions were drawn.[8]

An overview of the recent literature involving grazing effects on soil nutrients demonstrates that effectively managed grazing improves soil quality and specifically increases soil carbon content.[33-37] Soil organic matter, which is directly correlated with organic carbon, increases with the presence of cattle.[21] A secondary effect of this is the improvement of water infiltration.[21] The deposition of soil organic carbon and nitrogen, however, may be limited to the upper soil depth of 0-5cm and specific to the location of certain graminoid species.[38] In 2001, an extensive publication synthesized the results of 115 studies of soil carbon data from 17 different countries.[31] It concluded that the improved management of rangelands, by various means including grazing, can improve forage production, which is directly related to the sequestration of atmospheric carbon.[31] In this case, marginal grasslands can become “carbon sinks” by improvement through effective livestock management.[31]

Another equally extensive study examined soil data from 164 sites worldwide, which were used for extensive grazing.[39] Considering variation in grazing intensity and regional climate, the authors concluded that an increase or decrease in soil organic carbon was dependent upon both the climate and grazing intensity.[39] Additionally, high grazing intensity produced an overall increase in total nitrogen and a significant increase in soil organic carbon in areas dominated by C4 (warm season perennial) grasses compared to areas dominated by C3 (cool season perennial) grasses.[39] Researchers also concluded that if grazing intensity was modified to fit climate and grassland type, it could prevent soil degradation.[39]

Furthermore, 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.[15] The same study also showed that herbivory increases the spatial heterogeneity of available nitrogen, thus impacting plant productivity.[15] This conclusion is significant because nitrogen is the most limiting nutrient for plant production.[40] 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.[15; 41] Compared to other uses of farmable land like production of hay or silage, grazing actually removes less nitrogen from the soil.[41] In fact, 83%-90% of nitrogen consumed in the forage of grazing animals is returned to the soil through urine and manure.[18; 41] In another study, grazing was shown to increase nutrient cycling, specifically nitrogen availability, due to feedbacks between herbivory and plant response.[42]

VEGETATION COMPOSITION

Regarding vegetation responses to grazing, there is a wide array of methods and metrics available to researchers. Plant species composition via canopy cover or basal cover, plant species richness, and plant species diversity are all measures that are used as indicators for plant community structure.[10; 43] Methods used to collect these measures are well accepted. Then, there is the activity of grazing, where methods diverge. Some studies attempt to replicate the effects of grazing on rangeland or pasture in the form of clipping, allowing for greater experimental control and consistency. Historically, this has been performed in a laboratory setting in simulation chambers,[44] or in the field utilizing exclosures within which individual plants are clipped or defoliated at various intensities or for various lengths of time.[45; 46] While studies of this kind may show the effects of generic defoliation, such as how a mower cuts hay, these experimental methods are isolated either from natural environmental factors or from the natural secondary impacts of herbivores like cattle.[15]

The effects of natural herbivore activity are much more complex than the simple clipping of leaves. The significant impacts of trampling by hoof activity or the application of manure and urine are excluded from these types of studies.[15; 25] Therefore, their results are more challenging to realistically apply to grazing management because they lack comprehensiveness in grazing effects. To illustrate this point, an experiment testing the effects of bovine urine deposition on tallgrass prairie concluded that compared to control plots, areas treated with bovine urine resulted in increased grass cover, and leaf nitrogen content was also higher.[47] Hence, the secondary effects of defoliation by herbivores also contribute to measureable biological changes, which are multi-faceted.[15]

An overview of the recent literature demonstrates that grazing can actually improve plant community heterogeneity, a desirable trait of rangeland ecosystems.[25] Specifically, moderate grazing intensities demonstrated that residual stubble heights of 8 cm for cattle or 4 cm for sheep led to the greatest improvement in species biodiversity,[25] while a reduction in grazing intensity, such as in a continuous grazing scenario, led to a reduction in biodiversity.[25; 36]

Ungrazed areas encompass a lower level of biodiversity in vegetation than areas grazed at moderate or varying intensities.[48] A 55-year study conducted in central Colorado, which examined grazed versus ungrazed areas, demonstrated that the ungrazed exclosures actually contained the least amount of biodiversity.[49] Similarly, on the Konza Prairie in Kansas where bison have been introduced, grazing patches, compared to controls, showed an increase in overall plant species diversity of 15% as well as an increase in the presence of forbs.[15] In addition to graminoids, the presence of native forbs is an indicator of rangeland health, and it is believed that the grazing of dominant grasses by herbivores allows a “competitive release” for lesser competitive forbs to thrive.[50]

Furthermore, stocking rate is an important factor in the discussion of vegetation response, since some plants are sensitive to defoliation, while others are more tolerant.[10; 51] A study, which examined various cattle stocking rates and their effects on specific plant species, concluded that heavy grazing resulted in an increase in forbs and blue grama (*Bouteloua gracilis*) at the expense of western wheatgrass (*Pascopyrum smithii*), which is known to be defoliation sensitive. On the other hand, light grazing produced an increase in western wheatgrass.[34]

Another study compared long-term grazing effects on high productivity sites and low productivity sites. Significantly, plant diversity increased on the higher productivity sites (3.9 ± 1.3 number of species), but decreased on the lower productivity sites (-3.5 ± 1.2 number of species).[51] To illustrate this point, a 13-year evaluation in the Chihuahuan Desert showed that light grazing of 26% utilization resulted in improved survival of perennial plant species by 51% and no change in standing crop after the peak growing season.[52] 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.[52]

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.[53] Again, depending on the ecological biome of the research site, researchers attained different conclusions regarding the effects of grazing intensity. In one location, light grazing might have produced less desirable effects, while in another location, light grazing produced the most desirable effects.

Studies conducted in Mongolia utilized other indicators of biodiversity such as plant-pollinator interaction[54] and soil bacteria diversity.[55] Both studies concluded that grazed areas were highest in species richness and biodiversity compared to ungrazed areas.[54; 55] In summary, the return of grazing to rangelands, such as forests and grasslands, which are stressed or lacking in species diversity, can increase biodiversity.[56]

FORAGE QUALITY

Important to note are also the effects of grazing on forage quality. This is especially useful from a management perspective, and to inform the livestock manager of potential needs for supplemental nutrition. It is known that the oxidation of dead plant material, or litter, limits further plant productivity, although a certain amount of litter is necessary to retain soil moisture.[10] By the natural disturbance of grazing, standing dead or mature plant matter is removed, thinning a potentially thick and undesirable blanket of litter, allowing improved plant productivity. In a similar manner, grazing during the growing season prevents plant maturation into the reproductive stage, which is associated with a natural decrease in nutritive quality.[10; 57] Therefore, grazing contributes to the maintenance of higher levels of nutrients, by keeping plants in a growth stage containing more immature, nutrient-dense foliage.[57]

In Serengeti and Yellowstone National Parks, grazed areas contain greater overall plant biomass than ungrazed areas. [16] In addition to quantity, the quality of available forage was improved by herbivory, since it stimulates regrowth from the base of defoliated shoots and new stems.[16] This new plant material is more nutritious, digestible, and photosynthetically active.[16] Therefore, the movement of herbivores across grazing lands actually leaves higher quality forages in its wake.[16] Furthermore, by the deposition of urine, nitrogen in the form of urea can be mineralized in a matter of days.[15; 41] This naturally results in a measureable increase in nitrogen, a component of protein, content of plant leaves.[15; 41]

Forage quality, as indicated by crude protein content and digestibility, has also been an area of research in grazing management. In the uplands of the Czech Republic, it was demonstrated that compared to continuous grazing, intensive grazing produced more desirable effects such as increased total biomass production, crude protein, and forage digestibility.[58] In contrast, a study that used a clipping method to simulate defoliation by cattle recommended that light grazing has a more stable, long-term impact on protein and digestibility than heavy grazing or no grazing.[46] Note that this study did not take into account manure and urine impacts, which have measureable effects on such variables. In another study conducted on the Texas Experimental Ranch, crude protein and digestibility increased using a higher stocking rate, rotational grazing system compared to a lower stocking rate, continuous grazing system. Standing litter was higher in the latter system.[59] Similarly, in a study utilizing sheep as primary herbivores, crude protein and digestibility of graminoids and forbs in the fall season was increased in areas that were grazed in the spring versus ungrazed areas. Crude protein increased by 8-12% while dry matter digestibility increased by 2-31% depending on the plant species.[60]

CHALLENGES IN DESIGINING A GRAZING STUDY

Another challenge in the design and replication of grazing studies is structuring or quantifying the grazing method. In some studies, which have attempted to examine the effects of cattle grazing on soil and plant composition in a rangeland ecosystem, a description of the grazing method is completely avoided or lacks sufficient explanation, yet conclusions regarding the effects of grazing are made.[8; 24] In such cases, there is little to no consideration for the diverse methods with which various herbivorous species or various groups within the same species may graze a particular landscape. As established by Bell's research in the Serengeti and more recently by Dr. Fred Provenza at Utah State University, animals, by means of nature and nurture, develop selective ways in which they optimally fulfill their nutritional needs.[9; 61] For example, recently weaned calves might produce different grazing effects than mature dry cows. All grazing animals ingest forages by defoliation, but more importantly, the question is, *how* does a herd *collectively* defoliate a plot of land in terms of spatial heterogeneity.[9; 61]

An interesting study that illustrates this point compared the grazing effects of bison and cattle on select species of forbs.[50] Regarding the grazing method utilized, the researchers simply indicated that the grazing season for cattle was from May to October and that grazing intensity was maintained to equal that of the annually grazed bison.[50] Again, the details were lacking. Was this a continuous or rotational grazing system? How long were different grazing areas rested? What was the stocking density? This could tell us something about trampling and manure effects. Grazing is not a homogenous activity. In fact, it is very heterogeneous and complex. Therefore, in order to fully understand its effects, a more thorough description would be warranted.[50]

Furthermore, in grazing research there is the issue of scale, both spatial and temporal. The majority of grazing studies have been conducted on small plots, often 5-25 hectares, misrepresenting the typical grazing area of commercial ranches or rangeland leases.[8] The result of this is potential misinterpretation of data regarding forage quality and quantity, and the interaction between animals, plants, and soil.[8] Additionally, the management of small-scale plots is much different from that of an operational-scale ranch, regardless of whether or not it is sustainably managed.[8] Whereas there is little to no flexibility allowed in small-scale structured experiments, one of the most important tools for large-scale ranch management is flexibility.[8]

The temporality of grazing studies is equally important. When certain management strategies are applied to the land, it could take 2-3 years for variables such as soil and vegetation to adapt to new conditions, and even longer for changes to be measureable on the landscape level.[61] Taking into account animal adaptation, spatial heterogeneity of vegetation, random weather events, and ecosystem type, it is easy for grazing studies to produce results that represent a short-term temporal scale, not to mention an array of confounding variables.[8] It is important that the soil and plant response times are addressed in research and those conclusions indicated for long-term management are in fact suited for long-term management.[8; 61; 62] This is perhaps why previous research endeavors found no differences between grazing treatments or worse, that multi-paddock or rotational grazing decreased biological vitality.[8; 63]

In the case of domestic ruminants, *how* a herd grazes a plot of land is not only a direct result of that species' innate and learned mode of forage selection, but is especially related to the decisions made by the livestock manager, including stocking density, water placement, seasonality, and degree of forage utilization.[8; 61; 63] It is clear then, that the major component of grazing management, which research tends to exclude, is the existence of the livestock manager and his/her essential hand in controlling the impact made upon the landscape.

THE HUMAN DIMENSION

In 2011, a paper was published by a renowned group of scientists, which specifically addressed the role of the manager and the "human dimension" of grazing management.[63] The purpose of this paper was to respond to the conflicting results of grazing studies and the disconnect between case studies and managerial observation with scientific knowledge and systematic assessment.[63] It was noted that historical research on grazing management may have inadvertently misinformed management practices due to lack of rigorous scientific evaluation.[63] It is a discrepancy between case study and scientific method or experiential versus experimental knowledge. However, for the sake of controlling the sources of variability, past research also excluded a primary factor in grazing management, the manager him/herself, even though the manager's knowledge, ongoing decision-making, and capacity to adapt to ecological conditions are key to the success or failure of a grazing system.[8; 63]

After all, taking into account the dynamic role of the livestock manager is also problematic for the consistency of experimental treatments across time and space, an important factor in sound experimental design.[63] Good research is inherently stringent and inflexible in an attempt to eliminate causes for variation and confounding effects on results, yet confining a livestock manager to a treatment protocol without the ability to make informed decisions for his/her herd is unrealistic.[8; 63] "In short, reduced flexibility in grazing experiments removes many sources of potential variation, but at the risk of becoming unrealistically abstracted from management applications."[63]

In the end, if one were to develop a scientifically sound grazing study, utilizing experimental controls and accounting for the human dimension, there is still the obstacle of time. Change is gradual on the level of soil structure and plant species composition.[8; 61] To eliminate the confounding elements of random seasonality or weather patterns, it would be ideal to conduct a study that extends beyond a cycle of dry and wet years.[25] Quantitative models to detect this type of change are still being perfected. While one source of expert advice states that grazing experiments should extend 3-5 years,[63] others estimate that for such change to be detected, it takes 10-50 years, depending on grazing pressure and habitat.[25] However, it is in fact this level of change that is of interest if grazing management is to coincide with ecosystem conservation objectives.[25]

This is why Briske's 2011 publication noted that ongoing rangeland monitoring and recordkeeping strategies, like those taught in Holistic Resource Management, may be more effective at advising management decisions than most scientific research. It is the aptitude of the livestock manager to utilize experiential-based knowledge to inform his/her decisions to manage a grazing herd.[8; 63] This is a dynamic process of learning and application, which is difficult to encapsulate in an experimental model.[63]

In conclusion, rangeland ecosystems are very complex. The human dimension in grazing management adds yet another layer of complexity and variability to any research design. However, it is recommended that instead of breaking down this system to study isolated elements, such as defoliation, integrating all of the elements in order to illuminate the very essence of its complexity should be "complementary not contradictory."[8; 63] In other words, by examining the individual parts of a system, one cannot deduce the events caused by the interaction of those parts. Whereas scientists have focused solely on the biophysical aspects of rangeland management, ranching is not sustainable without attention to the human dimension. It is, therefore, recommended that current and future research programs incorporate both the biophysical and decision-making aspects of these complex working landscapes.[8; 62; 63]

THE ROLE OF MANAGEMENT

"Man operates as manager of complex systems whose behavior is the outcome of many variables. Measurement of those variables, so that man's activities can be placed in the context of the system, including its uncertainties, is an integral part of the management process."[64] For the purposes of academic progress and the production of scientific research, how should one proceed in light of this discussion? Fortunately, we are at the heels of a paradigm shift, where terms such as adaptive management, strategic grazing, management-intensive grazing, targeted grazing, holistic management, and planned grazing, are becoming common language in rangeland science and land management sectors.[8; 41; 64-71] The common theme highlighted in each of these methods is that of the human dimension, where management is adaptive and dynamic, and decisions are driven by the observation of environmental events. Each of these methods provides a framework for the integration of the human and biophysical dimensions of grazing management.

It is not the general presence of large herbivores that is potentially destructive to our rangelands, but the human errors in managing them. Studies of wild ungulates on the African Serengeti concluded that migratory behavior was vital to their co-existence with their habitat.[9] What drove herbivore migrations included the availability of substantial nutrition and water, predator activity, fire, and significant weather events.[9] The co-existence of wild ungulates and grasslands has been sustainable for millions of years.[9] Key to their evolutionary history was the spatial-temporal variability of their habitat and their response to that variability.[9; 16] The wild ancestral counterparts of domestic cattle, like the American bison (*Bison bison*), were also migratory.[15; 72] Just like our domesticated cattle, these wild ungulates preferred the highly nutritious plants of the early growing season, and just as quickly as they arrived and foraged, they moved on to seek out the next succulent pasture without returning to the previous ones until the next year. In turn, the areas defoliated in the early growing season had ample remaining growing season to recover from the impacts of herbivory.[16] The natural behavior of these animals was in fact, *adaptive*. If this was the way rangelands maintained an ecological balance for centuries, then why would we not manage our cattle in a way that also *adapts* to variable environmental events and effects?

The original concept of "adaptive management" by Holling in 1978 was intended to incorporate the uncertainty and variability of natural resource management into a scientific model.[64] It allowed for stakeholders, the human dimension, to formulate objectives, implement a design, monitor and interpret outcomes, and finally, revise management again (Figure 1.1).[63] It represents a cyclical process with feedback mechanisms, and one that also mimics the adaptive nature of herbivores on the land. For example, the animal creates an impact on a grazed area by instinctual design, by forage selection. The impact is observed by sensory integration of sight, smell, and taste. The animal might detect that the desirable plant species are no longer abundant. Then, through interpretation of these stimuli, a decision is made, like migrating to a new grazing area.

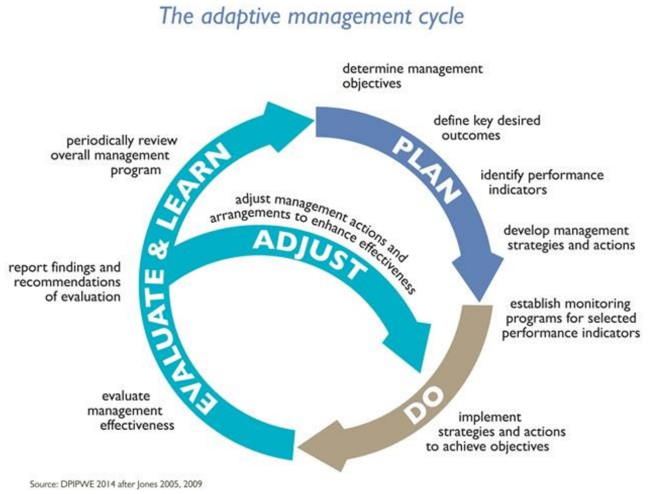


Figure 1.1: The adaptive management cycle.

By its inherent flexibility, adaptive management has earned a multitude of interpretations in the socio-ecological literature. Other descriptive terms for non-traditional grazing management (targeted, intensive, strategic, and planned) have since been implemented to denote similar management-focused strategies.[8; 41; 64-71] However, the bottom line is that experiential learning is incorporated and returned to the decision-making source.[73] Specifically, decision-making in regards to stocking density, pasture rest, seasonality of grazing, grazing intensity, and annual frequency of grazing, based upon the continuous monitoring and interpretation of environmental events by the livestock manager is inherent in these management strategies.[8; 41; 68; 69]

The spatial-temporal sensitivity of our rangelands to grazing activity cannot be ignored in future research endeavors, such as this one. Whereas traditional research methods were based on assumptions of homogeneity and continuity of time and space, the nature of management systems is nonlinear and continuously being updated.[68] Effective management calls for the integration of inputs and decisions within a system of monitoring; presuming that monitoring is performed on both the temporal and spatial scales. Therefore, there must be a way that these decisions are quantitatively or at least qualitatively incorporated into the research design.[68]

A leading researcher in the realm of adaptive management and grazing systems is Dr. Richard Teague of Texas A&M University. His team conducted a study that utilized cross-site comparisons to detect relative impacts based on different grazing management techniques.[36] The publication explained that due to the large-scale ecological questions and effects of grazing, true scientific replication, where all variables other than the treatment variable are held constant, was not possible.[36] In fact, he commented on other previous research endeavors, which were performed on small-scales and failed to utilize adaptive management for soil, plant, and livestock objectives. These types of studies resulted in invalid interpretations for real-scale and real-time rangeland management.[36] In this study, it was concluded that compared to light and heavy continuous grazing strategies, the adaptively managed, multi-pasture strategy produced healthier ecological effects. Such effects included higher percentages and biomass of tall grass and total standing vegetation with a lower proportion of short grasses, annuals, and bare ground.[36] It also produced higher levels of soil carbon, soil cation exchange capacity, soil magnesium and soil sodium, as well as a higher fungal/bacterial ratio.[36] It was concluded that while maintaining livestock performance and economic goals, the ranchers utilizing multi-pasture grazing were also able to maintain or improve ecosystem health objectives.[36]

Another study conducted in New Mexico compared strategic grazing management to continuously stocked cattle in both upland and riparian areas.[65] Researchers found that there was higher vegetation cover and less bare ground in the adaptively-managed areas, even across varying degrees of precipitation.[65]

A published case study, where adaptive management was utilized to achieve certain land management goals, found success in increasing desirable plants species while improving ranch profits on a private ranch in Colorado.[66] Key to this outcome was adaptive decision-making and flexibility in stocking rates, duration, seasonality, and frequency of grazing.[66]

In 2013, Dr. Teague united with another leading scientist in the world of grazing systems, Dr. Fred Provenza of Utah State University. The team published an extensive, information-dense paper, which further addressed the dichotomy between anecdotal rancher experience and scientific research, especially the vital role that adaptive management plays in large-scale land management and research.[8] Synthesizing the bulk of scientific principles and local knowledge, they proposed five "Management Principles" and four "Operating Actions" which can be used to apply the Principles (Figure 1.2).[8]

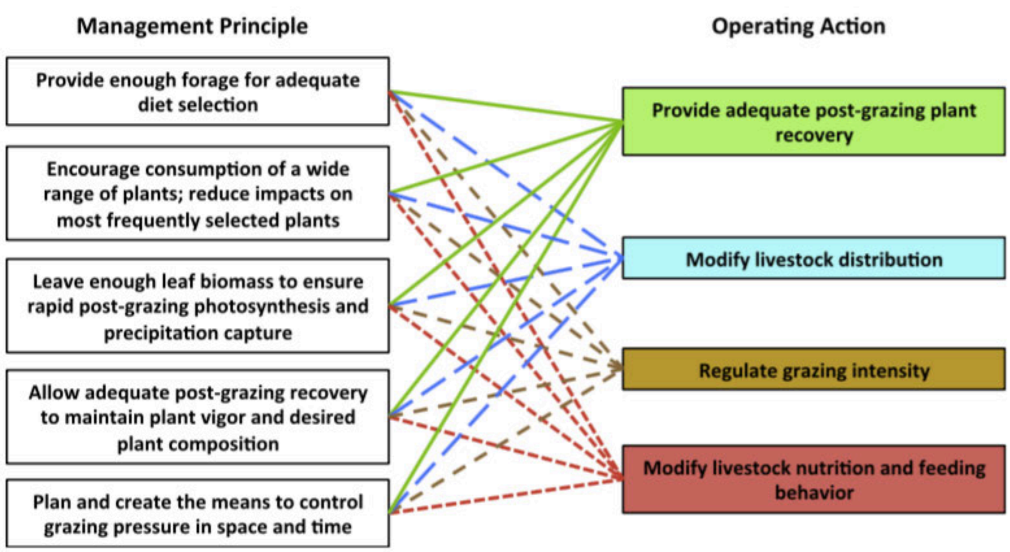


Figure 1.2: Principles of grazing management with operational action categories, proposed by Teague et al. 2013 [8].

Finally, this paper offered an alternative and poignant hypothesis: "At a ranch management scale, planned multi-paddock grazing, when managed to give best vegetation and animal performance, has the potential to produce superior conservation and restoration outcomes for rangeland resources, to provide superior ecosystem services for society, and to yield greater ranch profitability, and greater socio-ecological resilience in the long run compared to season-long stocking." The temporal-spatial aspect of rangeland ecosystems is inherent here, and research should consider this, if effective conclusions are to be drawn. The best ranchers and land managers are those who apply flexible strategies, monitor outcomes, and continuously adapt their strategies to achieve goals that benefit all levels: landscape, livestock, social, and economical.[8; 22; 68] Livestock managers should continuously adapt in this way, since the biophysical processes of rangelands are ever changing.

Therefore, research that represents a small slice in time, on a small plot of land, and which utilizes scientific methodology involving replicated assigned treatments is probably unrealistic. In the past, most grazing studies neglected the human element, the most important aspect of grazing management.[8; 63] The human element incorporates inevitable variability, yet without the human element, the web of livestock-land relationships is incomplete.[8] To attain sustainable rangelands, it may be best that grazing herbivores be moved frequently across the landscape, mimicking the way their wild ancestors migrated in the Mesozoic Era.[61] The capacity of the human element to make observations and formulate intelligent decisions replaces the natural motivators of free-ranging herbivores such as forage availability, fire, or predators. Without the motivation to migrate, whether by human management or natural events, evidence suggests that herbivores will return to preferred grazing areas repeatedly in a cycle of degradation.[36; 48; 61] Therefore, strategic yet adaptive, flexible management is vital to the health and sustainability of our earth's rangelands.[8]

A NEW DIRECTION FOR GRAZING RESEARCH

In the past, migratory movements, weather, and predators influenced and regulated the distribution of large herbivore herds, and today without these natural instigators, cattle in a continuous grazing system produce a much different impact on the landscape. If continuously stocked, their level of disturbance to native plant communities threatens biodiversity, encourages the growth of exotic and noxious plant species, and therefore changes key factors in ecosystem health such as soil composition.[29; 36; 71] That being the case, in a grazing system made up of domesticated livestock, it is the role of the livestock manager to simulate migratory behavior in the form of rotational grazing or multi-pasture grazing. By making informed management decisions based on plant response, precipitation, wildlife interaction, daily temperatures, and water location, the livestock manager creates certain impacts on the land. Management, the human decision-making dimension, is key to achieving desirable outcomes.[8; 15; 25; 63; 68; 71]

Several topics will need to be addressed in order to improve the efficacy of future grazing studies. These topics include the spatial and temporal aspect of grazing ecosystems, consistency of soil type, adequate recovery time, and the human dimension.[8; 63] By combining the interconnected dimensions of land, animal, and human, in a holistic framework, researchers may retrieve results with increased applicability to real-time, real-scale livestock and land management. Therefore, significant questions remain for future research in rangeland grazing studies:

1. How do indicators of rangeland health, including biodiversity and soil health, in areas under strategic grazing management compare to areas where cattle have been excluded or managed under continuous grazing?

2. Can strategic grazing management of cattle on rangeland positively affect factors that are important for livestock management, such as forage quality, compared to areas where cattle have been excluded or managed under continuous grazing?
3. Does strategic grazing management provide an effective and sustainable framework for cattle grazing on public or conservation lands?

LITERATURE CITED

1. Breckenridge, R., W. Kepner, and D. Mouat. 1995. A process for selecting indicators for monitoring conditions of rangeland health. Environmental Monitoring and Assessment 36: 45-60.

2. Shute, L. L. 2011. Building a Future with Farmers: Challenges Faced by Young, American Farmers and a National Strategy to Help Them Succeed. National Young Farmers' Coalition. p. 3-40.

3. Donahue, D. L. 1999. The western range revisited: removing livestock from public lands to conserve native biodiversity. University of Oklahoma Press.

4. Giovannucci, D., S. J. Scherr, D. Nierenberg, C. Hebebrand, J. Shapiro, J. Milder, and K. Wheeler. 2012. Food and agriculture: The future of sustainability. The sustainable development in the 21st century (SD21) Report for Rio 20.

5. Thorton, P. K. 2010. Livestock production: recent trends, future prospects. Philosophical Transactions of the Royal Society of London B: Biological Sciences 365: 2853-2867.

6. Ellis, J. E., and D. M. Swift. 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. Rangeland Ecology & Management/Journal of Range Management Archives 41: 450-459.

7. Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. Nature 418: 671.

8. Teague, R., F. Provenza, U. Kreuter, T. Steffens, and M. Barnes. 2013. Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? Journal of Environmental Management 128: 699-717.

9. Bell, R. H. 1971. A grazing ecosystem in the Serengeti. Scientific American 225: 86-93.

10. Gibson, D. J. 2009. Grasses and grassland ecology. Oxford University Press.

11. Yeo, J. J., J. M. Peek, W. T. Wittinger, and C. T. Kvale. 1993. Influence of rest-rotation cattle grazing on mule deer and elk habitat use in east-central Idaho. Journal of Range Management 46: 245-250.

12. Crane, K., J. Mosley, T. Brewer, W. Torstenson, and M. Tess. 2001. Influence of cattle grazing on elk habitat selection. PROCEEDINGS-AMERICAN SOCIETY OF ANIMAL SCIENCE WESTERN SECTION. p. 160-164.

13. Torstenson, W. L., J. C. Mosley, T. K. Brewer, M. W. Tess, and J. E. Knight. 2006. Elk, mule deer, and cattle foraging relationships on foothill and mountain rangeland. Rangeland Ecology & Management 59: 80-87.

14. Anderson, E. W., and R. J. Scherzinger. 1975. Improving quality of winter forage for elk by cattle grazing. Journal of Range Management 28: 120-125.

15. Knapp, A. K., J. M. Blair, J. M. Briggs, S. L. Collins, D. C. Hartnett, L. C. Johnson, and E. G. Towne. 1999. The keystone role of bison in North American tallgrass prairie: Bison increase habitat heterogeneity and alter a broad array of plant, community, and ecosystem processes. BioScience 49: 39-50.

16. Frank, D. A., S. J. McNaughton, and B. F. Tracy. 1998. The ecology of the earth's grazing ecosystems. BioScience 48: 513-521.

17. Grove, R. H. 1996. Green imperialism: colonial expansion, tropical island Edens and the origins of environmentalism, 1600-1860. Cambridge University Press.

18. Barnes, R. N., CJ. 2003. Forages and grasslands in a changing world. Forages, an Introduction to Grassland Agriculture, 6th ed., Iowa State Press, A Blackwell Publishing Company, Ames, Iowa, USA: 3-23.

19. Sessions, G. 1987. The deep ecology movement: a review. Environmental Review: ER 11: 105-125.

20. Brulle, R. J. 1996. Environmental discourse and social movement organizations: A historical and rhetorical perspective on the development of US environmental organizations. Sociological Inquiry 66: 58-83.

21. Niman, N. H. 2014. Defending beef: The case for sustainable meat production. Chelsea Green Publishing.

22. Winder, J. 1999. Restorative Grazing. The Future of Arid Grasslands: Identifying Issues, Seeking Solutions: 283.

23. Horn, M. 2016. Rancher, Farmer, Fisherman: Conservation Heroes of the American Heartland. WW Norton & Company.

24. Timmins, S. M. 2002. Impact of cattle on conservation land licensed for grazing in South Westland, New Zealand. New Zealand Journal of Ecology: 107-120.

25. Milne, J., and K. Osoro. 1997. The role of livestock in habitat management. Livestock systems in European rural development (ed. JP Laker and JA Milne): 75-80.

26. Curtin, C. G., N. F. Sayre, and B. D. Lane. 2002. Transformations of the Chihuahuan Borderlands: grazing, fragmentation, and biodiversity conservation in desert grasslands. Environmental Science & Policy 5: 55-68.

27. Sulak, A., and L. Huntsinger. 2007. Public Land Grazing in California: Untapped Conservation Potential for Private Lands? Working landscapes may be linked to public lands. Rangelands 29: 9-12.

28. Brunson, M. W., and L. Huntsinger. 2008. Ranching as a conservation strategy: can old ranchers save the new west? Rangeland Ecology & Management 61: 137-147.

29. Vavra, M., C. G. Parks, and M. J. Wisdom. 2007. Biodiversity, exotic plant species, and herbivory: the good, the bad, and the ungulate. Forest Ecology and Management 246: 66-72.

30. Nelson, D. W. a. L. E. S. 1982. Total Carbon, Organic Carbon, and Organic Matter. *In* Methods of Soil Analysis. Pt. 2. Chemical and Microbiological Properties. 2nd Ed. A.L. Page, Ed. Madison, WI: American Society of Agronomy, Soil Science Society of Agronomy.

31. Conant, R. T., K. Paustian, and E. T. Elliott. 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecological Applications 11: 343-355.

32. Augustine, D. J., and D. A. Frank. 2001. Effects of migratory grazers on spatial heterogeneity of soil nitrogen properties in a grassland ecosystem. Ecology 82: 3149-3162.

33. Beukes, P. C., and R. M. Cowling. 2003. Non-selective grazing impacts on soil-properties of the Nama Karoo. Journal of Range Management: 547-552.

34. Schuman, G., J. Reeder, J. Manley, R. Hart, and W. Manley. 1999. Impact of grazing management on the carbon and nitrogen balance of a mixed-grass rangeland. Ecological Applications 9: 65-71.

35. Manley, J., G. Schuman, J. Reeder, and R. Hart. 1995. Rangeland soil carbon and nitrogen responses to grazing. Journal of soil and water conservation 50: 294-298.

36. Teague, W., S. Dowhower, S. Baker, N. Haile, P. DeLaune, and D. Conover. 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agriculture, Ecosystems & Environment 141: 310-322.

37. Teague, W., S. Apfelbaum, R. Lal, U. Kreuter, J. Rowntree, C. Davies, R. Conser, M. Rasmussen, J. Hatfield, and T. Wang. 2016. The role of ruminants in reducing agriculture's carbon footprint in North America. Journal of Soil and Water Conservation 71: 156-164.

38. Derner, J., D. Briske, and T. Boutton. 1997. Does grazing mediate soil carbon and nitrogen accumulation beneath C 4, perennial grasses along an environmental gradient? Plant and Soil 191: 147-156.

39. Abdalla, M., A. Hastings, D. R. Chadwick, D. L. Jones, C. D. Evans, M. B. Jones, R. M. Rees, and P. Smith. 2018. Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agriculture, Ecosystems & Environment 253: 62-81.

40. Myrold, D. D. 2005. Chapter 14 Transformations of Nitrogen. Principles and Applications of Soil Microbiology. New Jersey: Pearson-Prentice Hall. p. 33-372.

41. Gerrish, J. 2004. Management-intensive grazing: the grassroots of grass farming.

42. Holland, E. A., W. J. Parton, J. K. Detling, and D. L. Coppock. 1992. Physiological responses of plant populations to herbivory and their consequences for ecosystem nutrient flow. The American Naturalist 140: 685-706.

43. Symstad, A. J., and J. L. Jonas. 2011. Incorporating biodiversity into rangeland health: plant species richness and diversity in Great Plains grasslands. Rangeland ecology & management 64: 555-572.

44. Wilsey, B. J., J. S. Coleman, and S. J. McNaughton. 1997. Effects of elevated CO2 and defoliation on grasses: a comparative ecosystem approach. Ecological Applications 7: 844-853.

45. Buwai, M., and M. Trlica. 1977. Multiple defoliation effects on herbage yield, vigor, and total nonstructural carbohydrates of five range species. Journal of Range Management: 164-171.

46. Milchunas, D., A. Varnamkhasti, W. Lauenroth, and H. Goetz. 1995. Forage quality in relation to long-term grazing history, current-year defoliation, and water resource. Oecologia 101: 366-374.

47. Steinauer, E., and S. Collins. 1995. Effects of urine deposition on small-scale patch structure in prairie vegetation. Ecology 76: 1195-1205.

48. Toombs, T. P., J. D. Derner, D. J. Augustine, B. Krueger, and S. Gallagher. 2010. Managing for Biodiversity and Livestock: A scale-dependent approach for promoting vegetation heterogeneity in western Great Plains grasslands. Rangelands 32: 10-15.

49. Hart, R. H. 2001. Plant biodiversity on shortgrass steppe after 55 years of zero, light, moderate, or heavy cattle grazing. Plant Ecology 155: 111-118.

50. Damhoureyeh, S., and D. Hartnett. 1997. Effects of bison and cattle on growth, reproduction, and abundances of five tallgrass prairie forbs. American Journal of Botany 84: 1719-1719.

51. Bakker, E. S., M. E. Ritchie, H. Olff, D. G. Milchunas, and J. M. Knops. 2006. Herbivore impact on grassland plant diversity depends on habitat productivity and herbivore size. Ecology letters 9: 780-788.

52. Holechek, J., D. Galt, J. Joseph, J. Navarro, G. Kumalo, F. Molinar, and M. Thomas. 2003. Moderate and light cattle grazing effects on Chihuahuan Desert rangelands. Journal of Range Management: 133-139.

53. Vassilev, K., H. Pedashenko, S. Nikolov, I. Apostolova, and J. Dengler. 2011. Effect of land abandonment on the vegetation of upland semi-natural grasslands in the Western Balkan Mts., Bulgaria. Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology 145: 654-665.

54. Yoshihara, Y., B. Chimeddorj, B. Buuveibaatar, B. Lhagvasuren, and S. Takatsuki. 2008. Effects of livestock grazing on pollination on a steppe in eastern Mongolia. Biological Conservation 141: 2376-2386.

55. Zhou, X., J. Wang, Y. Hao, and Y. Wang. 2010. Intermediate grazing intensities by sheep increase soil bacterial diversities in an Inner Mongolian steppe. Biology and Fertility of Soils 46: 817-824.

56. Collins, S. L., A. K. Knapp, J. M. Briggs, J. M. Blair, and E. M. Steinauer. 1998. Modulation of diversity by grazing and mowing in native tallgrass prairie. Science 280: 745-747.

57. Kilcher, M. 1981. Plant development, stage of maturity and nutrient composition. Rangeland Ecology & Management/Journal of Range Management Archives 34: 363-364.

58. Pavlů, V., M. Hejcman, L. Pavlů, J. Gaisler, and P. Nežerková. 2006. Effect of continuous grazing on forage quality, quantity and animal performance. Agriculture, ecosystems & environment 113: 349-355.

59. Heitschmidt, R., S. Dowhower, and J. Walker. 1987. Some effects of a rotational grazing treatment on quantity and quality of available forage and amount of ground litter. Journal of Range Management 40: 318-321.

60. Rhodes, B. D., and S. H. Sharrow. 1990. Effect of grazing by sheep on the quantity and quality of forage available to big game in Oregon's Coast Range. Journal of range management 43: 235-237.

61. Provenza, F. D., J. J. Villalba, L. Dziba, S. B. Atwood, and R. E. Banner. 2003. Linking herbivore experience, varied diets, and plant biochemical diversity. Small ruminant research 49: 257-274.

62. Lynam, T. J., and M. Stafford Smith. 2004. Monitoring in a complex world—seeking slow variables, a scaled focus, and speedier learning. African Journal of Range and Forage Science 21: 69-78.

63. Briske, D. D., N. F. Sayre, L. Huntsinger, M. Fernandez-Gimenez, B. Budd, and J. D. Derner. 2011. Origin, Persistence, and Resolution of the Rotational Grazing Debate: Integrating Human Dimensions Into Rangeland Research. Rangeland Ecology & Management 64: 325-334.

64. Holling, C. S. 1978. Adaptive environmental assessment and management. John Wiley & Sons.

65. Danvir, R., G. Simonds, E. Sant, E. Thacker, R. Larsen, T. Svejcar, D. Ramsey, F. Provenza, and C. Boyd. 2018. Upland Bare Ground and Riparian Vegetative Cover Under Strategic Grazing Management, Continuous Stocking, and Multiyear Rest in New Mexico Mid-grass Prairie. Rangelands.

66. Grissom, G., and T. Steffens. 2013. Case study: adaptive grazing management at Rancho Largo Cattle Company. Rangelands 35: 35-44.

67. Steffens, T., G. Grissom, M. Barnes, F. Provenza, and R. Roath. 2013. Adaptive Grazing Management for Recovery: Know why you're moving from paddock to paddock. Rangelands 35: 28-34.

68. Laca, E. A. 2009. New approaches and tools for grazing management. Rangeland ecology & management 62: 407-417.

69. Barnes, M., and A. Hild. 2013. Foreword: Strategic Grazing Management for Complex Creative Systems. Rangelands 35: 3-5.

70. Barnes, M. 2015. Low-stress herding improves herd instinct, facilitates strategic grazing management. Stockmanship Journal 4: 31-43.

71. Kemp, D., P. Dowling, and D. Michalk. 1996. Managing the composition of native and naturalised pastures with grazing. New Zealand Journal of Agricultural Research 39: 569-578.

72. Hartnett, D., and P. Fay. 1998. Plant populations: patterns and processes. Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, New York: 81-100.

73. Allen, C. R., J. J. Fontaine, K. L. Pope, and A. S. Garmestani. 2011. Adaptive management for a turbulent future. Journal of environmental management 92: 1339-1345.

CHAPTER 2: CATTLE AS PARTNERS IN CONSERVATION

ON THE GROUND

- Recommendations for cattle management on public rangelands are conflictual. The resolution is not to remove grazing from rangelands, but to effectively manage grazing for specific landscapes and ecosystem types. Collaborative partnerships between private and public sectors provide a way to use cattle as partners in conservation, while maintaining animal performance and beef production objectives.
- The livestock manager's role (the human dimension) in effective grazing management is key. There is great challenge in designing research, which incorporates the human dimension and biological variability of grazing management with the spatial-temporal intricacies of rangeland ecology.
- This study investigated some of the effects of strategic grazing on rangeland managed under a conservation plan. This grazing regime provided a framework for integrating the human and biophysical dimensions of grazing management with natural resource management.
- Among measured indicators of rangeland health, (soil organic carbon, total nitrogen, and plant species abundance) there were no significant differences in grazed versus ungrazed areas after 1 year of strategic grazing management.
- Compared to ungrazed areas, forage quality was lower shortly following the conclusion of grazing, but was higher in areas that were grazed in the spring and received 2-3

months of rest compared to areas that were grazed in the fall and received 9-10 months of rest.

- Continued research is needed to determine if collaborative, strategic grazing management can aid in the attainment of land conservation goals with respect to vegetation and soil health objectives.

LEARNING FROM THE PAST

As our world's private farm and ranch land is converted to urban and non-agricultural development at an extraordinary pace, it has become more important that we carefully and optimally manage our remaining open space and rangelands.[1; 2] The beef cattle industry has had a longstanding relationship with United States government public land management agencies, including the Bureau of Land Management and the United States Forest Service, for livestock grazing. However, over the last 30 years, the debate over the use of public lands has intensified.[3] With interest growing in conservation biology and natural resource management, cattle (*Bos taurus*) are often seen as dangerous competitors to ecosystem balance – and they can be, if managed ineffectively.[3]

The growing global population's rising demand for livestock products and by-products will continue to instigate competition for land and water between food production, feed production, bioenergy sources, development, and recreation.[4] By consuming highly fibrous plants and dry roughage from non-arable landscapes and transforming them into nutritious meat and dairy food products for human consumption, ruminants can produce food products from locations that could never sustain traditional crop agriculture.[4] The challenge, however, is doing so without compromising environmental sustainability.

It is not the general presence of large herbivores that is potentially destructive to our rangelands, but the human errors in managing them. Studies of wild ungulates on the African Serengeti concluded that migratory behavior was vital to a sustainable relationship with their habitat.[5] What drove herbivore migrations included the availability of substantial nutrition and water, predator activity, fire, and significant weather events.[5] Therefore, key to the evolutionary history of wild ungulates was the spatial-temporal variability of their habitat and their response to that variability.[5; 6] The wild ancestral counterparts of domestic cattle, like the American bison (*Bison bison*), were also migratory.[7; 8] The natural behavior of these animals was *adaptive*. If this was the way rangelands maintained an ecological balance for centuries, then why would cattle not also be managed in a way that *adapts* to environmental variability?

A key element to successful grazing management, which is often disregarded in scientific grazing studies, is that of the "human dimension" as proposed by Briske et al. (2011).[9] The capacity of the human element to make observations and formulate decisions may replace the natural motivators of free-ranging herbivores, such as forage availability, fire, or predators. Without the motivation to migrate, whether by human management or natural events, evidence suggests that herbivores will return to preferred grazing areas repeatedly in a cycle of degradation.[10-12] Therefore, strategic yet adaptive, flexible management is not only vital to the health and sustainability of our earth's rangelands, but it is also a framework that should be utilized in grazing research, since it integrates both the human and biophysical dimensions of grazing management.[9; 13] In this way, researchers and livestock managers may embark on a cyclical process with feedback mechanisms, which may also mimic the adaptive nature of wild herbivores on the land.[9]

In the literature regarding grazing systems for domestic livestock, there is often disagreement between case study and scientific assessment.[9] This has led to conflictual recommendations for the application of grazing on rangeland and has even instigated heightened sentiments aimed at removing or at least limiting the grazing of domestic livestock on public lands.[3; 14] Recent publications have investigated reasons why there are inconsistencies in grazing studies.[9; 13] Whereas traditional research methods are based on assumptions of homogeneity of time and space, the nature of management systems is actually nonlinear and continuously being updated.[15] Therefore, a conundrum in the scientific study of grazing is this extreme sensitivity to space and time. Strict adherence to the scientific method to provide replicability, while controlling for all sources of variation other than the treatment variable, is a nearly impossible feat, and in the end, produces unrealistic results.[9] This gives efficacy to case study-type investigations.[9] There is a need for more evidence-based study regarding soil and vegetation health as affected by cattle grazing, which is strategically and flexibly managed through dynamic decision-making in response to real-time, real-scale events and observations.

GRAZING: A TOOL FOR LAND MANAGEMENT

It is a matter of shifting the collective mentality from the previous image of a traditional continuously-grazed cattle herd, to a rotational grazing system where temporary pastures are used to simulate migratory grazing behavior, therefore mimicking the patterns of wild herbivores. Winder (1999), conceptualized the idea of using cattle as “tools” for land restoration.[16] The study reported here took this a step further to conceptualize cattle as *partners* in conservation, by using their natural migratory behavior as a platform for strategic grazing management.

Grazing management integrates the role of decision-making with the interconnected systems of humans and nature. Because the ecological processes of rangelands are ever changing, scientific models for effective management should incorporate this uncertainty and variability.[9; 13; 17; 18] Cattle grazing is one such area where an adaptive, flexible approach has shown positive outcomes.[13; 19-21] Stocking density, seasonality, grazing intensity, and rest period are all factors in a flexible grazing regime, which are implemented, monitored, and evaluated for future decision-making purposes in continuum.[22] Qualitative and quantitative observations regarding plant stubble height, forage utilization, cattle behavioral cues, precipitation and temperature events, interaction with wildlife, soil compaction, and availability of water are examples of variables that inform such managerial decisions.

The grazing approach utilized in this study is in contrast to the traditional strategy of continuous grazing.[11; 13; 23] It is an inclusive, rather than exclusive, concept that echoes other approaches of more recent works in the rangeland science and grazing management sectors, such as adaptive management, strategic grazing, management-intensive grazing, targeted grazing, holistic management, and planned grazing.[13; 15; 18-22; 24-26] The common theme highlighted in each of these methods is that of the human dimension, where management is flexible and dynamic, and decisions are driven by the observation of environmental events. Each of these methods provides a framework for the integration of the human and biophysical dimensions of grazing management. The term, strategic grazing management, will be used to denote the grazing strategy utilized in this study. Specifically, this term will signify the management strategy of real-time, real-scale ranching where factors such as seasonality of grazing, grazing intensity, stocking density, and herd type are based upon logistical needs of the ranch and the continuous monitoring and interpretation of environmental events by the livestock manager, researcher, and land management agency.

This study was intended to contribute to the body the scientific literature modeling a collaborative approach to grazing management on public land, and specifically examining if strategic grazing management could be used to assist the land management agency in the attainment of certain conservation goals. Therefore, the objective of this study was to compare selected indicators of rangeland health in ungrazed areas to adjacent areas where strategic grazing management had been implemented. It was hypothesized that compared to areas excluded from grazing, areas where strategic grazing was implemented would exhibit: increased nutrient cycling by integration of organic carbon and nitrogen into the soil, increased abundance of native graminoids and native forbs, and reduced abundance of noxious weeds. It was hypothesized that forage quality would follow a particular pattern because of grazing: a decrease in forage quality shortly following grazing, an increase in forage quality with a period of rest, and a decrease in forage quality with continued absence of grazing.

RESEARCH SITE HISTORY AND ECOLOGY

The Foothills Grasslands of the Rocky Mountain Front Range are transitional landscapes that lie wedged between two ecoregions, the Colorado Rockies Forests to the west and the Western Short Grasslands of Colorado's central plains to the east.[27; 28] The Foothills Grassland is one of the most severely modified and fragmented ecosystems in the Rocky Mountain region, with most of these changes due to housing and water development, cropland conversion, and fire suppression.[29] Without natural disturbances like herbivory, the Front Range grasslands are vulnerable to increased bare ground, erosion, and invasion by exotic species.[29]

Bobcat Ridge Natural Area (BRNA), 25% of which is Foothills Grassland, was previously a privately-owned ranch homesteaded in the 1800s.[28] By the presence of Native American tipi rings and large ungulate wildlife observed today, it could be assumed that the area once provided productive hunting grounds. Over the last century, however, it became a hay, alfalfa, wheat, and cattle operation because of European settlement. Bobcat Ridge and surrounding areas were used for agriculture as an economic focus during the homestead period in Northern Colorado.[28]

The City of Fort Collins purchased the ranch in 2003 and placed its management under the Natural Areas Program of the city's Land Conservation and Stewardship Master Plan.[28] This protected area lies west of the city of Loveland, Colorado, where it is contiguous on the north and west to National Forest Service land and the Sylvan Dale Ranch Conservation Easement (40º 28' 47" N; 105º 13' 33" W and 1,646 m of elevation). On the east and south are residential areas that have seen increased urban encroachment over the past few decades.[28] In BRNA, careful management using modern tools, such as herbicides and mowing, has attempted to restore and sustain its native ecology. Because BRNA experienced more than a 10-year rest period from cattle grazing following the transfer of ownership to the City of Fort Collins, it provided an optimal research site to study the effects of livestock grazing on public lands from which grazing had been purposefully excluded.

There is a range of 610 m in elevation across BRNA's 1,052 hectares. The mixed soils of the valley were formed in the Carboniferous Period followed by Quarternary Era alluvial fan deposits, resulting primarily in sandstone and siltstone.[28] Depending on the location, the valley's soils vary in slope, texture, and series classification. There are over 10 different soils classified on the valley floor, but they are primarily loams of Kirtely-Purner and Satanta series.[28]

BRNA is comprised of 5 ecosystems: Foothills Grassland, Lower Montane Riparian Woodland, Ponderosa Pine Woodland, Ponderosa Pine Savanna, and Lower Montane-Foothill Shrubland.[28] The Ponderosa Pine Woodland is the ecosystem of highest elevation, which also characterizes the majority of the adjacent Sylvan Dale Conservation Easement and National Forest land. These ecosystems are currently under the ranking of “vulnerable” or “imperiled”.[28] They are threatened by exotic and undesirable plant species such as smooth brome (*Bromus inermis*), Canada thistle (*Cirsium arvense*), and cheatgrass (*Bromus tectorum*). Alfalfa (*Medicago stavia*) and crested wheatgrass (*Agropyron cristatum*) are also among the introduced species that are undesirable, yet abundant on BRNA. Interspersed across the landscape, there are still patches of native vegetation dominated by blue grama (*Bouteloua gracilis*), needle-and-thread (*Hesperostipa comata*), sand dropseed (*Sporobolus cryptandrus*), western wheatgrass (*Pascopyrum smithii*), fringed sage (*Artemisia frigida*), spike fescue (*Leucopoa kingii*), and big bluestem (*Andropogon gerardii*).[28] Plant nomenclature follows the USDA Plants database.[30]

The Foothills Grassland ecosystem encompasses the BRNA valley floor, and was the location for this study. The Ecological Site Description (ESD) of this Loamy Foothill ecosystem (Site ID: R049XD202CO), provided by the USDA’s Natural Resources Conservation Service,[31] describes the following climatic features. Annual precipitation can vary from 28-56 cm per year, but averages 35-48 cm annually. The majority of precipitation occurs from April to September during the growing season. Snowfall averages 160 cm per year, and the average freeze-free period is 142 days annually, usually occurring between May and September. Average daytime temperatures during the summer are 27°C and nighttime temperatures average 10°C. The humidity in the summer is “low”, while evaporation is “moderate.”[31] Soil features, as described by the ESD, involve well-drained, loamy alluvium and residuum from deposits of sandstone, siltstone, and shale. The water holding capacity is high, and the soil pH ranges from neutral to moderately alkaline.[31]

DESIGNING A GRAZING STUDY ON PUBLIC LANDS

As the landowner and manager in this research collaboration, the City of Fort Collins intended to investigate if the use of strategic grazing management would aid in their restoration goals as an alternative to herbicide use, controlled burning, and/or mowing. As collective stakeholders in this project, a select committee from the city’s Natural Areas Department, the owner and livestock manager of Sylvan Dale Ranch, and the Colorado State University research team held multiple planning meetings prior to the initiation of research. In 2016, 6 pairs of 50 m linear transects were established throughout the BRNA grassland valley (Figure 2.1). A public announcement to BRNA recreationists, issued by the City of Fort Collins, can be found in Appendix A.

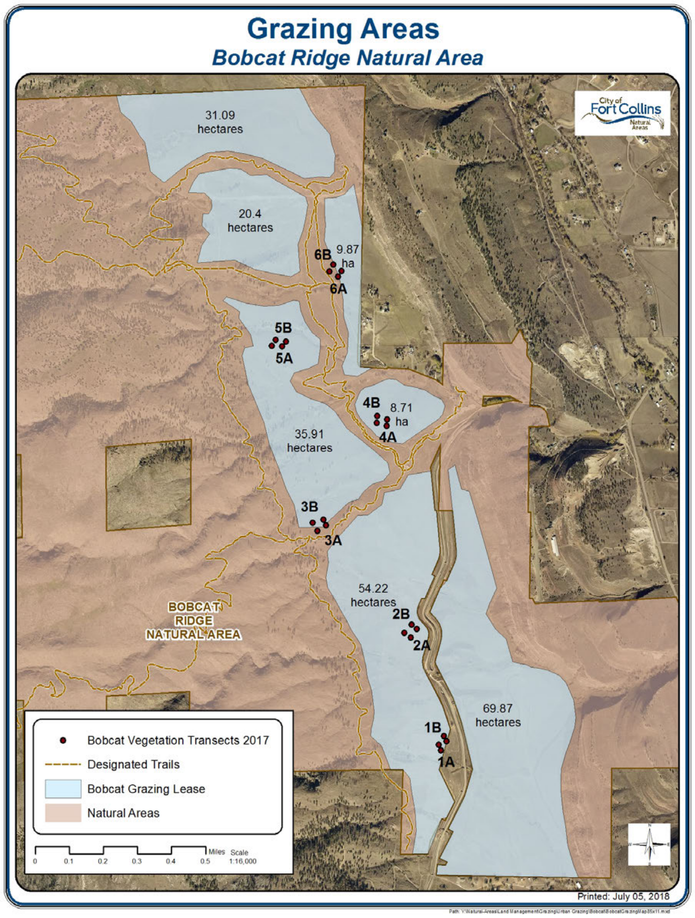


Figure 2.1: Map of designated grazing areas at Bobcat Ridge Natural Area issued by the City of Fort Collins in 2017, showing 6 pairs of linear transects, 1A, 1B; 2A, 2B; 3A, 3B; 4A, 4B; 5A, 5B; 6A, 6B. Each red dot represents the beginning or end point of a 50 m transect.

To decrease biological variability, the location of the linear transects was determined by the primary soil type on the BRNA valley, Kirtley-Purner loam. This soil type comprises 62% of the BRNA grassland valley. Therefore, transects were randomly selected within areas containing this soil type, and where there had been no previous use of herbicides by the City of Fort Collins since its purchase in 2003. Photographs of various transect markers on BRNA are included in Appendix B. As seen in Figure 2.1, the transect pairs were distributed across the valley floor, with approximately 2.5 km between the northernmost and southernmost set. The paired transects were set parallel to each other and placed 30 m apart with adequate distance to fence lines or water troughs to reduce the effects of heavier hoof traffic around these areas. During grazing periods, the fenced transects would act as ungrazed areas of 1,000 m^2, while the paired open transects would be grazed. Figure 2.2 presents a diagram of the experimental design.

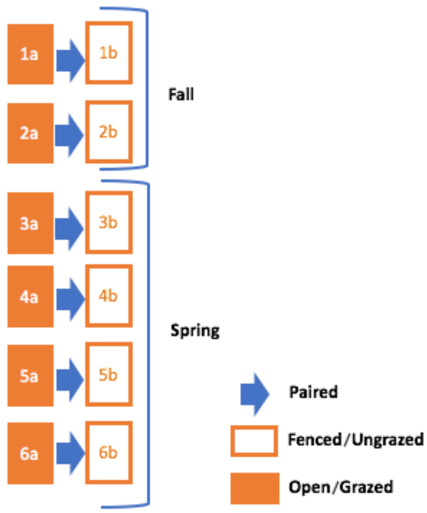


Figure 2.2: Experimental design illustrating 6 transect pairs and the season in which are was grazed. Transects labeled “a” were exposed to grazing. Transects labeled “b” were located within fenced exclosures that prevented cattle from grazing.

Because BRNA is a public lands recreation area, the City of Fort Collins restricted the use of permanent fencing in order to maintain visual appeal for recreationists. Because of this restriction, during the grazing period only, the team constructed temporary rectangular exclosures, 50 m x 20 m, to prevent grazing around those transects upon which data were collected for ungrazed effects. These mobile structures consisted of 4 metal T-posts (1 in each corner) and 14 plastic step-in posts interspersed along the perimeter to secure 2 levels (upper and lower) of single strand poly electric tape attached to a portable solar-powered fence charger. Common wildlife to the area, like deer, rabbit, and elk, were able to pass freely through data collection sites at all times, but cattle were inhibited by the 1.2 m tall exclosures. This design isolated the effects of livestock from the effects of naturally-occurring wildlife.

In a similar manner, utilizing plastic step-in posts and poly electric tape attached to a portable solar-powered fence charge, temporary pastures were created to enclose cattle during a grazing period around those transects upon which data were collected for grazed effects. The 50 m x 20 m exclosures (ungrazed areas) were enclosed within these larger pastures. Therefore, any given pasture at any point in time included 1 pair of transects (grazed and ungrazed). As cattle were rotationally grazed across the BCNA valley, they were managed within these temporary pastures of varying sizes depending on geography, herd size, and land management objectives. This gave a unique management strategy to each grazed area.

Research Methods Timeline and Grazing Regime

Eight response variables were chosen to study the effects of strategic grazing management. These variables coincided with land management goals of the City of Fort Collins (soil and vegetation), as well as livestock management goals of Sylvan Dale Ranch (forage quality) (Table 2.1).

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

Soil	**Vegetation**	**Forage Quality**
Total nitrogen	Relative abundance native graminoids	Crude protein
Organic carbon	Relative abundance native forbs/subshrubs	Acid detergent fiber
	Relative abundance noxious species	Neutral detergent fiber

The timeline for research methods was determined by various factors inherent in a collaborative study between public and private sectors. Baseline data for soil and vegetation variables were collected from each transect in July 2016 before cattle were introduced to the area. To avoid interference with the peak recreation season for hikers, mountain bikers and horseback riders on BRNA, the City of Fort Collins designated two grazing seasons per year.

Spring graze was to occur sometime between March and early June, and fall graze was to occur sometime between September and November. Drinking water for the cattle was available in BRNA's natural drainages in the spring season and available via pumping from an irrigation ditch in the fall. Due to these logistics and BRNA transect locations, cattle were grazed on the following schedule: pastures 1 and 2 in September 18 - October 4 in 2016, and pastures 3, 4, 5, and 6 from March 16 - June 5 of 2017. Vegetation samples for forage quality analysis and utilization calculations were collected from each transect within 3 days of removal of cattle from a pasture. Following 1 year of strategic grazing, data for soil and vegetation variables as well as post-recovery forage clippings from grazed areas were collected in July of 2017. This timeline is summarized in Table 2.2.

Table 2.2: Timeline of research methods for each of the 6 pastures (P1, P2, P3, P4, P5, P6), indicated by month and year.

		P1	**P2**	**P3**	**P4**	**P5**	**P6**
Year 2016	**Baseline soil & vegetation data collected**	7/16	7/16	7/16	7/16	7/16	7/16
	Start of fall grazing period	9/16	10/16				
	Utilization and forage quality samples collected from treatment and control plots	9/16	10/16				
Year 2017	**Start of spring grazing period**			3/17	4/17	5/17	6/17
	Utilization and forage quality samples collected from treatment and control plots			3/17	4/17	5/17	6/17
	Post-graze soil & vegetation data collected	7/17	7/17	7/17	7/17	7/17	7/17
	Forage quality samples collected from treatment plots only (after rest period)	7/17	7/17	7/17	7/17	7/17	7/17

In order to reduce observer variability and confounding methodological effects, the same researchers collected data for each of the response variables throughout the entire study .[32]

Soil & Vegetation Measures

Vegetation data and soil samples were collected from quadrats measuring 2 m x 0.5 m along each transect. There were 10 quadrats placed along each of the 12 transects at measurements ending in 2's and 7's, for example at 2 m, 7 m, 12 m, 17 m, and so on to the 47 m mark as the last quadrat placement. This resulted in 120 individual observations that were measured along transects for each of the response variables pertaining to soil and vegetation categories. Soil response variables of total nitrogen (N) and organic carbon (SOC) were selected due to their importance in plant growth and as indicators of nutrient cycling between biotic and abiotic ecosystem factors.[27; 33] Vegetation response variables of relative abundance of native graminoids (NG), native forbs/subshrubs (NF), and noxious plant species (NS) were selected as indicators of increasing plant species diversity in lieu of dominating exotic species, and because increased native species abundance was an objective of the land manager's conservation goals.[28; 34]

Soil samples were collected using a stainless steel soil probe with a 2 cm diameter. A single core from a random location in each quadrat was taken to a 10 cm depth. Each core was divided into 2 sub-cores representing 2 levels of depth, 0-5 cm and 5-10 cm. This resulted in the collection of 20 sub-cores per transect, 10 from the 0-5 cm depth and 10 from the 5-10 cm depth. In total, 240 samples were collected per sampling period from the 12 transects. These samples were stored in individual bags and air-dried for 4 weeks. The samples were then finely ground using a mechanical porcelain pestle. The samples were then analyzed for percent total carbon and percent total N as determined by LECO combustion analysis.[35] Inorganic carbon was analyzed using the "method of gravimetric determination of calcium carbonate".[36] Percent inorganic carbon was subtracted from percent total carbon to determine percent SOC. These analyses were performed in Colorado State University's Soil, Water, and Plant Testing Laboratory in August-September of 2016 for baseline data and August-September of 2017 for post-grazing period data. Photographs of various data collection methods are included in Appendix C.

Vegetation composition was measured by basal cover inventory. Within each quadrat, the percent basal cover of every plant species, litter, rock, fungi, manure, and bare ground was estimated by a botanist from the City of Fort Collin's Natural Areas Department. The basal cover of each quadrat totaled 100%. Plant species were then grouped into the following categories: total vegetation, native graminoids, exotic graminoids, native forbs/subshrubs, exotic forb/subshrubs, and noxious species (as declared by the Colorado Department of Agriculture).[37] From these measurements of absolute abundance, the proportion of relative abundance of NG, NF, and NS ($\%\ relative\ abundance = \frac{\%\ absolute\ abundance}{\%\ total\ vegetation}$) was calculated and utilized for statistical analysis. Baseline data collection for these variables was conducted in July 2016 and post-grazing period data were collected in July 2017. These collection times correlated with the season of peak vegetation growth.

Forage Quality Measures

As an essential factor of livestock management, forage quality, was also analyzed as response to grazing. Crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) were chosen as response variables due to their significance in ruminant performance and digestibility.[38] Forage samples were not collected along the linear transects to avoid interference with soil and vegetation data collection. Instead, 6 forage samples were collected from random locations within each ungrazed area to be used as a baseline measure, and 6 forage samples were collected from random locations within each grazed area within 3 days of removal of cattle from that pasture. In accordance with the grazing schedule, these samples were collected from pastures 1 and 2 in fall 2016, and 3, 4, 5, and 6 in spring 2017. Post-grazing period samples were collected from grazed areas in July 2017 during peak vegetative growth. Table 2.3 summarizes the sample collection schedule for each of the pastures, including grazed and ungrazed areas. Note that this schedule coincides with the research methods timeline in Table 2.2.

Table 2.3: Forage sampling schedule, indicating rest period prior to sampling for each of the 6 pastures. $_a$ indicates grazed. $_b$ indicates ungrazed. "no rest" indicates samples were collected within 3 days post-grazing. Summer 2017 samples were collected during the season of peak vegetative growth.

	Fall 2016	Spring 2017	Summer 2017
1_a	Sample 1, no rest		Sample 2, 10 month rest
1_b	Baseline Sample		
2_a	Sample 1, no rest		Sample 2, 9 month rest
2_b	Baseline Sample		
3_a		Sample 1, no rest	Sample 2 , 9 month rest
3_b		Baseline Sample	
4_a		Sample 1, no rest	Sample 2, 2 month rest
4_b		Baseline Sample	
5_a		Sample 1, no rest	Sample 2, 3 month rest
5_b		Baseline Sample	
6_a		Sample 1, no rest	Sample 2, 3 month rest
6_b		Baseline Sample	

Forage samples were collected by clipping all standing biomass at ground level within 0.25 m x 0.25 m frames. The samples were oven-dried at 55°C for a minimum of 3 days, ground to pass through a 2-mm sieve using a Wiley Model 4 grinder. Samples were ground a second time to pass through a 1-mm sieve using a Foss Tecator Mode l093 Cyclone Mill. These finely ground samples were then analyzed with Near Infrared Reflectance Spectroscopy (NIR) using a Spectrastar XT 2600 XT-R, Reflectance monochromator (680 –2600 nm) with Rotating Top Window Configuration built in Windows 7 computer with 17" touch screen, UScan software, with multi cup adapter and ISI ring cup/powder cup adapter. NIR was calibrated for detection accuracy using the results of a sample subset analyzed by wet chemistry. Sample preparation and NIR analyses were conducted in Colorado State University's Department of Animal Sciences' Nutrition Lab.

Strategic Grazing Management Factors

Inferential methods were not used to assess the individual effects of 4 strategic grazing management factors: grazing season, herd type, grazing intensity, and stocking density. Instead, these factors of the grazing management were recorded or calculated in order to provide descriptive statistics of the regime that evolved throughout the study. Grazing season was determined by the land management agency and location of available water. Cattle herd composition was variable and dependent upon the logistical needs of the ranch, while grazing intensity, and stocking density were determined by target plant species presence, weather events, cattle behavior, and rancher interpretation of plant and soil responses such as residual stubble height and compaction.

Specifically, grazing intensity was based on forage utilization, which was measured at a point-in-time within 3 days following each grazing period. Forage utilization was calculated using the following equation of weights of dried forage samples from grazed and ungrazed areas, ($\%\ utilization = \frac{mean\ ungrazed\ biomass - mean\ grazed\ biomass}{mean\ ungrazed\ total\ biomass}\ kg/ha$). These measurements are summarized in Table 2.4.

Table 2.4: Mean (m) and standard deviation (sd) of total above ground biomass for each pasture (P1, P2, P3, P4, P5, P6) prior to grazing and after grazing, using 6 forage samples per pasture. Grazing utilization was calculated by ($\% \boldsymbol{utilization} = \frac{\boldsymbol{mean\ ungrazed\ biomass - mean\ grazed\ biomass}}{\boldsymbol{mean\ ungrazed\ total\ biomass}}$).

	P1		P2		P3		P4		P5		P6	
	m	**sd**	**m**	**sd**	**m**	**sd**	**m**	**sd**	**m**	**sd**	**m**	**sd**
Total above ground biomass (kg/ha) before grazing	1,723.3	725.5	1,503.3	516.8	1,310.0	753.3	2,063.3	443.5	1,883.3	816.5	2,096.7	1724.3
Total above ground biomass (kg/ha) after grazing	203.3	93.3	596.7	422.3	990.0	287.5	553.3	298.4	506.7	364.8	880.0	1003.0
Utilization (%)	88.2		60.3		24.4		73.2		73.1		58.0	

For descriptive purposes, categorical measures of grazing intensity based on point-in-time utilization were applied from a standardized classification system (Table 2.5).[39] Photographs exemplifying various degrees of forage utilization during the study are included in Appendix D.

Table 2.5: Grazing intensity classification based on utilization (Holechek, 2000).

Utilization	**Class**
0-30%	Light
31-40%	Conservative
41-50%	Moderate
51-60%	Heavy
61% +	Severe

Strategic, yet flexible decisions regarding seasonality, grazing intensity, and stocking density were determined through continuous collaboration between the ranch manager, land manager, and researcher as grazing periods progressed. The cattle were contained in a temporarily fenced rotational grazing system where there was enough flexibility for the team to manage the herd with land management objectives in mind. This strategic grazing management strategy resulted in a unique grazing regime implemented on each of the 6 pastures. The resulting grazing regime for each pasture is discussed in detail below and summarized in Table 2.6.

Except for pasture 3 where grazing intensity was “light,” the grazing intensity used during these grazing periods was “heavy” to “severe.”[39] The livestock manager’s strategy here was to heavily impact and remove large amounts of standing dead biomass as well as trample the thick blanket of litter that had accumulated over the previous 10 years of grazing absence. The goal was aid in decomposition, nutrient cycling, and light penetration.

The fall grazing period was characterized by a 96 head cow-calf herd (1.2 AU per pair) at lower stocking densities. Due to the presence of young calves, ample space was given to this herd in an effort to reduce stress associated with crowding. The majority of forage during this grazing period was observed as standing dead or approaching the dormant stage, which was indicative of lower nutritional value. Therefore, it was intended that a lighter stocking density would give the herd increased ability to be selective in their grazing and fulfill their nutritional needs more adequately.

The spring grazing period was characterized by a 41-60 head dry cow/stocker herd (0.8 AU average per head) at higher stocking densities. The livestock manager chose this approach due to the presence of new plant growth and emerging young shoots. Cheatgrass, an undesirable exotic graminoid, was also abundant in the area and more palatable in its early growth stage this time of year. Using a more intense, short duration approach (Table 2.6), the animals were not allowed to be as selective in their grazing and did not have time to return to choice plants as they recovered from initial defoliation. With less space to be more selective, the cattle were forced to consume the cheatgrass, standing dead biomass, and dormant vegetation, along with the more succulent spring growth. This strategy was used in an attempt to negatively impact the cheatgrass population, while allowing a competitive release of the desirable species.

Pasture 3 was the only area where a light grazing intensity was used. This was because the pasture was located in proximity to a recreation trail and proved difficult for water transport. Therefore, the herd was moved on and off this site more quickly in order to return cattle to an ample water source and avoid interference with recreationists.

Table 2.6: Grazing regime for each of the 6 pastures (P1, P2, P3, P4, P5, P6) based on strategic grazing management approach. Grazing factors such as season, grazing intensity, stocking density, and herd type were implemented based land management and livestock management necessities and objectives. Stocking density is in animal units per hectare per number of days.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**
Season	Fall	Fall	Spring	Spring	Spring	Spring
Grazing intensity	severe	heavy	light	severe	severe	heavy
Stocking Density	0.14AU/ha 7 days	0.14AU/ha 5 days	32.8AU/ha 0.5 days	16.4AU/ha 2 days	12AU/ha 2 days	12AU/ha 6 days
Herd Type	cow-calf	cow-calf	dry cow/ stocker	dry cow/ stocker	dry cow/ stocker	dry cow/ stocker

STATISTICAL MODELING AND OUTCOMES

General

To compare effects on grazed versus ungrazed areas, statistical analyses were performed using RStudio, Version 1.1.383 (2009-2017). Eight response variables were placed into linear mixed models. Restricted maximum likelihood (REML) t-tests were used to determine differences in the means of soil and vegetation variables between year 2016 and 2017. Paired t-tests were used to examine the effect of grazing and Welch two-sample t-tests were used to examine the effect of rest on forage quality variables. A block effect of transect pair was incorporated in all analyses to account for biological variability from one pasture to another across the landscape. The grazing effect and random block effect were treated as main effects, while year 2016 was treated as a covariate. Significance was set at $\alpha \leq 0.05$ with a 95% confidence interval. Model assumptions were tested using a residual versus fitted plot and a normal Q-Q plot, in order to ensure appropriateness of the model. The Shapiro-Wilk test was used to test normality. All data sets utilized in this study satisfied model assumptions by illustrating equal variance, linearity, and a normal distribution. For all response variables and their statistical analyses, detailed means and standard deviations tables can be found in Appendix E, and statistical output tables can be found in Appendix F.

To better explore and interpret data and statistical results, weather conditions during the period of research were considered. Average temperature during the growing season of March-September was 14.6°C in 2016 and 14.5°C in 2017.[40] Maximum temperatures for each growing season were similar except during the month of July, where the maximum temperature of 36°C was reached 20 days in 2017, but only 11 days in 2016.[40] Minimum temperatures during spring of 2016 and 2017 were quite different. During the months of April and May of 2017, minimum temperatures of -6.7°C and -1.7°C, respectively, were met 50 out of 60 days, compared to only 3 out of 60 days in 2016.[40] For the remainder of both growing seasons, minimum temperatures were similar. Annual precipitation was 21.2 cm in 2016 and 41.1 cm in 2017, nearly double.

The majority of this difference could be attributed to precipitation during the months of April-October.[40]

Soil Variables

It was hypothesized that compared to ungrazed areas, grazed areas will exhibit higher levels of total N and SOC. Analysis for percent N and SOC was performed using 2 fixed effects, grazing and depth, and 1 covariate, the baseline year 2016. Likelihood ratio tests did not support the use of models additionally testing the two-way interactions between fixed effects, since the interaction terms were not significant (N P = 0.06; SOC P = 0.13). Figure 2.3 summarizes 2016 baseline measurements averaged across all 12 transects.

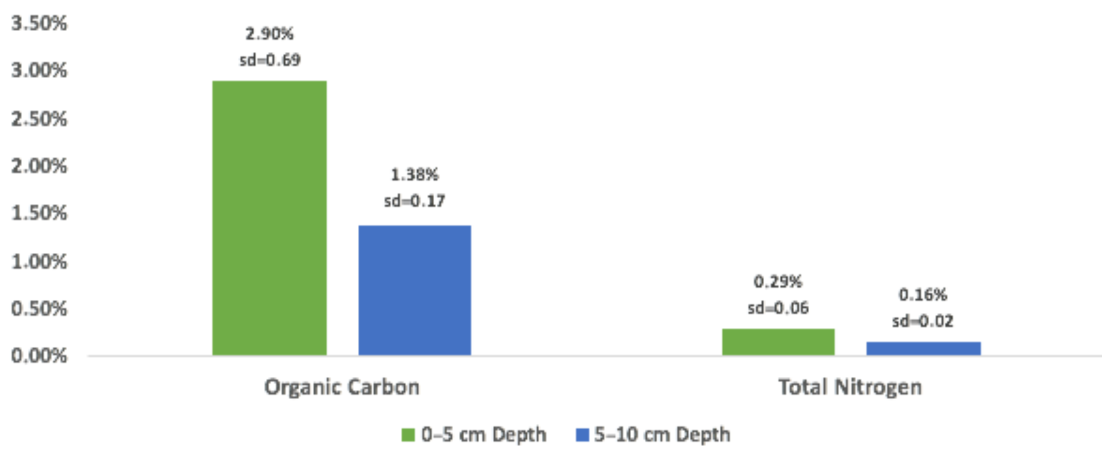


Figure 2.3: Baseline measures of mean soil organic carbon and total nitrogen, with standard deviations (sd), at 2 levels of depth, for all 12 transects. Baseline data was collected on Bobcat Ridge Natural Area in July 2016.

Results indicated there was no difference in SOC between grazed and ungrazed areas (P = 0.97) from year 2016 to 2017. There was also no difference in SOC between the lower and upper soil depths (P = 0.12). Means and standard deviations for SOC are summarized in Table 2.7. In addition, there was no block-to-block (pasture-to-pasture) variation (P = 0.73).

Table 2.7: Summary of means and standard deviations of soil organic carbon (SOC) at 2 levels of depth in grazed and ungrazed areas in July 2016, before grazing, and July 2017, after grazing.

	Grazed 2016		**Ungrazed 2016**		**Grazed 2017**		**Ungrazed 2017**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
SOC 0-5 cm	2.96	0.56	2.83	0.84	2.62	0.37	2.49	0.52
SOC 5-10 cm	1.41	0.13	1.36	0.20	1.49	0.38	1.54	0.39

Regarding total N, results indicated there was no difference between grazed and ungrazed plots ($P = 0.64$) from 2016 to 2017. There was also no difference in N between the lower and upper soil depths ($P = 0.40$). Means and standard deviations for total N are summarized in Table 2.8. In addition, there was no block-to-block variation ($P = 0.50$).

Table 2.8: Summary of means and standard deviations of total nitrogen (N) at 2 levels of depth in grazed and ungrazed areas in July 2016, before grazing, and July 2017, after grazing.

	Grazed 2016		**Ungrazed 2016**		**Grazed 2017**		**Ungrazed 2017**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
N 0-5 cm	0.29	0.04	0.28	0.08	0.28	0.04	0.25	0.08
N 5-10 cm	0.16	0.02	0.16	0.02	0.15	0.03	0.15	0.06

As illustrated in Figures 2.4 and 2.5, for both SOC and N, the grazed and ungrazed data points were fitted to lines that were nearly equal in origin and slope. This showed the lack of difference in mean SOC and N values between grazed and ungrazed areas. Therefore, grazing did not have a significant effect on SOC or N. The 95% confidence intervals were also relatively wide indicating low precision in the ability of the estimates to predict the relative population means.

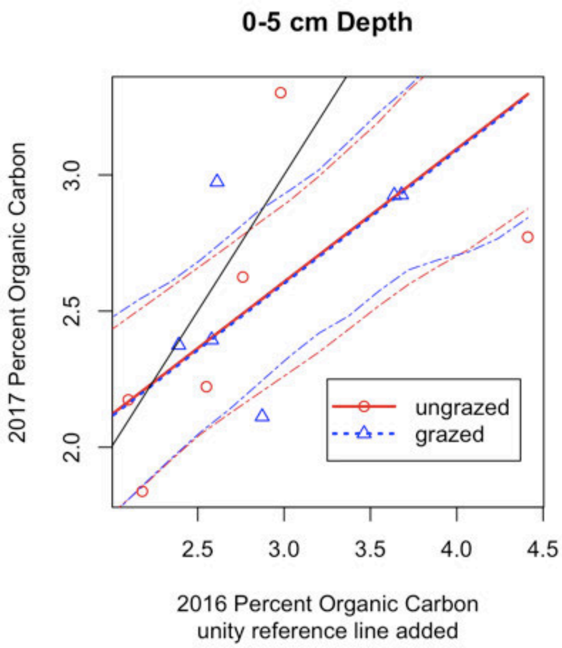


Figure 2.4: Percent organic carbon (bold lines) with 95% confidence intervals (faded lines) for the 0-5 cm soil depth with respect to the baseline year (2016) and post-grazing year (2017). The grey reference line was used to show agreement between year 2016 and 2017 with an origin of (0, 0) and slope = 1.

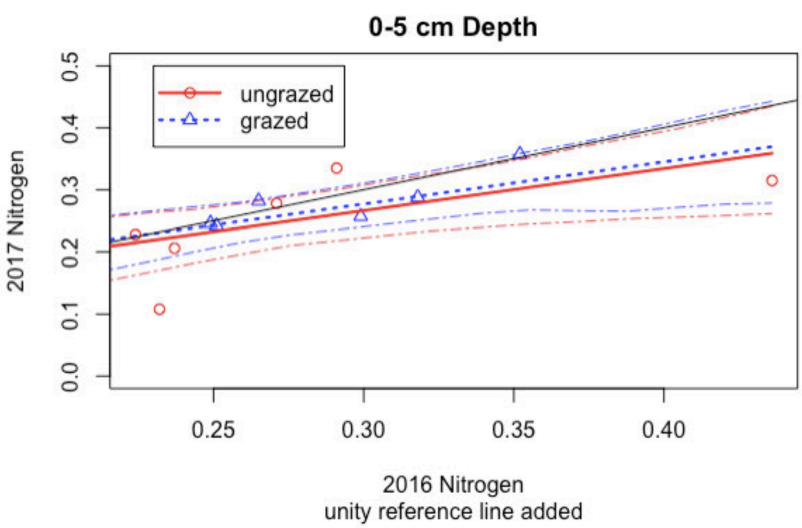


Figure 2.5: Percent total nitrogen (bold lines) with 95% confidence intervals (faded lines) for the 0-5 cm soil depth with respect to the baseline year (2016) and post-grazing year (2017). The grey reference line was used to show agreement between year 2016 and 2017 with an origin of (0, 0) and slope = 1.

Vegetation Variables

It was hypothesized that compared to ungrazed areas, grazed areas will exhibit a higher relative abundance of native graminoids and native forbs/subshrubs, and a lower relative abundance of noxious species. The vegetation analyses were performed using the fixed effect of grazing and covariate of the baseline year 2016. Statistical analyses were successfully performed on 2 of the 3 measures of plant species composition: relative abundance of NG and NF. Fitting a model for relative abundance of NS was attempted. However, due to a lack of presence of NS along grazed and ungrazed transects and an excess of zeros in the data (16 out of 24 measurements were 0), the analysis could not be executed.

Baseline vegetation data was collected after a 10-year absence from livestock grazing. In summary, total vegetation basal cover comprised the smallest portion of above ground composition with respect to bare ground and litter (Figure 2.6).

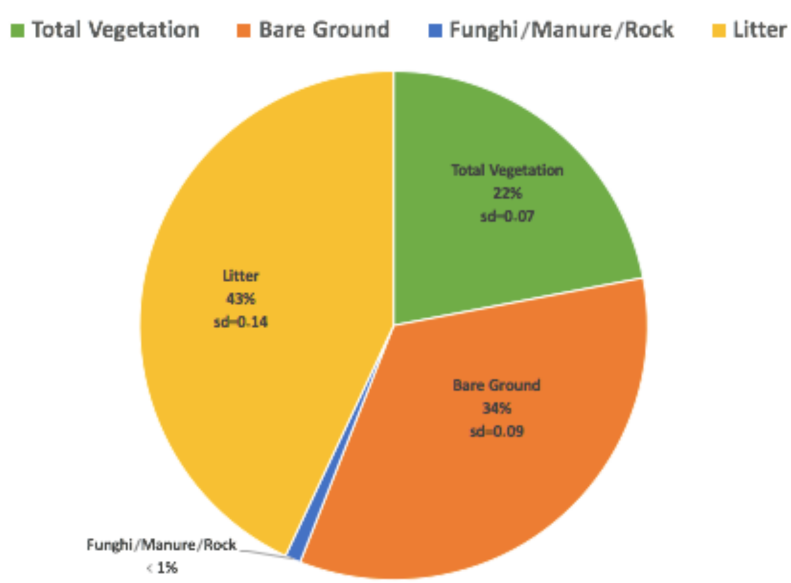


Figure 2.6: Baseline measures of vegetation basal cover, with standard deviations (sd), for all 12 transects. Baseline data was collected on Bobcat Ridge Natural Area in July 2016.

For descriptive purposes, Figure 2.7 summarizes baseline relative abundance of 5 groups of plant species prior to grazing. Exotic graminoids had the greatest relative abundance based on basal cover, nearly 7 times greater than the next most abundant plant species group of NF, and nearly 10 times greater than NG.

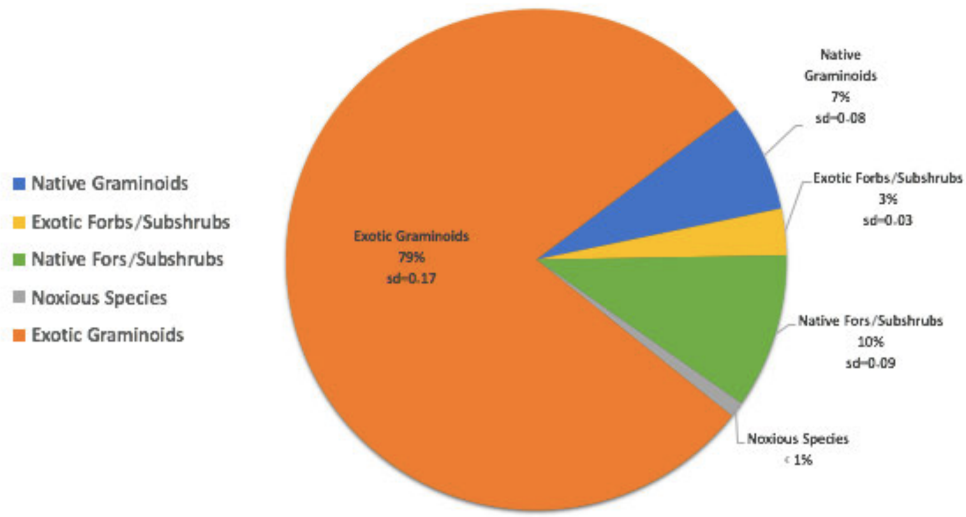


Figure 2.7: Baseline measures of relative abundance of 5 groups of plant species, with standard deviations (sd), for all 12 transects. Baseline data was collected on Bobcat Ridge Natural Area in July 2016.

Results indicated that there were no differences in the relative abundance of NG (P = 0.15) or NF (P = 0.74) between grazed and ungrazed plots. Means and standard deviations for relative abundance of NG and NF are summarized in Table 2.9. In addition, there was no block-to-block variation in either model (NG P = 1.00; NF P = 0.40).

Table 2.9: Summary of means and standard deviations of relative abundance of native graminoids and native forbs/subshrubs in grazed and ungrazed areas in July 2016, before grazing, and July 2017, after grazing.

	Grazed 2016		Ungrazed 2016		Grazed 2017		Ungrazed 2017	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev**
Native Graminoids	0.05	0.08	0.08	0.09	0.05	0.09	0.14	0.16
Native Forbs/Subshrubs	0.12	0.11	0.80	0.07	0.09	0.08	0.06	0.07

As illustrated in Figure 2.8 for NG, the grazed and ungrazed data points were fitted to lines that were nearly equal in slope. This showed the lack of difference in mean NG values between grazed and ungrazed areas. Therefore, grazing did not have a significant effect on NG. The 95% confidence intervals were also relatively wide indicating low precision in the ability of the estimates to predict the relative population means.

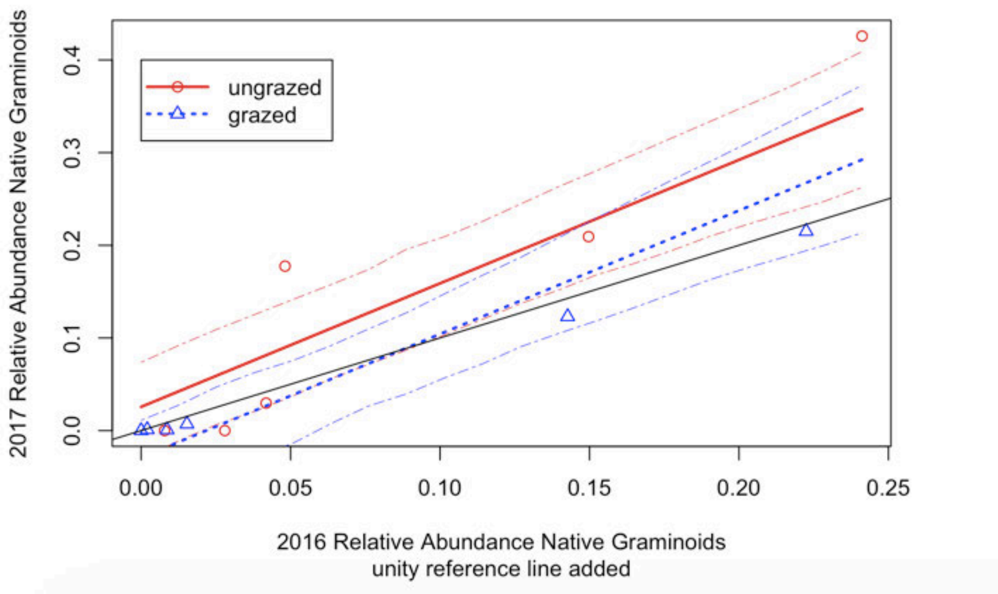


Figure 2.8: Relative abundance of native graminoids (bold lines) with 95% confidence intervals (faded lines) with respect to the baseline (2016) and post-grazing year (2017). The grey reference line was used to show agreement between year 2016 and 2017 with an origin of (0, 0) and slope = 1.

For NF, the model detected a significant year-to-year difference averaged across both grazed and ungrazed areas ($P = <0.01$) with a lower presence of NF in 2017 compared to 2016. In Figure 2.9, this difference was illustrated by the slopes of the fitted lines for grazed and ungrazed means, which were less than 1, as referenced by the unity line (grey). An explanation for this could only be explored outside the effects of grazing, since it appeared to be a landscape-scale shift. Because forbs are temporally sensitive to weather events, especially precipitation and temperature, these effects were considered.[27]

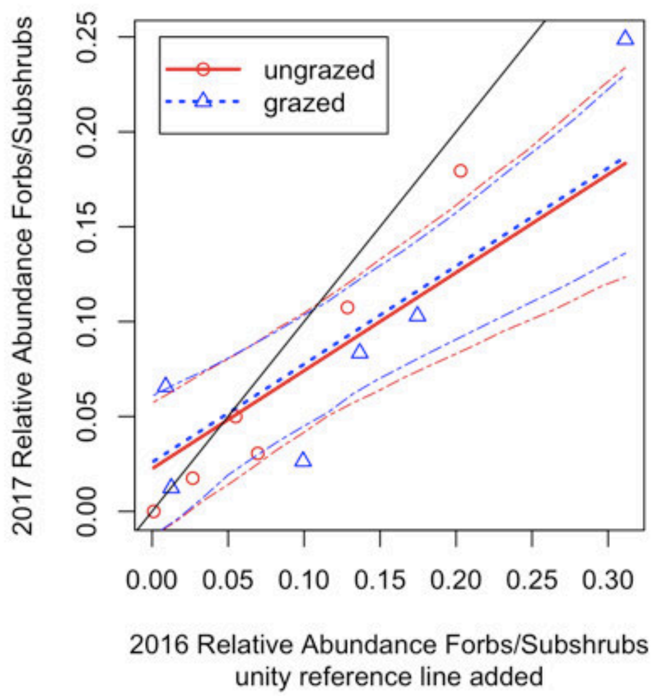


Figure 2.9: Relative abundance of native forbs/subshrubs (bold lines) with 95% confidence intervals (faded lines) with respect to the baseline (2016) and post-grazing year (2017). The grey reference line was used to show agreement between year 2016 and 2017 with an origin of (0, 0) and slope = 1.

Forage Quality Variables

It was hypothesized that forage quality would follow a particular pattern because of grazing: a decrease in forage quality shortly following grazing, an increase in forage quality with a period of rest, and a decrease in forage quality with continued absence of grazing. Therefore, there were 2 effects investigated in this study, the effect of grazing and the effect of rest.

The results of the analysis of the effect of grazing on CP, ADF, and NDF indicated that crude protein was lower (P = <0.01) and neutral detergent fiber was higher (P = 0.05) shortly following grazing, but acid detergent fiber did not differ (P = 0.51) in grazed versus ungrazed areas. This means that forage quality was lower within 3 days following a grazing period compared to areas that had not been grazed in at least 10 years. In other words, the act of defoliation removed plant parts that included cell contents such as CP, but left behind plant parts that were mostly cell wall components (ADF and NDF). This remaining plant material (stubble) was of lower forage quality than plants that were ungrazed. Sample means and standard deviations for this analysis are summarized in Table 2.10.

Table 2.10: Summary of means and standard deviations of crude protein (CP), acid detergent fiber (ADF) and neutral detergent fiber (NDF) in ungrazed areas and grazed areas within 3 days of grazing.

	Ungrazed		**Grazed**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**
CP (%)	7.94	3.87	6.77	3.54
ADF (%)	40.62	4.03	41.36	2.53
NDF (%)	61.84	4.57	63.60	4.88

The results of the analysis of the effect of rest on CP, ADF, and NDF indicated that areas grazed in the spring, receiving 2-3 months of rest, demonstrated higher forage quality than areas grazed in the fall, receiving 9-10 months of rest. This was detected by higher crude protein (P = 0.03), and a tendency for lower neutral detergent fiber (P = 0.06), but no difference in acid detergent fiber (P = 0.97). This means that 2-3 months after grazing, following a period of rest and regrowth, plants exhibited higher forage quality than plants who had endured a prolonged, 9-10 month, absence from grazing. Sample means and standard deviations for this analysis are summarized in Table 2.11.

Table 2.11: Summary of means and standard deviations of crude protein (CP), acid detergent fiber (ADF) and neutral detergent fiber (NDF) for areas grazed in Fall 2016 receiving 9-10 months of rest and areas grazed in Spring 2017 receiving 2-3 months of rest. Samples were collected in July 2017, during peak vegetative growth.

	Grazed in Fall, Rested 9-10 months		**Grazed in Spring, Rested 2-3 months**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**
CP (%)	6.22	0.57	8.34	0.89
ADF (%)	37.0	0.86	36.9	1.08
NDF (%)	60.6	0.83	57.6	1.89

It is well evidenced that cell wall components (ADF and NDF) of plant tissue increase, and digestibility decreases with increased stages of plant maturity.[6; 27; 38] Through the disturbance of grazing, standing dead or mature plant matter is removed, allowing improved plant productivity.[27; 41] In a similar manner, adequate grazing during the growth stage, prevents plant maturation into the reproductive stage, which is associated with a natural decrease in nutritive quality and digestibility.[27; 41] Therefore, grazing may contribute to the maintenance of higher levels of nutrients, by keeping plants in a growth stage containing more immature, nutrient-dense foliage.[6; 38; 41]

In this study, samples collected within 3 days after grazing mostly included stubble, or stem, and less leaf tissue, which encompassed lower quality forage than samples that hadn't been grazed for over 10 years, despite large amounts of standing dead biomass in the latter. However, after cattle grazing and only 2-3 months of rest, grazing areas contained less standing dead and increased amounts of younger foliage containing higher crude protein and lower lignin, cellulose, and hemicellulose (less ADF and NDF) and therefore improved digestibility. With continued rest in absence of grazing, the plants were allowed to enter into advanced stages of maturity, which reflected lower digestibility, lower CP and a tendency for higher NDF. This trend in the data supported the hypothesis that defoliation due to grazing followed by a certain rest period may improve forage quality by preventing or delaying increased stages of plant maturity. However, continued absence of grazing and a prolonged rest period may cause a decrease in forage quality because of plant maturity.

BRINGING MEANING TO THE METRICS

There were several challenges common to grazing research, which were addressed by the design and implementation of this study. The spatial-temporal challenge of grazing studies was addressed by the use of pastures containing paired, grazed and ungrazed, linear transects where data were collected systematically and repeatedly to detect changes in specific plant communities and soils through time.[13] Transects were randomly selected within the confines of a single soil type to control for confounding biological variation. Ample recovery time between the baseline and final sampling dates was provided for each grazing area. Soil and vegetation data collection was performed during the same month of each year. The study was also designed to reflect real-time real-scale ranching, and therefore the use of irregularly shaped pastures of various sizes were used, instead of small-scale plots of equal size and shape. Due to the spatial-temporal nature of this study, results should only be interpreted for the specific region and conditions under which the study was conducted.[13]

The human dimension and the method of strategic grazing management was incorporated by allowing the collaborating ranch manager to make decisions regarding stocking density, grazing intensity, and the timing of pasture rotations based upon his knowledge and observation of plant response, weather occurrences, and cattle behavioral cues.[9] Despite the various grazing regimes implemented on each pasture, there was no pasture-to-pasture variation. Due to these homogenous effects of grazing across the landscape, despite adaptations in factors such as grazing intensity, stocking density, and seasonality, specific outcomes could not be attributed to particular managerial decisions or strategies. In other words, variations in the grazing factors, for example the use of higher or lower stocking densities, made no difference in the recovery potential of grazed vegetation or trampled soil.

The only response variables that showed notable differences in grazed versus ungrazed areas were in regards to forage quality, CP and NDF. The lack of differences predicted by the statistical modeling of the other response variables could be due in part to the short duration of the study.[9; 13; 20; 42] However, in this study, the lack of detectable change in these indicators of rangeland health also spoke to the resiliency of plant and soil communities in the face of intensive grazing. In less than 1 year, and after enduring light to severe grazing intensities, soil and vegetation was able to recover and regenerate, returning plant community composition to a state relative to the pre-grazed condition.

The limitation of sample size was considered in the interpretation of statistical outcomes. This research team believes that the analyses could be more conclusive with a larger sample size. The study integrated 240 individual observations of soil N and SOC, nearly 2,400 individual measures of plant species presence, and 108 measurements of each forage quality constituent. However, multiple data observations collected along a single transect could not be considered true replications, a mistake often made in ecological research of this nature.[43; 44] They were therefore considered pseudo replicates and averaged across each transect, resulting in a single observation per variable for each of the 12 transects. These transect averages were entered into statistical analysis, resulting in a reduced sample size compared to the number of individual observations made for each response variable.

It was hypothesized that compared to areas excluded from grazing, areas where strategic grazing was implemented would exhibit: increased nutrient cycling by integration of organic carbon and nitrogen into the soil, increased abundance of native graminoids and native forbs/subshrubs, and reduced abundance of noxious weeds. It was also hypothesized that forage quality would follow a particular pattern because of grazing: a decrease in forage quality shortly following grazing, an increase in forage quality with a period of rest, and a decrease in forage quality with continued absence of grazing. In summary, after analyzing all data and investigating possible main effects, random effects, strengths, and limitations of this study, the following concluding points were made:

1. Forage quality was lower shortly after grazing, but was higher in areas that were grazed in the spring and rested for 2-3 months, than areas that were grazed in the fall and rested for 9-10 months. This was indicated by significant differences in levels of CP and NDF.

2. Percent SOC, N, relative abundance of NG and NF, and percent ADF did not exhibit significant changes due to grazing.
3. Random environmental events outside of the effects of grazing produced an overall decrease in forb/subshrub growth in 2017 compared to 2016.
4. Varying levels of grazing factors, such as grazing intensity, stocking density, seasonality, and herd type, implemented under strategic grazing management, produced homogenous effects across all experimental pastures.

WHERE DO WE GO FROM HERE

This study exemplified a model for collaborative conservation utilizing strategic grazing management as an effective and sustainable framework for grazing cattle on conservation lands. This was achieved through partnership between academic (Colorado State University), government (City of Fort Collins), and private sectors (Sylvan Dale Ranch). The response variables selected for the experimental design coincided with the land manager's ecological goals of restoring native ecology to the Natural Area. Rangeland health attributes as indicated by Pyke et. al (2002) were converted into response variables that were scientifically evaluated: soil nitrogen, soil organic carbon, native graminoids, native forbs/subshrubs, and noxious species.[32] Forage quality was also evaluated, since it is an important factor to livestock management, especially on biologically diverse landscapes.

The research team acknowledged the fact that long-term ecological change on the landscape level of our earth's rangelands is gradual.[9; 13; 20; 42] For several of the response variables measured in this study, change in either direction was not detected, meaning that 1 year of strategically managed cattle grazing may not have been productive nor counterproductive for rangeland vitality. The scientific literature has shown that the return of grazing to rangelands can increase biodiversity and nutrient cycling.[6-8; 12; 13; 45-47] Herbivory is a natural dynamic and driver of rangeland balance, which can maintain and even restore the health of these resilient habitats.[7; 27] It was therefore recommended that this study be continued, in order to obtain more conclusive results for sustainable long-term rangeland management.[9; 13] As part of a long-term project, this collection of data and analysis was important for the initiation of a collaborative monitoring process, which will eventually determine if strategic grazing management proves to be helpful or harmful for land management goals on BRNA. Continued research will aid ranchers and land managers in developing collaborations so that cattle might serve as partners in the conservation of rangelands, while maintaining animal performance and beef production objectives. Effective livestock management is key. Therefore, the human decision-making dimension is imperative to incorporate in future grazing studies.

It is this researcher's belief that the world's rangelands, and especially those in the state of Colorado, are natural treasures. They house some of the largest animal biomass on the planet and provide respite and inspiration for individuals who wish to reconnect with their own primitive roots in the wild. By anthropomorphic error, many rangelands are in poor condition, but are not irrevocably altered. It is the combination of wisdom and experience along with knowledge and science that will provide the tools with which to embark on this journey of restorative ranching, a necessary shift in the land management paradigm.

Nature works only in cycles, there are no straight lines.
The forward movement is provided by time. Everything within it must revolve.

-Anonymous

LITERATURE CITED

1. Breckenridge, R., W. Kepner, and D. Mouat. 1995. A process for selecting indicators for monitoring conditions of rangeland health. Environmental Monitoring and Assessment 36: 45-60.

2. Shute, L. L. 2011. Building a Future with Farmers: Challenges Faced by Young, American Farmers and a National Strategy to Help Them Succeed. National Young Farmers' Coalition. p. 3-40.

3. Donahue, D. L. 1999. The western range revisited: removing livestock from public lands to conserve native biodiversity. University of Oklahoma Press.

4. Ellis, J. E., and D. M. Swift. 1988. Stability of African pastoral ecosystems: alternate paradigms and implications for development. Rangeland Ecology & Management/Journal of Range Management Archives 41: 450-459.

5. Bell, R. H. 1971. A grazing ecosystem in the Serengeti. Scientific American 225: 86-93.

6. Frank, D. A., S. J. McNaughton, and B. F. Tracy. 1998. The ecology of the earth's grazing ecosystems. BioScience 48: 513-521.

7. Knapp, A. K., J. M. Blair, J. M. Briggs, S. L. Collins, D. C. Hartnett, L. C. Johnson, and E. G. Towne. 1999. The keystone role of bison in North American tallgrass prairie: Bison increase habitat heterogeneity and alter a broad array of plant, community, and ecosystem processes. BioScience 49: 39-50.

8. Hartnett, D., and P. Fay. 1998. Plant populations: patterns and processes. Grassland dynamics: long-term ecological research in tallgrass prairie. Oxford University Press, New York: 81-100.

9. Briske, D. D., N. F. Sayre, L. Huntsinger, M. Fernandez-Gimenez, B. Budd, and J. D. Derner. 2011. Origin, Persistence, and Resolution of the Rotational Grazing Debate: Integrating Human Dimensions Into Rangeland Research. Rangeland Ecology & Management 64: 325-334.

10. Provenza, F. D., J. J. Villalba, L. Dziba, S. B. Atwood, and R. E. Banner. 2003. Linking herbivore experience, varied diets, and plant biochemical diversity. Small ruminant research 49: 257-274.

11. Teague, W., S. Dowhower, S. Baker, N. Haile, P. DeLaune, and D. Conover. 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agriculture, Ecosystems & Environment 141: 310-322.

12. Toombs, T. P., J. D. Derner, D. J. Augustine, B. Krueger, and S. Gallagher. 2010. Managing for Biodiversity and Livestock: A scale-dependent approach for promoting vegetation heterogeneity in western Great Plains grasslands. Rangelands 32: 10-15.

13. Teague, R., F. Provenza, U. Kreuter, T. Steffens, and M. Barnes. 2013. Multi-paddock grazing on rangelands: why the perceptual dichotomy between research results and rancher experience? Journal of Environmental Management 128: 699-717.

14. Timmins, S. M. 2002. Impact of cattle on conservation land licensed for grazing in South Westland, New Zealand. New Zealand Journal of Ecology: 107-120.

15. Laca, E. A. 2009. New approaches and tools for grazing management. Rangeland ecology & management 62: 407-417.

16. Winder, J. 1999. Restorative Grazing. The Future of Arid Grasslands: Identifying Issues, Seeking Solutions: 283.

17. Fernandez-Gimenez, M., H. Ballard, and V. Sturtevant. 2008. Adaptive management and social learning in collaborative and community-based monitoring: a study of five community-based forestry organizations in the western USA. Ecology and Society 13.

18. Holling, C. S. 1978. Adaptive environmental assessment and management. John Wiley & Sons.

19. Grissom, G., and T. Steffens. 2013. Case study: adaptive grazing management at Rancho Largo Cattle Company. Rangelands 35: 35-44.

20. Danvir, R., G. Simonds, E. Sant, E. Thacker, R. Larsen, T. Svejcar, D. Ramsey, F. Provenza, and C. Boyd. 2018. Upland Bare Ground and Riparian Vegetative Cover Under Strategic Grazing Management, Continuous Stocking, and Multiyear Rest in New Mexico Mid-grass Prairie. Rangelands.

21. Steffens, T., G. Grissom, M. Barnes, F. Provenza, and R. Roath. 2013. Adaptive Grazing Management for Recovery: Know why you're moving from paddock to paddock. Rangelands 35: 28-34.

22. Gerrish, J. 2004. Management-intensive grazing: the grassroots of grass farming.

23. Briske, D. D., J. Derner, J. Brown, S. Fuhlendorf, W. Teague, K. Havstad, R. L. Gillen, A. J. Ash, and W. Willms. 2008. Rotational grazing on rangelands: reconciliation of perception and experimental evidence. Rangeland Ecology & Management 61: 3-17.

24. Barnes, M., and A. Hild. 2013. Foreword: Strategic Grazing Management for Complex Creative Systems. Rangelands 35: 3-5.

25. Barnes, M. 2015. Low-stress herding improves herd instinct, facilitates strategic grazing management. Stockmanship Journal 4: 31-43.

26. Kemp, D., P. Dowling, and D. Michalk. 1996. Managing the composition of native and naturalised pastures with grazing. New Zealand Journal of Agricultural Research 39: 569-578.

27. Gibson, D. J. 2009. Grasses and grassland ecology. Oxford University Press.

28. City of Fort Collins, N. A. P., Natural Resources Department. 2005. Bobcat Ridge Natural Area Management Plan.

29. Rondeau, R. e. J. 2001. Ecological system viability specifications for Southern Rocky Mountain ecoregion.

30. United States Department of Agriculture, N. R. C. S. N. 2018. *PLANTS Database*. Available at: http://plants.usda.gov/, 30 May 2018.

31. H. A. Sprock, D. A. N., B. P. Berlinger, K. A. Diller. 2013. *Ecological Site Description, Loamy Foothill*. Available at: https://esis.sc.egov.usda.gov/ESDReport/fsReport.aspx?approved=yes&repType=regular&id=R049XD202CO.

32. Pyke, D. A., J. E. Herrick, P. Shaver, and M. Pellant. 2002. Rangeland health attributes and indicators for qualitative assessment. Journal of range management: 584-597.

33. Wedin, D. A. 1996. Nutrient cycling in grasslands: an ecologist's perspective. Nutrient cycling in forage systems. Columbia: University of Missouri: 29-44.

34. Symstad, A. J., and J. L. Jonas. 2011. Incorporating biodiversity into rangeland health: plant species richness and diversity in Great Plains grasslands. Rangeland ecology & management 64: 555-572.

35. Nelson, D. W. a. L. E. S. 1982. Total Carbon, Organic Carbon, and Organic Matter. *In* Methods of Soil Analysis. Pt. 2. Chemical and Microbiological Properties. 2nd Ed. A.L. Page, Ed. Madison, WI: American Society of Agronomy, Soil Science Society of Agronomy.

36. Burt, R. 2004. Soil survey laboratory methods manual.

37. Colorado Department of Agriculture. *Noxious Weed Species*. Available at: https://www.colorado.gov/pacific/agconservation/noxious-weed-species. Accessed September 2016.

38. Kilcher, M. 1981. Plant development, stage of maturity and nutrient composition. Rangeland Ecology & Management/Journal of Range Management Archives 34: 363-364.

39. Holechek, J. L. 2000. Grazing intensity guidelines. Rangelands 22: 11-14.

40. High Plains Regional Climate Center. 2018. Available at: https://hprcc.unl.edu/. Accessed January 28 2018.

41. Heitschmidt, R., S. Dowhower, and J. Walker. 1987. Some effects of a rotational grazing treatment on quantity and quality of available forage and amount of ground litter. Journal of Range Management 40: 318-321.

42. Milne, J., and K. Osoro. 1997. The role of livestock in habitat management. Livestock systems in European rural development (ed. JP Laker and JA Milne): 75-80.

43. Heffner, R. A., M. J. Butler, and C. K. Reilly. 1996. Pseudoreplication revisited. Ecology 77: 2558-2562.

44. Hurlbert, S. H. 1984. Pseudoreplication and the design of ecological field experiments. Ecological monographs 54: 187-211.

APPENDIX A

Public announcement issued by the City of Fort Collins, 2017, for Chapter 2.

Grazing mimics the natural disturbance cycle.

A herd of about 60 cattle from Sylvan Dale Ranch will be in pastures that do not bisect trails.

Cattle may cross trails for grazing rotations, see *fcgov.com/naturalareas/status.php* for updates.

Questions?
Justin Fredrickson, Land Manag. Technician, 970-416-2527
Rangers, 970-416-2147

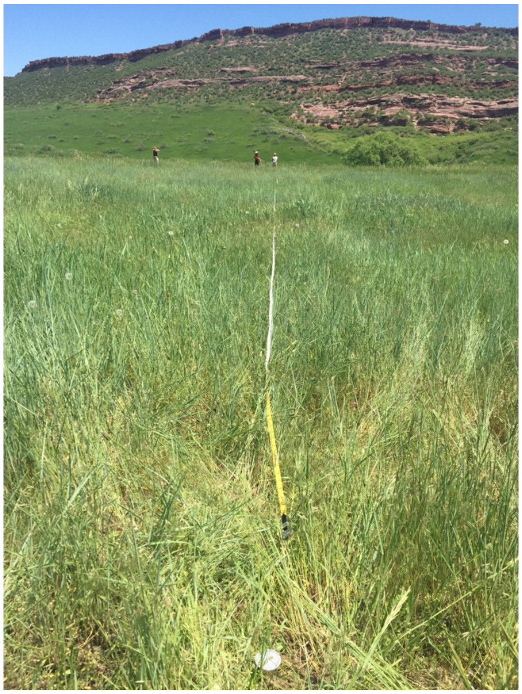
City of Fort Collins Natural Areas *naturally yours*

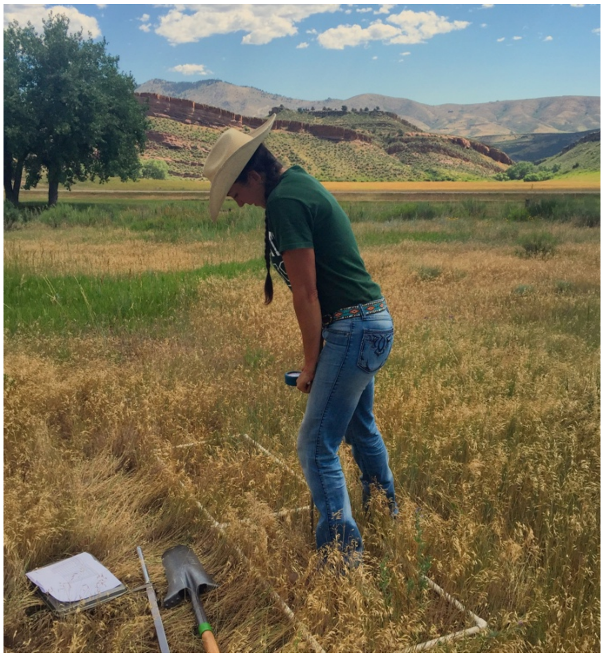
APPENDIX B

Photographs of transect markers on Bobcat Ridge Natural Area, for Chapter 2.

APPENDIX C

Photographs of research methods including the use of a linear transect, a quadrat, and temporary exclosures on Bobcat Ridge Natural Area, for Chapter 2.





APPENDIX D

Photographs of borders between grazed and ungrazed plots demonstrating various grazing intensities on Bobcat Ridge Natural Area, for Chapter 2.

APPENDIX E

Summarized mean and standard deviation tables for soil, vegetation and forage quality variables, for Chapter 2.

Table A2.1: Means and standard deviations for percent soil total organic carbon for 12 transects. $_a$ indicates grazed. $_b$ indicates ungrazed.

	2016				2017			
	0-5cm		5-10cm		0-5cm		5-10cm	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
$\mathbf{1_a}$	2.58	0.73	1.20	0.29	2.39	0.80	1.83	0.66
$\mathbf{1_b}$	2.98	1.17	1.56	0.52	3.30	1.49	2.22	0.89
$\mathbf{2_a}$	2.87	1.36	1.45	0.52	2.11	0.72	1.22	0.17
$\mathbf{2_b}$	2.10	0.83	1.13	0.25	2.17	0.76	1.35	0.40
$\mathbf{3_a}$	3.68	1.51	1.32	0.33	2.98	1.03	1.24	0.25
$\mathbf{3_b}$	2.55	0.59	1.14	0.17	2.22	0.66	1.31	0.65
$\mathbf{4_a}$	3.64	3.30	1.46	1.03	2.93	1.89	1.11	0.23
$\mathbf{4_b}$	4.41	3.13	1.39	0.72	2.77	1.13	1.29	0.30
$\mathbf{5_a}$	2.39	0.87	1.40	0.47	2.38	0.88	1.46	0.52
$\mathbf{5_b}$	2.76	0.75	1.62	0.28	2.63	0.55	1.80	0.45
$\mathbf{6_a}$	2.61	0.70	1.60	0.38	2.97	0.84	2.06	0.33
$\mathbf{6_b}$	2.18	0.78	1.32	0.51	1.84	0.51	1.28	0.41

Table A2.2: Means and standard deviations for percent soil total nitrogen for 12 transects. $_a$ indicates grazed. $_b$ indicates ungrazed.

	2016				2017			
	0-5cm		5-10cm		0-5cm		5-10cm	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
$\mathbf{1_a}$	0.25	0.07	0.13	0.03	0.24	0.08	0.20	0.07
$\mathbf{1_b}$	0.29	0.10	0.17	0.05	0.34	0.14	0.23	0.08
$\mathbf{2_a}$	0.30	0.12	0.18	0.04	0.26	0.08	0.16	0.01
$\mathbf{2_b}$	0.22	0.06	0.15	0.02	0.23	0.07	0.15	0.04
$\mathbf{3_a}$	0.32	0.10	0.15	0.03	0.29	0.10	0.14	0.01
$\mathbf{3_b}$	0.24	0.04	0.13	0.02	0.21	0.05	0.13	0.05
$\mathbf{4_a}$	0.35	0.23	0.19	0.09	0.36	0.31	0.11	0.04
$\mathbf{4_b}$	0.44	0.25	0.18	0.06	0.31	0.12	0.15	0.03
$\mathbf{5_a}$	0.25	0.07	0.17	0.04	0.25	0.10	0.15	0.06
$\mathbf{5_b}$	0.27	0.04	0.18	0.02	0.28	0.05	0.19	0.03
$\mathbf{6_a}$	0.27	0.06	0.18	0.05	0.28	0.11	0.13	0.06
$\mathbf{6_b}$	0.23	0.07	0.15	0.05	0.11	0.04	0.06	0.07

Table A2.3: Means and standard deviations for relative abundance of native graminoids and native forbs/subshrubs for 12 transects. $_a$ indicates grazed. $_b$ indicates ungrazed.

	Graminoids				**Forbs/Subshrubs**			
	2016		**2017**		**2016**		**2017**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
$\mathbf{1_a}$	0.22	0.18	0.22	0.15	0.17	0.23	0.10	0.15
$\mathbf{1_b}$	0.24	0.31	0.43	0.37	0.06	0.13	0.05	0.07
$\mathbf{2_a}$	0.02	0.05	0.01	0.02	0.01	0.01	0.07	0.11
$\mathbf{2_b}$	0.05	0.11	0.18	0.27	0.13	0.16	0.11	0.28
$\mathbf{3_a}$	0.14	0.21	0.12	0.10	0.31	0.15	0.25	0.19
$\mathbf{3_b}$	0.15	0.08	0.21	0.15	0.20	0.09	0.18	0.14
$\mathbf{4_a}$	0.00	0.00	0.00	0.00	0.14	0.17	0.08	0.16
$\mathbf{4_b}$	0.03	0.09	0.00	0.00	0.07	0.09	0.03	0.05
$\mathbf{5_a}$	0.00	0.00	0.00	0.00	0.10	0.20	0.03	0.07
$\mathbf{5_b}$	0.01	0.00	0.00	0.00	0.03	0.08	0.02	0.05
$\mathbf{6_a}$	0.01	0.00	0.00	0.00	0.01	0.02	0.01	0.03
$\mathbf{6_b}$	0.04	0.00	0.03	0.06	0.00	0.00	0.00	0.00

Table A2.4: Mean (M) crude protein (%) and standard deviations (SD) of 6 forage samples at each sampling period for each pasture (P1, P2, P3, P4, P5, P6). The 6 forage samples for Sample 1 were combined prior to NIR analysis, due to low volume of each individual sample. Therefore, sd is not available for those means. Baseline sample and Sample 1 for P1 and P2 were collected in Fall 2016. Baseline sample and Sample 1 for P3, P4, P5, and P6 were collected in Spring 2017. Sample 2 for all pastures was collected in July 2017.

	P1		**P2**		**P3**		**P4**		**P5**		**P6**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Baseline Sample	3.60	0.42	3.20	0.28	10.54	0.39	12.10	1.01	10.96	0.42	7.24	1.20
Sample 1 – within 3 days of conclusion of grazing	2.68	n/a	2.50	n/a	9.42	n/a	10.86	n/a	8.72	n/a	6.43	n/a
Sample 2 – post grazing sample, 1 year after baseline sample	6.62	0.40	5.81	0.58	8.00	0.45	7.24	0.98	9.16	0.50	8.95	1.42

Table A2.5: Mean (M) acid detergent fiber (%) and standard deviations (SD) of 6 forage samples at each sampling period for each pasture (P1, P2, P3, P4, P5, P6). The 6 forage samples for Sample 1 were combined prior to NIR analysis, due to low volume of each individual sample. Therefore, sd is not available for those means. Baseline sample and Sample 1 for P1 and P2 were collected in Fall 2016. Baseline sample and Sample 1 for P3, P4, P5, and P6 were collected in Spring 2017. Sample 2 for all pastures was collected in July 2017.

	P1		**P2**		**P3**		**P4**		**P5**		**P6**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Baseline Sample	47.85	2.47	39.43	0.98	41.19	2.30	36.29	1.66	37.77	2.04	41.20	3.53
Sample 1 – within 3 days of conclusion of grazing	45.07	n/a	41.82	n/a	39.12	n/a	38.02	n/a	41.39	n/a	42.75	n/a
Sample 2 – post grazing sample, 1 year after baseline sample	37.57	1.00	36.36	0.00	38.18	3.00	36.96	1.00	35.51	0.46	37.13	3.18

Table A2.6: Mean (M) neutral detergent fiber (%) and standard deviations (SD) of 6 forage samples at each sampling period for each pasture (P1, P2, P3, P4, P5, P6). The 6 forage samples for Sample 1 were combined prior to NIR analysis, due to low volume of each individual sample. Therefore, sd is not available for those means. Baseline sample and Sample 1 for P1 and P2 were collected in Fall 2016. Baseline sample and Sample 1 for P3, P4, P5, and P6 were collected in Spring 2017. Sample 2 for all pastures was collected in July 2017.

	P1		**P2**		**P3**		**P4**		**P5**		**P6**	
	M	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**	**M**	**SD**
Baseline Sample	69.61	2.95	62.52	1.67	57.72	1.88	58.01	1.20	59.16	1.97	64.01	3.13
Sample 1 – within 3 days of conclusion of grazing	70.42	n/a	65.84	n/a	56.61	n/a	60.43	n/a	62.14	n/a	66.14	n/a
Sample 2 – post grazing sample, 1 year after baseline sample	61.16	1.51	59.99	1.30	56.70	3.71	57.50	2.84	55.89	1.26	60.25	4.77

APPENDIX F

Statistical output tables for soil, vegetation and forage quality variables, for Chapter 2.

Table A2.7: Results of t-test for soil organic carbon.

	Estimate	Std Error	df	t statistic	*p* value
Grazing	0.00	0.93	4.9	0.04	0.973
Depth	-0.15	0.09	12.4	-1.68	0.118

Table A2.8: Results of t-test for soil total nitrogen.

	Estimate	Std Error	df	t statistic	*p* value
Grazing	-0.01	0.01	4.73	-0.49	0.644
Depth	-0.01	0.02	17.17	-0.87	0.397

Table A2.9: Results of t-test for relative abundance native graminoids.

	Estimate	Std Error	df	t statistic	*p* value
Year 2016	1.33	0.19	4.04	6.91	0.002
Grazing	0.03	0.02	5.1	1.67	0.154

Table A2.10: Results of t-test for relative abundance native forbs/subshrubs.

	Estimate	Std Error	df	t statistic	*p* value
Year 2016	0.52	0.09	6.49	4.90	0.002
Grazing	-0.002	0.01	4.42	-0.36	0.736

Table A2.11: Results of paired t-tests for effect of grazing on crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF).

	Confidence Interval	**df**	**t statistic**	***p* value**
CP	0.58 – 1.79	5	5.13	0.004
ADF	-3.43 – 1.95	5	-0.71	0.512
NDF	-3.49 – -0.03	5	-2.61	0.048

Table A2.12: Results of two-sample t-tests for effect of rest on crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF).

	Confidence Interval	**df**	**t statistic**	***p* value**
CP	-3.95 – -0.30	3.28	-3.53	0.034
ADF	-2.74 – 2.81	2.66	0.04	0.971
NDF	-0.11 – 6.09	3.99	2.69	0.055