THESIS

EFFECTS OF MANAGEMENT-INTENSIVE GRAZING IN RELATION TO SOIL HEALTH AND FORAGE PRODUCTION IN AN IRRIGATED PERENNIAL PASTURE SYSTEM

Submitted by

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ABSTRACT

EFFECTS OF MANAGEMENT-INTENSIVE GRAZING IN RELATION TO SOIL HEALTH AND FORAGE PRODUCTION IN AN IRRIGATED PERENNIAL PASTURE SYSTEM

Interest in Management-intensive Grazing (MiG) on irrigated, perennial, cool-season pasture has increased steadily in Colorado due to pressure to reduce public lands grazing, overall declining space available for pasture, and declining commodity prices. However, there are still many unknowns about how forage production, forage quality, plant diversity, and soil quality are affected by this management over the long-term. To investigate potential effects on these variables, a study was undertaken on a full-scale, 82 ha, center pivot-irrigated, perennial pasture that had recently been planted with four different species mixtures at the Colorado State University Agriculture, Research, Development and Education Center located 13 km northeast of Fort Collins, CO. During the first one and a half years of production, approximately 230 animal units (AUs) consisting of cow-calf pairs, yearling heifers, and yearling steers were grazed using management-intensive practices. Paddock size was dynamic and determined based on number of animals and forage availability with animals generally moved daily. Forage yield and quality, botanical composition and cover, animal unit days (AUDs), and soil quality parameters were measured. In both 2017 and 2018, species mixtures that were either hayed or grazed first in the rotation induced vegetative regrowth resulting in the greatest quality. Quality remained high enough through the grazing season to meet cattle nutrient requirements regardless of the species mixture. There was no significant difference between seasonal mean yields in 2017. The simple grass-legume mixture resulted in the greatest seasonal mean yield in 2018 with 3916 kg/ha^{-1} but the complex grass mixture resulted in greatest AUDs (7493.93 AUDs). Bare patches developed around patches of non-soft leaf tall fescue (*Festuca arundinacea* Shreb.) in this mix, which made it evident that cattle were selecting against this type of tall fescue. Botanical composition assessments did not align with the initial seeding rates in some cases, which suggests soil conditions, plant phenology, and competitive advantages contributed to differences between seeded and established composition of the mixtures. Ground cover showed that litter was similar among species mixtures that were planted and grazed earlier compared to the species mixture that was not. Mean plant cover (23.75%) was similar among all mixtures. Soil analysis included 11 biological, chemical, nutrient, and physical parameters that were aggregated into the Soil Management Assessment Framework (SMAF) program resulting in soil quality index (SQI) values. Positive soil quality effects were observed in the biological SQI with increases in microbial and enzymatic activities. Soil organic carbon remained relatively unchanged. Negative impacts occurred to the soil physical SQI, driven primarily by increasing bulk density. The nutrient SQI value declined due to the observed reduction in extractable soil P due to low concentrations occurring in multiple soil samples; similar observations occurred in all three extractions. In a separate soil physical property study, penetrometer resistance was measured due to grazing that occurred during wet conditions. Soil resistance was greater for paddocks grazed under wet conditions but was not yet at levels that would affect root growth and plant productivity. The overall results of this study suggest that this irrigated, MiG system has the potential for success in regard to forage production and quality and its ability to support grazing, but will need further research to determine the long-term impacts of grazing on soil quality and species composition shifts.

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INTRODUCTION

Management-intensive grazing (MiG) is often defined as “A flexible approach to rotational grazing management whereby animal nutrient demand through the grazing season is balanced with forage supply and available forage is allocated based on animal requirements” (Martz, et al., 1999). It has also been expressed more simply as “a flexible version of rotational grazing that balances forage supply with animal demand (Stout et al., 2000).” Over the past decade, interest in MiG has increased steadily due to the prospects of reduced production costs, increased animal output, land use efficiency, and environmental benefits. Some benefits often associated with MiG include improved grazing and manure distribution due to increased stocking density and quicker pasture regrowth associated with short duration grazing events. Improved pastures are being considered as an option by many ranchers due to pressure to reduce grazing on public lands and the declining space available for pasture (Cox et al., 2017). This system has the potential to bring the benefits of intensively managed, improved pastures into already established irrigation infrastructure that exists on many ranches. Combining these two systems could provide drought management options for ranchers in dry climates as well as the ability to reap the yields and benefits of improved pastures as a full or supplemental feed source. However, there are still many unknowns about how overall soil quality, plant diversity, forage yield, and forage quality are affected in irrigated pasture systems over the long-term. Measuring change in these parameters is integral to understanding how management practices are affecting overall system functionality. More specifically, understanding these processes are important for effective integration of this system into beef systems in Colorado and throughout the west.

This irrigated forage system project was established in 2017 at the Colorado State University Agricultural Research, Development, and Education Center (ARDEC) located 13 km northeast of Fort Collins, Colorado. This collaborative project between the Departments of Soil and Crop Sciences and Animal Sciences at Colorado State University aimed to explore the potential benefits of MiG at the farm scale utilizing the Colorado State University cow herd. The main objectives of this research included acquiring baseline soil quality data for future comparison as well as quantify the impacts of transitioning land from a tilled, annual cropping system to a cool-season, grazed perennial pasture. In addition to soil quality, soil penetrometer resistance was measured to provide insight to how grazing a clay-loam soil is impacted by hoof action in an irrigated grazing system. In terms of forage production, comparisons were made for forage yield, quality, and animal unit days of grazing of four cool-season forage mixes as a means of determining their ability to support MiG under irrigation. Botanical composition and ground cover were measured in each of the four cool-season forage mixes as a means of determining establishment success, plant species heterogeneity, and changes over time.

Based on available literature, we hypothesized that from pre- to post-grazing: 1) Soil microbial biomass carbon and enzymatic levels will increase; 2) Soil bulk density will increase due to hoof pressure; and 3) Soil phosphorus and potassium concentrations will significantly increase from manure accumulation during the grazing season. I hypothesized that forage yield would be greater in the complex mixtures due to the diversity of cool-season species. I also hypothesized that there would be no significant difference in forage quality between the species mixtures due to similarities among the cool-season species.

Site Description and Establishment

The study was conducted at the Colorado State University Agriculture Research, Development and Education Center 13 km northeast of Fort Collins, CO (40°39’30.40” N, 104°59’11.24” W). The research area encompassed 82 ha, irrigated by a center pivot. Elevation at the location is 1,554 meters above sea level. The climate in this area is mid-latitude dry, cold, semi-arid steppe (Kottek et al., 2006). Average low and high temperatures range from 1.0 °C to 16.83 °C (WRCC, 2018). Average annual rainfall of this area is 33.78 cm (WRCC, 2018). For our study period, 2017 and 2018, mean minimum and maximum temperatures ranged from and 6.90 °C to 22.7 °C and 10.74 °C to 27.46 °C, respectively (CoAgMet, 2018). Yearly irrigation and growing season precipitation totals for 2017 and 2018 can be found in table 1. The topography of the project area is relatively flat with a slope of 3% or less (NRCS, 2017). The following soil types are found on the area: Aquepts (loamy), Connerton-Barnum complex, Garrett loam, Kim loam, Nunn clay loam, Otero sandy loam, and Thedalund loam (Table 1). The soil types that make up the majority of the project area are Nunn clay loam at 53%, Kim loam at 12%, and Garrett Loam at 9% (NRCS, 2017; Table 2).

Table 1. Irrigation and precipitation by species mixture and totals for each grazing season from April-October.

2017				**2018**		
Species Mixture	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**
A†	9.75	32.5	**22.55**	14.1	38.3	**29.1**
B	12.35	32.5	**25.15**	15.45	38.3	**30.5**
C	11.9	32.5	**24.7**	13.85	38.3	**28.9**
D	11.6	32.5	**24.4**	15.45	38.3	**30.5**

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

Table 2. Soil series present within the project area with descriptions and percent of the project area.

Soil Series	**Description**	**Percent of Project Area**

Nunn clay loam	Fine, smectitic, mesic Aridic Argiustolls	Somewhat poorly drained; restrictive layer > 200 cm	56.3
Thedalund loam	Fine-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer 50-100 cm	0.5
Connerton-Barnum complex	Fine-loamy, mixed, superactive, mesic Torriorthentic Haplustolls	Well drained; restrictive layer > 200 cm	2.6
Otero sandy loam	Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents	Somewhat excessively drained; restrictive layer > 200 cm	13.6
Garrett loam	Fine-loamy, mixed, superactive, mesic Pachic Argiustolls	Well-drained; restrictive layer > 200 cm	9.2
Kim loam	Fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer > 200 cm	11.7
Aquepts loamy	Inceptisol with a water table near the surface	Poorly drained; restrictive layer greater than 200 cm	6.1

Table 3. Forage species planted in each 50-acre portion of the 200-acre project area.

Forage Mixture	**Species**
A - Grass/Legume Mix	Meadow brome (*Bromus biebersteinii Roem. & Shult.),* Orchardgrass (*Dactylis glomerata L.),* Creeping meadow foxtail (*Alopecurus arundinaceus* Poir.*),* Birdsfoot trefoil (*Lotus corniculatus L.),* Strawberry clover (*Trifolium fragiferum L.),* White clover (*Trifolium repens L.)*
B - Complex Grass Mix	Meadow brome (*Bromus biebersteinii Roem. & Shult.)*, Orchardgrass (*Dactylis glomerata),* Creeping meadow foxtail *(Alopecurus arundinaceus* Poir.), Tall fescue (*Festuca arundinacea*), Festulolium (*xFestulolium*), Smooth brome (*Bromis inermis L.*)
C - Simple Grass Mix	Meadow brome (*Bromus biebersteinii Roem. & Shult.),* Orchardgrass (*Dactylis glomerata L.),* Creeping meadow foxtail (*Alopecurus arundinaceus* Poir.*)*
D - Complex Grass/Legume Mix	Meadow brome (*Bromus biebersteinii Roem. & Shult.),* Orchardgrass (*Dactylis glomerata L.*), Tall fescue (*Festuca arundinacea*), Perennial ryegrass (*Lolium perenne),* Meadow fescue (*Festuca*

	pratensis), Festulolium (*xFestulolium),* Red clover (*Trifolium pretense L.),* Alsike clover (*Trifolium hybridum L.)*, White clover (*Trifolium repens L.),* Birdsfoot trefoil (*Lotus corniculatus L.*)

This project area was split into four quarters approximately 50 acres in size (referred to as A, B, C, and D). Each individual quarter was planted with a different cool-season, perennial forage mixture ranging from a simple grass mixture to a complex grass-legume mix (Table 3). Prior to forage establishment, the project area was a tilled, cropping system for approximately 8 years. The rotation included corn silage, dry beans (*Phaseolus vulgaris* L.), and alfalfa (*Medicago sativa* L.). Due to the clay soil type and previous management, a deep-ripper was used to alleviate a plow pan that had formed. In addition, multiple tillage events were necessary to break up large soil aggregates to prepare the seedbed for stand establishment. Species mixtures A, B, C, and D were planted between August 22 and September 9, 2016. Species mixture A failed due to winds that moved loose soil and damaged small seedlings. Oats were planted in this quarter on March 23, 2017 to avoid further wind erosion. This mixture was re-planted in August 2017.

During spring of the first growing season, legumes were cross-drilled on March 15-16th of 2017. However, due to a hard frost event that occurred at the seedling stage, almost all of the establishing plants were killed. Legumes were again interseeded in early August of 2017. Thus, the forage mixtures with legumes contained few if any for the duration of this initial research.

Permanent infrastructure that was installed included a permanent electrified perimeter fence with two concentric permanent fences (Fig. 1). Paddocks were created on a daily basis using poly-wire and step-in posts and the fences that delineated paddocks were re-constructed in the same locations throughout each grazing rotation using the GPS and paddock drawing tools on the mobile application PastureMap™ (PastureMap, San Francisco, CA). Further subdivisions to these paddocks were also made on an as-needed basis using polywire to adjust for forage availability. These fences were not placed in the same location each grazing rotation.

Figure 1: Project design map including concentric, permanent, high-tensile fence, water locations, individual management unit locations, and sampling units (in yellow) associated with each species mixture (Image from PastureMap^{TM}).

CHAPTER 1: LITERATURE REVIEW

1.1. Forage and Pasture Management

Management-intensive Grazing (MiG)

Management-intensive Grazing (MiG) is often defined as “a flexible approach to rotational grazing management whereby animal nutrient demand through the grazing season is balanced with forage supply and available forage is allocated based on animal requirements” (Martz, et al., 1999). This grazing method has been promoted to provide benefits such as more homogenous utilization of available forage, increased forage yield and quality, mitigated soil compaction, improved soil quality, and more evenly distributed manure and urine over an area (Hanson, 1995).

Supporting the theory that MiG improves grazing distribution and forage use efficiency, a study by Hart et al. (1993) looked at the difference between cattle behavior in large pastures with continuous grazing, continuously grazed small pastures, and small pastures utilizing “time-controlled grazing”. Cows traveled about 70% farther in the large continuous system than in both smaller pasture systems (Hart et al., 1993). When cattle spend less time traveling, this often translates to more time spent grazing. This evidence could also mean that less forage is being trampled and more efficient utilization is occurring.

MiG has the potential to more efficiently utilize forages and reduce animal selectivity by increasing stocking density. Animals that would typically focus on consuming the most palatable species in a mixture are encouraged to consume more evenly across the pasture due to limited space, animal behavior, length of time, and plant composition (Shewmaker and Bohle, 2010). In a study comparing management-intensive grazing and continuous grazing, MiG pastures had more structurally diverse vegetation that tended to be more conducive to supporting taller species than continuously grazed pastures (Paine et al., 1999). Having more diversity in a pasture generally means that less grazing selectivity and overgrazing of individual plants has occurred. In a continuous system, cattle have free will to return to lush regrowth on individual plants of their choosing and re-graze. This cycle can lead to eliminating certain species from stands due to grazing frequency ultimately reducing vigor, leading to plant loss and a less diverse species mixture. Thus, managing grazing to maintain species diversity and richness may be as simple as using the MiG approach.

Having a more evenly distributed grazing pattern (e.g., using MiG) leads to the removal of more apical meristems on a variety of individual plants resulting in greater live shoot density (i.e., increased tillering and vegetative growth) (Lemaire, 2001). Greater live shoot density creates more ground cover and higher quality feed. According to a study by Oates et al. (2011), MiG has greater relative feed quality (RFQ) during the summer grazing season than continuous grazing. Paine et al. (1999) found that in management-intensive rotational grazing systems, seasonal mean heights of forage stands were 5.8 cm taller than in continuously grazed pastures. However, Walker et al. (1989) concluded that cattle were less selective under continuous grazing and more selective in rotational systems; the authors concluded that selectivity was more related to forage availability and grazing pressure than the grazing system itself.

The basis of MiG relies on adequate periods of reduced grazing pressure, or “rest”, to allow for photosynthesis and regrowth to occur, thereby replenishing carbohydrate reserves in plant roots. It has been established that root biomass and elongation decreases as intensity and grazing frequency increases (Dawson et al., 2000; Oates et al., 2011). The rest period is integral for not only replenishing the plant’s resources but also the resources that are relied upon by microbial populations in the rhizosphere. After a defoliation event, the plant shifts resource allocation which can have an impact on the quality and quantity of carbon exudates that microbes receive (Dawson et al., 2000). This phenomenon can have indirect impacts on biological processes like nitrogen, phosphorus, and potassium nutrient cycling.

With continuous grazing, nitrogen, phosphorous, potassium, and other nutrients deposited in manure and urine tend to accumulate near water and shade sources, reaching concentrations up to five times greater than other areas (Shewmaker and Bohle, 2010). MiG has been promoted to improve distribution of these nutrients by controlling space, which encourages a more homogenous use of the area provided. White et al. (2001) found that dairy cattle grazing in an "intensively managed system" (moving every 2-3 days) had manure that was distributed more evenly except near water sources during hot conditions (White et al., 2001).

Perennial cool-season grasses and their influence on forage quality and pasture systems

Forage quality is an essential factor influencing animal performance in a grazing system. Many factors such as plant species and maturity level contribute to the overall quality and ability of a feed source to meet the nutritional needs of an animal. Cool-season grasses, also known as C_3 grasses due to their photosynthetic pathway, are often chosen for planting in pastures due to their high forage quality, yield potential, and palatability to ruminants. In addition, cool-season species provide a much longer growing season and fill the gaps early and late in the season when other forages are dormant. This helps improve overall foraging and most likely forage quality.

One of the most significant factors influencing overall forage quality is maturity at time of harvest or grazing, which can be linked to cool season plant species. As a plant ages, more lignin and structural carbohydrates are formed, decreasing overall quality and digestibility of the plant (Ball et al., 2001). If allowed to grow until maturity, this results in a slower rate of digestibility and reduced dry matter intake. In young, vegetative growth or regrowth, cool-season grasses have digestibility surpassing 80% (Ball et al., 2001). In most instances, cool-season grasses have a lower percentage of structural carbohydrates than warm season species, allowing them to breakdown more quickly in the ruminant animal. On average, digestibility of cool-season grasses is 9% higher than warm-season species (Ball et. al., 2001). The majority of cool-season, perennial grasses are short-shooted, producing apical meristems that remain close to the ground (Shewmaker and Bohle, 2010). During regrowth cycles, these plants produce primarily stem-less, vegetative growth. This is an advantage when grazing cool-season grasses because biomass removal and regrowth cycles encourage leafy, vegetative growth that is generally high in quality.

In the spring and fall, cool-season grasses yield higher due to lower (more favorable) temperatures, higher soil moisture levels, and shortened photoperiods. The temperature range that allows these plants to grow optimally is approximately 65-75 ^{o}F (Collins et al., 2017). During mid-summer, many C_3 species will slow in growth and enter semi-dormancy due to increased temperatures. C_3 species, on average, will require 2.5 times longer rest during this period (Oates et al., 2011). However, providing moisture through irrigation helps mitigate this growth fluctuation; providing a more diverse plant species mix may also help shorten the rest period.

Mixed species in pastures provide numerous benefits to the physical properties of the soil. Varied root morphologies alter soil structure in different ways due to their impact on macropores (McCallum et al., 2004). Increased macropores improve water infiltration and aeration. McCallum et al. (2004) concluded that perennial grass roots could partially remediate dense soils that are compacted from grazing or other adverse pressures to the soil surface. Other benefits to having diverse root morphologies in a pasture are to enhance nutrient and water uptake. Grass species varying in root lengths and densities can enable greater access to nutrients and water at different depths in the soil profile (Barber and Bouldin, 1984). Legumes contribute to root diversity by having a tap root, different from grasses which generally have a fibrous root system. Taproots can generally grow deeper within the profile than a fibrous root system, accessing water and nutrients as well as altering soil physical structure at deeper depths.

1.2. Soil Quality

Quantifying soil quality

Perennial pasture systems can enhance soil quality by reducing erosion, building soil organic matter, sequestering carbon, increasing macro and micropore space, and retaining more plant available water. However, negative impacts can also occur to soil physical properties due to hoof action by livestock, especially cattle. Compaction and increased bulk density are often unavoidable consequences associated with grazing. Positive and negative impacts of grazing in a perennial pasture system can make or break the viability of a livestock enterprise. Functioning soil is a primary driver behind forage yield and quality, which ultimately affect profitability.

Measuring changes in soil quality parameters is integral to understanding how management practices affect various soil functions. Soil quality is most commonly defined as “the capacity of a soil to function” (Karlen et al., 1997). The Soil Management Assessment Framework (SMAF) is a soil quality assessment program developed by Andrews et al. (2004) that quantifies nutrient, chemical, physical, and biological soil functions while using soil taxonomy as a foundation. Soil quality is dependent on a soil's inherent properties, climatic conditions of the area, how the soil is utilized, and type of management practiced. These points are considered within SMAF to create an output that reflects the specific limitations of the analyzed soil. Site specific location details allow output values to be relative to input (soil texture, climate, precipitation, etc.), allowing SMAF to be utilized across environments and locations.

1.2.1. Soil Quality Indicators

Physical Indicators:

Bulk density

Perennial pasture plants establish root systems that increase the structural stability of soils and improve overall physical properties, resulting in increased aggregate stability, water-infiltration, sub-soil macroporosity, and organic matter when grazed at proper animal density levels (McCallum et al., 2004). However, grazing, particularly in irrigated systems, raises concerns about potential adverse effects on soil physical properties. Bulk density is one of the primary variables of concern in this type of grazing system because it can increase as a result of compaction caused by hoof-to-soil contact, which can be further exacerbated on wet soils. At some level, compaction is present in most grazing systems. As the surface of the soil becomes compacted from grazing, pore space in the O and A horizons of the soil profile decreases which increases soil bulk density, mainly when wet soils are grazed (Tate et al., 2004; Warren et al., 1986). Increased bulk density can lead to reduced water infiltration due to a decrease in soil porosity (Warren et al., 1986). These changes in physical properties can impede root growth of perennial species and water movement through the soil, subsequently reducing pasture yields (Greenwood and McKenzie, 2001). In multiple studies, soil health degradation has been shown to depend on soil type, litter accumulation, and soil moisture (Chanasyk and Naeth, 1995;

Chiavegato et al., 2015; Drewry et al., 2008), as well as manipulations in management such as stocking density (animals per unit of area) and grazing duration.

Different management strategies have been studied as a way to mitigate the issues caused by unavoidable hoof action in these systems. In a study at Michigan State, researchers concluded that soils exposed to rotational grazing, where cattle were moved once a day, were found to have lower bulk densities and compaction levels than more intensive, higher stocking density practices (Chiavegato et al., 2015). Chanasyk and Naeth (1995) and Warren et al. (1986) found that bulk densities were higher in systems with very heavy grazing, whether that be continuous or short-duration rotational. At higher stocking densities, animals will walk over an area multiple times which can lead to a breakdown in soil structural integrity (Bilotta et al., 2007). This issues may be somewhat mitigated by simply having surface residue present.

Having residue on the soil surface has the potential to mitigate increases in bulk density. In a study looking at short-term irrigated pasture systems, it was concluded that penetrometer resistance was significantly higher for treatments with less post-graze residue (Johnson, 2012). In the same study, systems that had a shorter grazing duration (rotated daily) had greater amounts of litter on the soil surface than more intensive grazing. Naeth et al. (1991) found that decreased litter and vegetation cover was correlated with higher soil resistance and bulk density which supports the findings by Johnson (2012).

Warren et al. (1986) found that increases in bulk density can be reversible with adequate time for recovery. This finding may explain why shorter duration rotational grazing often has lower bulk density levels than continuous grazing due to the period of recovery given to a paddock for forage regrowth (Warren et al., 1986a). Freeze-thaw cycles over the winter also have a regenerative impact on soils affected by increased bulk density. In a study by Pardini et al. (1996), evidence suggested that that freeze-thaw cycles modified the physical structure of the soil, increasing the bulk volume by creating irregular and rounded pore spaces (Pardini et al., 1996).

Water stable aggregates

Soil aggregates are a combination of minerals and organic and inorganic substances. Soil particles, when bonded together by various agents, form stable aggregates. Many factors can aid in soil aggregation including soil organic carbon, carbonates, microbial activity, soil moisture, texture, and management practices (Bronick and Lal, 2005). Warren et al. (1986) found that soil aggregate size was negatively correlated to trampling rate. However, trampling rate was dependent on the type and size of the grazing animal. Cattle have the greatest structural impact on soils creating a static pressure of approximately 200 kPa when standing and 400 kPa when traveling (Bilotta et al., 2007). However, soil aggregate formation relies heavily on microbial activity which is often greater in grazed, improved pasture systems than in native or tilled systems (Sparling, 1992; Warren et al., 1986); microbial activity might help negate static pressure created by cattle. Other contributors to soil aggregation include wetting and drying, particularly in soils with higher shrink-swell potential (Warren et al., 1986). Soil organic and inorganic carbon aid in the bonding of primary soil particles. The presence of calcium carbonates can also lead to more resistant water stable aggregates that are more stable under grazing (Bilotta et al., 2007).

Chemical:

pH

Grazing practices do not generally impact soil pH; however, soil pH can have an impact on system productivity due to its influence on soil functions. Soils in Colorado are generally alkaline due to the natural presence of carbonates and bicarbonates (McCauley et al., 2009). In terms of soil functions, pH has a significant impact on cation exchange capacity (CEC) and nutrient availability in the soil solution (McCauley et al., 2009). Due to the alkalinity of soils in Colorado, in combination with the high clay content of the project area, the CEC is relatively higher, leading to greater buffering capacity that is more resistant to pH changes. High CEC soils are also generally less susceptible to leaching of nutrients due to overall lower H^+ concentrations that would be occupying exchange sites in acidic soils. This knowledge is especially crucial in a grazing system where manure that is generally high in N, P, and K accumulates. Also, soils with a pH between 6.5 and 8 have greater macronutrient availability than more acidic soils (McCauley et al., 2009). Soils in this pH range are advantageous in a system that is heavily reliant on nutrient availability from manure to provide fertility to the perennial forage stand.

Electrical conductivity (EC)

Electrical conductivity (EC) is an important indicator of soil quality in an irrigated system and is impacted by changes in management in a relatively short amount of time. Inherent soil properties, such as texture and parent material, influence EC. However, irrigation, fertilization, and land-use also have significant impacts on EC which can be minimized through management decisions (USDA-NRCS, 2014). Having quality irrigation water low in salts is necessary to avoid rapid soil salinization. The amount of water applied is also a factor in managing salinity. If a soil has an EC issue, applying small amounts of water at a time cannot leach salts from the soil profile, creating a saline zone that generally occurs in the main plant rooting area. This can have negative consequences to plant health and the overall productivity of a perennial pasture.

Biological:

Soil organic matter (SOM) and soil organic carbon (SOC)

Soil organic matter is an assemblage of organic macromolecules that are measured as a quantity of organic carbon. Nearly all organic matter added to a system is derived from plant material directly or indirectly in the form of detritus, soluble exudates, or in a digested form such as animal manure (Condron et al., 2010). The amount of organic matter added to a system is mainly influenced above- and below-ground productivity levels. Management practices, such as MiG, can often improve forage biomass production in livestock systems and increase soil organic matter content. Thriving perennial pasture species with increased productivity have healthy, actively growing and sloughing root systems. Root and root exudates contribute 60-80% to soil organic matter (Chiavegato et al., 2015; Condron et al., 2010). Also, of the total carbon fixed through photosynthesis, soluble root exudates make up 10-40% which drives microbial processes in the rhizosphere important for decomposition (Condron et al., 2010). In moderately intensive rotational grazing systems, Rasse et al. (2005) found that there was more root production than in mob (high density, high intensity grazing) grazing allowing more soil organic matter to accumulate over time.

Pasture systems provide a constant supply of plant litter to the soil surface as a source of organic matter. Litter and residue that remains following rotational grazing aids in providing lower soil temperatures, greater moisture retention, and overall improved soil organic matter (Chiavegato et al., 2015). Inherent soil properties can also influence soil organic matter levels.

Soils high in clay, like those in the project area, are generally higher in organic matter than sandy soils (McCauley et al., 2009). Higher levels of soil organic matter can also lead to greater amounts of sequestered carbon (Condron et al., 2010).

In addition, management can have considerable influence on the amount of soil organic matter that accumulates which is correlated to potential carbon sequestration (McCauley et al., 2009). Soil cultivation can cause carbon losses of 30-50% while pasture can act as a carbon sink (Kucharik et al., 2001). Improved perennial pastures can increase soil carbon, particularly in situations where cultivated land is converted to pasture, irrigation is applied, and grazing is intensively managed (Conant et al., 2009). According to a meta-analysis by Conant et al. (2009), seeding perennial grasses and legumes led to a mean annual increase in carbon of 2.0% and 2.3%, respectively. Irrigated, MiG pasture can also lead to an increase in forage production which benefits belowground production of root biomass, resulting in increased carbon inputs (Conant et al., 2009). Cattle grazing inherently brings the addition of manure to the soil which increases overall production and leads to increases in atmospheric carbon sequestration (Conant et al., 2011). Soil organic carbon has also been shown to increase along with water stable aggregates under pasture, leading to physical improvements in the soil and associated hydrological processes (Martens et al., 2004).

Microbial biomass carbon (MBC)

Microbial biomass carbon (MBC) is the living portion of organic matter in the soil. Microbial biomass levels are positively correlated with multiple soil processes related to soil quality. MBC and β-glucosidase (discussed below) are positively correlated due to this enzyme's role in releasing simple sugars that feed microbial populations (Acosta-Martínez et al., 2008).

Microbial biomass levels are often greater in surface soils in systems without tillage due to surface residue acting as a carbon source for microorganisms. Because this is where a large portion of microbial activity occurs, this also is where potentially mineralizable nitrogen (discussed below) is often greater (Doran, 1987). Biological activity is also largely dependent on soil moisture and oxygen. An irrigated grazing system can provide optimal soil water content for microbial activity (Doran, 1987). However, grazing is often associated with increases in bulk density which causes a reduction in pore space. If pore space becomes severely reduced, this could result in reduced MBC.

Determining MBC has been suggested to be a more sensitive measure of change in soil organic matter concentration as opposed to total soil organic carbon (Sparling, 1992). Changes in MBC can be detectable much earlier than soil organic carbon because of the rapid microbial turnover rate and can provide an early indication of long-term soil carbon accumulation (Sparling, 1992). The author reported that microbial biomass carbon and soil organic carbon at nine different sites and analyzed two different soil types. The sites consisted of two types of native forest, a shrub ecosystem, an unimproved pasture, and improved pasture. There was a clear trend that overall MBC and SOC percentages were greater in both pasture systems. SOC in these systems tended to accumulate in the top 10 cm of the soil profile (Sparling, 1992).

A soil ecology study by Acosta-Martinez et al. (2008) quantified microbial biomass in cropped and permanent pasture systems (Acosta-Martínez et al., 2008). The authors hypothesized that soil microbial activity would be highest under pasture. This hypothesis was based on previous work by Acosta-Martinez in which the authors found that native pasture had 2-5-fold higher MBC in the top 0-5 cm in comparison to cropped systems. In the 2008 study, she concluded that MBC was 2.4, 3, and 6.6 times higher under pasture than the cropped systems

(Acosta-Martínez et al., 2008). Microbes rely heavily on carbon derived from plant roots, thus having a permanent pasture stand should naturally support greater microbial populations (Dawson et al., 2000).

Beta-glucosidase

Enzymes are integral to all soil biological activity, including nutrient cycling and organic matter decomposition. The β-glucosidase enzyme plays an important role in the process of cellulose degradation. As a group, the enzymes referred to as “glucosidases” release significant energy sources in the form of sugars that are important for sustaining soil microbial populations (Bandick and Dick, 1999).

Turner et al. (2002) performed a study comparing 29 permanent pasture soils and their respective β-glucosidase, carbon, and microbial carbon levels. They found that β-glucosidase was positively correlated with concentrations of both soil and microbial carbon (Turner et al. 2002). A study by Bandick and Dick (1999) focused on developing soil enzyme assays that were sensitive indicators of soil quality in different systems with varying management regimes. The authors compared sites that were cover cropped, under permanent pasture, and winter fallowed. Results showed that sites with cover crops and permanent pasture had greater β-glucosidase activity present than the winter fallow site. Also, the permanent pasture site had greater overall enzyme activity than the other sites (Bandick and Dick, 1999). Acosta-Martinez et al. (2008) investigated enzyme and microbial activity under different management regimes including pasture, vegetable production, and tree fruit production. These authors found that β-glucosidase levels were 3-5 times greater under pasture than in the other sites.

In terms of β-glucosidase as an indicator of soil quality, Bandick and Dick (1999) suggested that β-glucosidase is a good reflection of soil management effects due to its role in the carbon cycle. They also suggest that enzymes in the soil may be used as early indicators of biological change when management practices are altered. The results of both the Turner et al. (2002) and Bandick and Dick (1999) studies suggest that β-glucosidase is a valued assay to include when measuring soil changes in grazed pasture systems. It also suggests that an uninterrupted rhizosphere and greater organic matter additions harbor greater enzymatic activity (Bandick and Dick, 1999). In general, evidence suggests that the upper part of the soil profile will contain more carbohydrates produced by β-glucosidase type enzymes as long as management continues to contribute plant biomass and maintains conservation practices that avoid tillage (Martens et al., 2004).

Potentially mineralizable nitrogen (PMN)

The primary nitrogen sources in grazing systems are manure and plant litter decomposition. These sources are generally in organic forms that are not readily available for plant use until mineralization has occurred. Potentially mineralizable nitrogen (PMN) is the fraction of organic nitrogen that could potentially be converted to mineral forms under certain environmental conditions. The rate at which nitrogen is mineralized from organic forms is mainly dependent on soil microorganisms, which are dependent on soil properties, climate, management, and residue quality (Drinkwater et al., 1996; Mikha et al., 2006). Climate, particularly precipitation, is positively correlated with PMN levels (Doran, 1987). Thus, irrigated systems should have an advantage over dryland pastures in terms of how quickly manure N is mineralized.

PMN may also be enhanced in other management systems. In a study by Doran (1987), the author found that in a no-tillage system, soil microbial biomass and PMN distributions in the soil profile were very similar. Both MBC and PMN were found to be greatest in the top 7.5 cm of the soil (Doran, 1987). In long-term grazing systems, manure and plant litter decomposition are the primary sources of fertility but are found on the surface and are not incorporated into the soil. Having proportionately more MBC and PMN in the top few centimeters of soil is advantageous for nutrient cycling and breakdown of plant material in this type of system because that is the main location of potential fertility.

According to a study by Motavalli et al. (1992), eliminating nitrogen fertilizer applications for seven years led to an increase in N uptake from soil organic matter mineralization. Converting from an annual cropping system to a perennial grazing system may initially show signs of nitrogen deficiency in forages due to N immobilization. However, based on findings by Motavalli et al. (1992), over time there is potential for greater soil mineralization that could minimize any N deficiency issues.

Nutrient:

Phosphorus

When passing through the animal, approximately 96% of ingested phosphorus (P) is excreted in manure (Eghball et al., 2002). Cattle manure P availability reaches and often exceeds 70%, with P primarily present in inorganic forms (Eghball et al., 2002). Remaining P availability is mostly controlled by microbial mineralization which is influenced by soil temperature, moisture, and manure characteristics which, in turn, are affected by such factors as animal species and diet (Eghball et al., 2002; Slavich, and Petterson, 1993).

Potassium

About 73% of potassium (K) is excreted by cattle in urine, of which 100% is often bioavailable (Eghball et al., 2002). K is generally considered immobile and only leaches in extreme cases of low soil pH and cation exchange capacity, and thus does not constitute a major environmental concern in pasture systems. In a study determining K fate under irrigated pasture, K losses through leaching were negligible at 0.99 g m^{-2} yr^{-1} (Early et al., 1998).

Grazed pastures tend to accumulate more P and K in the A horizon than in systems that remove forage by hay harvest (Mathews et al., 1994). In terms of grazing system comparisons, Mathews et al. (1994) concluded that there were no differences in nutrient concentrations between short-duration rotational grazing, long-duration rotational grazing, and continuous grazing. MiG grazing is promoted as providing greater distribution of manure and nutrients due to managing stocking density (Shewmaker and Bohle, 2010). However, even in MiG systems, greater concentrations of P and K are found near watering locations (McCallum et al., 2004; Shewmaker and Bohle, 2010; Wilkinson et al., 1989). K is generally more of an issue in these areas than P due to the lack of K retainment in cattle (McCallum et al., 2004).

1.3. Compaction in Grazing Systems

Research has shown that perennial pasture plants establish root systems that can increase soil structural stability and improve overall physical properties such as increased aggregate stability, water infiltration, and sub-soil macroporosity when grazed at proper animal densities (Carter et al., 1994; McCallum et al., 2004). However, livestock pasture grazing has historically been associated with negative impacts on soil physical properties. Compaction is one of the main concerns in these systems due to effects on bulk density that degrades soil macro-porosity.

Compaction occurs when pressure from grazing animals exceeds the load-bearing capacity of the soil under non-saturated conditions (Bilotta et al., 2007). These changes in physical properties can impede root growth and water movement through the soil, subsequently reducing pasture yields.

In multiple studies, soil health degradation has been shown to depend on stocking density, soil type, and soil moisture (Drewry et al., 2008; Greenwood and McKenzie, 2001). Compaction often occurs when soil moisture nears field capacity. In this state, the soil is malleable and more susceptible to pressure from hooves of grazing animals which can compress and thus reduce porosity in the top portion of the soil (Mackay, 2017). Compaction that occurs at depths greater than 15 cm is often caused by grazing on pastures when they reach moisture levels greater than field capacity (Greenwood and McKenzie, 2001).

Other damage associated with compaction includes pugging and poaching which generally causes damage in the top 5 cm (Drewry et al., 2008). Pugging occurs when soil moisture is moderate and plastic. When soil becomes plastic, the soil moisture has reached a limit in which it changes from friable to plastic. For some soils, this occurs at field capacity (Drewry et al., 2008). It is generally characterized by visible indentations on the soil surface caused by hoof pressure. These indentations create microtopography across the soil surface making it appear rough. This impact affects porosity of the upper soil layer and can cause direct damage to plant crowns. Poaching, a term used to describe the rearrangement of soil particles, occurs when soils are saturated (Greenwood and McKenzie, 2001). This impact causes loss of stability in soil aggregates in the top 5 cm (Bilotta et al., 2007; Drewry et al., 2008). Pugging and poaching both contribute to reduced porosity leading to increased bulk density and decreased water infiltration (Bilotta et al., 2007; Greenwood and McKenzie, 2001). Damage at the soil surface interferes with soil hydrology, particularly water infiltration (Bilotta et al., 2007). This is a significant concern in irrigated systems due to the limited means of alleviation and the length of time required for natural recovery.

It is nearly impossible to avoid compaction entirely due to cattle treading pressure, which ranges from 200-400 kPa (Mackay, 2017). In a study at Michigan State, soils exposed to rotational grazing where cattle were moved once a day were found to have lower compaction levels than more intensive, higher stocking density practices (Chiavegato et al., 2015). In a study looking at similar comparisons, it was found that pastures where livestock was moved once daily had greater amounts of litter on the soil surface which was positively correlated with lower penetrometer resistance (and thus less compaction; Johnson, 2012). These studies suggest grazing management can potentially mitigate compaction keeping soil resistance at a level that does not impact the system productivity.

1.4. Summary

Current literature indicates that MiG within an irrigated, perennial pasture has the potential to produce productive, quality forage while contributing to soil organic matter, microbial biomass, and eventually, carbon sequestration. The caveat of this system is managing compaction and bulk density at a level that does not impact water infiltration, root growth, forage productivity, and ultimately the overall system.

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CHAPTER 2: FORAGES

2.1. Introduction

Management-intensive Grazing (MiG) is often defined as “a flexible approach to rotational grazing management whereby animal nutrient demand through the grazing season is balanced with forage supply and available forage is allocated based on animal requirements” (Martz, et al., 1999). It has also been expressed more simply as “a flexible version of rotational grazing that balances forage supply with animal demand” (Stout et al., 2000). Over the past decade, interest in MiG has increased steadily due to the prospects of reduced production costs, increased animal output, land use efficiency, and environmental benefits. Improved pastures are being considered as an option by many ranchers due to pressure to reduce grazing on public lands and declining space available for pasture (Cox et al., 2017). The MiG system has the potential to bring the benefits of intensively managed, improved pastures into established irrigation infrastructure that exists on many ranches. Combining these two systems can provide drought management options for ranchers in dry climates as well as the ability to reap the yields and benefits of improved pastures as a full or supplemental feed source. However, there are still many unknowns about how forage production, forage quality, and plant diversity are affected in irrigated pasture systems over the long-term. Measuring these parameters over time is integral to understanding how management practices affect the overall system functionality.

MiG focuses on controlling space and time to efficiently utilize available forage while maintaining plant carbon balances between root and shoot for stand longevity with adequate periods of rest. This method of grazing has been promoted to provide benefits such as decreased selectivity and increased forage yield and quality (Hanson, 1995; Shewmaker and Bohle, 2010). Opposite of the MiG approach, more homogenous grazing distribution can lead to decreased plant selectivity. In a study comparing MiG and continuous grazing, it was found that MiG pastures had more structurally diverse vegetation that tended to result in more taller statured species than continuously grazed pastures (Paine et al., 1999). Studies by Belesky et al. (2002) and Piano and Annicchiarico (1995) concluded that complex mixtures can result in greater dry matter yields due to variability in seasonal growth patterns. Another grazing study found that when comparing a simple mixture (2-3 species) with a more complex mixture (6-9 species), the complex mixture produced the greatest yield (Deak et al., 2007). However, the authors also concluded that forage quality in the latter scenario was likely more related to individual species in the mix rather than plant mixture complexity.

Linked to forage quality is the need to meet animal nutritional demands. A lactating beef cow can generally meet her nutritional requirements when forage crude protein levels meet or exceed 10% (Adams et al., 1996). Pasture systems utilizing MiG aim to maintain forage in a vegetative state, with plants in a vegetative state generally containing at least 10% crude protein (Adams et al., 1996). Therefore, in theory, forages in MiG systems should meet or exceed the nutrient requirements of a cow-calf herd.

The aforementioned research, although similar in subject matter, does not include a MiG irrigation component. There is little research quantifying botanical composition and forage yield and quality in irrigated pasture systems over time among varied species mixtures with a full-size grazing herd. Based on the literature, I hypothesized that forage yield would be greater in the complex mixtures due to the diversity of cool-season species. I also hypothesized that there would be no significant difference in forage quality between the species mixtures due to similarities among the cool-season species.

2.2. Materials and Methods

2.2.1. Site Description and Establishment

The study was conducted at the Colorado State University Agriculture Research, Development and Education Center located 13 km northeast of Fort Collins, CO (40°39’30.40” N, 104°59’11.24” W). The research area was 82 ha in size and irrigated by a center pivot. Elevation at the location is 1,554 meters above sea level. The climate in this area is mid-latitude dry, cold, semi-arid steppe (Kottek et al., 2006). Average low and high temperatures range from 1.0°C to 16.83°C (WRCC, 2018). Average annual rainfall for this area is 33.78 cm (WRCC, 2018). For the study period, 2017 and 2018, mean temperatures ranged from and 6.90°C to 22.7°C and 10.74°C to 27.46°C, respectively (CoAgMet, 2018). Yearly irrigation and growing season precipitation totals for 2017 and 2018 can be found in table 4. The topography of the project area was relatively flat with a slope of 3% or less (NRCS, 2017). The following soil types were found on the area, which included Aquepts (loamy), Connerton-Barnum complex, Garrett loam, Kim loam, Nunn clay loam, Otero sandy loam, and Thedalund loam (Table 5). The soil types that make up the majority of the project area are Nunn clay loam at 53%, Kim loam at 12%, and Garrett Loam at 9% (NRCS, 2017; Table 5).

Table 4. Irrigation applied by species mixture and total precipitation that occurred from April to October.

	2017			**2018**		
Species Mixture	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**
A†	9.75	32.5	**22.55**	14.1	38.3	**29.1**
B	12.35	32.5	**25.15**	15.45	38.3	**30.5**
C	11.9	32.5	**24.7**	13.85	38.3	**28.9**
D	11.6	32.5	**24.4**	15.45	38.3	**30.5**

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

Table 5. Soil series present within the project area with descriptions and percent of the project area.

Soil Series	Description		Percent of Project Area
Nunn clay loam	Fine, smectitic, mesic Aridic Argiustolls	Somewhat poorly drained; restrictive layer > 200 cm	56.3
Thedalund loam	Fine-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer 50-100 cm	0.5
Connerton-Barnum complex	Fine-loamy, mixed, superactive, mesic Torriorthentic Haplustolls	Well drained; restrictive layer > 200 cm	2.6
Otero sandy loam	Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents	Somewhat excessively drained; restrictive layer > 200 cm	13.6
Garrett loam	Fine-loamy, mixed, superactive, mesic Pachic Argiustolls	Well-drained; restrictive layer > 200 cm	9.2
Kim loam	Fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer > 200 cm	11.7
Aquepts loamy	Inceptisol with a water table near the surface	Poorly drained; restrictive layer greater than 200 cm	6.1

The project area was split into four quarters approximately 20 hectares in size (referred to as A, B, C, and D; Fig. 2). Each individual quarter was planted with a different cool-season, perennial forage mixture ranging from a simple grass mixture to a complex grass-legume mix (Table 6). Prior to establishment of the forages, the project area was used to grow agronomic crops for approximately 8 years. The rotation included corn silage (*Zea mays* L.), corn grain, dry beans (*Phaseolus vulgaris* L.), and alfalfa (*Medicago sativa* L.). Due to the clay soil type and previous management, a deep-ripper was used to alleviate a plow pan that had formed. Following deep ripping, the field was moldboard plowed, disked twice, cultipacked twice, and then rolled with a heavy steel roller to break up large soil aggregates and firm the soil surface prior to stand establishment. Cool-season grasses were planted in late August/early September 2016 and legumes were cross-drilled in March 2017. Unfortunate climatic circumstances in the spring of 2017 led to multiple issues in establishment. Species mixture A failed due to winds that moved loose soil and damaged small seedlings. Oats were planted in this quarter on March 23, 2017 to reduce further wind erosion. This mixture was re-planted in August 2017. Most of the legumes that were cross-drilled in early March were killed due to a hard freeze that occurred shortly after germination. Legumes were again interseeded in early August of 2017. Thus, the forage mixtures with legumes contained few if any for the duration of this initial research.

2.2.2. Project Design

Permanent infrastructure that was installed included an electrified perimeter fence with two concentric inner fences constructed using high-tensile wire (Fig. 2). Ten permanent water blocks were located around the pivot with eight within the outer concentric high-tensile fence line and two in the center. The eight water blocks within the outer concentric fence had four sides with electrified rope gates for controlling access to paddocks. Paddocks or “management units” were created every 1-3 days using polywire and step-in posts. These management unit areas and fences were re-constructed in approximately the same locations throughout each grazing rotation using GPS and paddock drawing tools on the mobile application PastureMap™ (PastureMap, San Fransico, CA. 2019). These management units were often subdivided on an as-needed basis using additional polywire and step-in posts to adjust for forage availability and animal numbers. These fences were not placed in the same locations each grazing rotation.

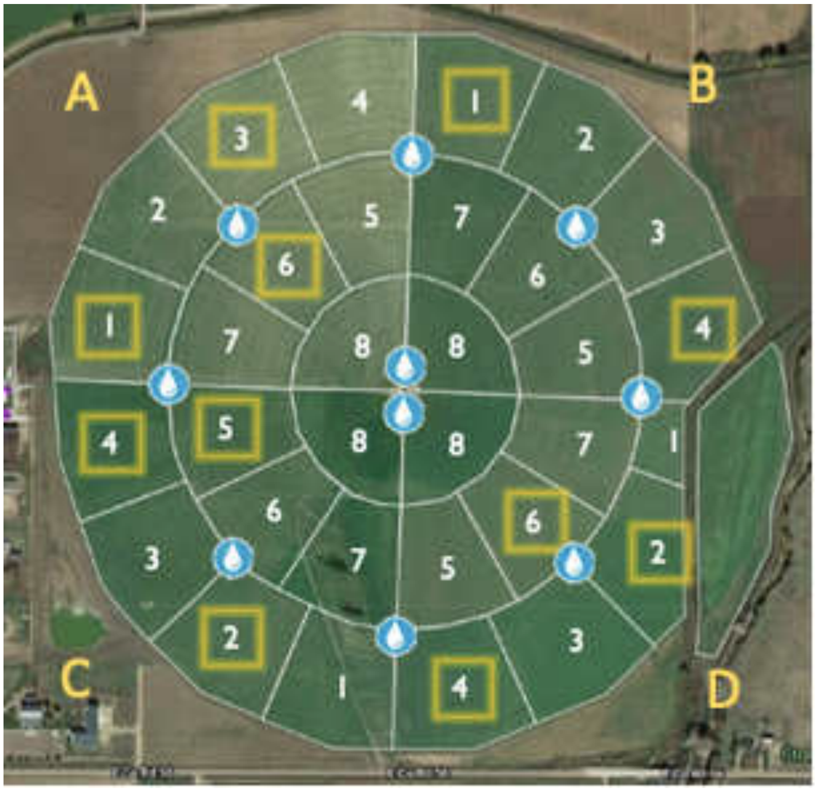

Figure 2: Project design map including concentric, permanent, high-tensile fence, water locations, individual management unit locations, and sampling units (in yellow) associated with each species mixture (Image from PastureMap^{TM}).

In 2017, approximately 171 cow-calf pairs (231 AUs) were grazed from August 18 until October 24. The grazing season was delayed due to fencing and water infrastructure being constructed. The herd was initially separated in about half by breed (Angus and Hereford) for breeding purposes. At the conclusion of breeding, the herds were then combined on September 21 and grazed as one group until October 24. In 2018, approximately 136 cow-calf pairs, 49 yearling replacement heifers, and 5 yearling steers were grazed from May 4 until October 7 (234 AUs). The entire cow herd was not initially present on the pivot at the beginning of the grazing season. A portion of the cows calved on the pivot and the remainder were added post calving. Throughout the grazing season, up to 3 herds were grazed at one time. Groups were rearranged for breeding purposes at different points in the grazing season, but the number of animals stayed relatively constant.

Table 6: Cool-season perennial species mixtures planted in each quarter of the project area.

Species and Cultivar	**Bulk Seeding Rate (kg ha^{-1})**	**Pure Live Seed (PLS) %**	**Seeds ha^{-1} (PLS)**	**% Composition of Seed Mix**
Simple Grass/Legume (A)				
Meadow Brome (*Bromus biebersteinii* Roem. & Shult.) 'Cache'	9.5	98%	3,402,995	29%
Orchardgrass (*Dactylis glomerata* L.) 'Latar'	3.9	89%	7,139,019	62%
Creeping Meadow Foxtail (*Alopecurus arundinaceus* Poir.*)* 'Garrison'	3.36	18%	1,025,368	9%
Birdsfoot Trefoil (*Lotus corniculatus* L.) 'Norcen'	3.36	93%	2,573,942	32%
Strawberry Clover (*Trifolium fragiferum* L.) 'Palestine'	4.48	55%	1,621,534	20%
White Clover (*Trifolium repens* L.) 'Kopu II'	2.24	96%	3,799,503	48%
Complex Grass (B)				
Meadow Brome 'Cache'	9.5	92%	1,805,388	19%
Orchardgrass 'Crown Royale'	3.9	55%	2,577,145	27%
Creeping Meadow Foxtail 'Garrison'	3.36	20%	1,129,727	12%
Tall Fescue (*Festuca arundinacea* Shreb.) 'Texoma MaxQ II'	3.9	89%	1,588,998	17%
Festulolium (*xFestulolium*) 'Spring Green'	3.9	95%	1,882,105	20%
Smooth Brome (*Bromis inermis* L.) 'Manchar'	2.24	84%	603,456	6%
Simple Grass (C)				
Meadow Brome 'Cache'	16.8	93%	1,835,566	26%
Orchardgrass 'Latar'	6.7	86%	4,048,158	58%
Creeping Meadow Foxtail 'Garrison'	3.36	20%	1,110,819	16%
Complex Grass/Legume (D)				
Meadow Brome 'Arsenal'	6.7	83%	1,151,950	11%
Orchardgrass 'Intensiv'	3.9	78%	3,666,328	34%
Tall Fescue (*Festuca arundinacea*) 'Baroptima plus E34'	3.9	85%	1,504,597	14%
Perennial Ryegrass (*Lolium perenne)* 'Remington plus NEA2'	3.36	85%	1,554,855	15%

Meadow Fescue (*Festuca pratensis*) 'Pradel'	3.36	85%	1,380,824	13%
Festulolium 'Barfest'	3.36	83%	1,403,776	13%
Red Clover (*Trifolium pretense* L.) 'Freedom'	3.36	57%	1,156,604	17%
Alsike Clover (*Trifolium hybridum* L.) 'VNS'	1.68	108%	2,808,996	41%
White Clover 'RegalGraze'	1.12	62%	1,227,167	18%
Birdsfoot Trefoil (*Lotus corniculatus* L.) 'Norcen'	2.8	71%	1,635,926	24%

2.2.3. Forage Sampling, Processing, and Management

Forage Yield and Quality

Management of this project was farm-scale and operated in regard to the needs of the cattle, forage availability, and soil moisture following irrigation or precipitation events. Thus, there was no set order that the cattle grazed the units. This made forage quality a difficult parameter to measure because each paddock were at various stages of growth and re-growth throughout the grazing season. Because of this, samples were clipped within 24 hours before cattle entered a paddock in order to capture the forage quality they were directly consuming and to estimate dry matter (DM) yield that was available at that point in time. Three random grazing units (paddocks) were chosen per species mixture (or quarter section of the pivot) and consistently sampled throughout the grazing season (Fig. 1). Before cattle entered, a total of ten, 0.25 m^2 quadrat samples were clipped to ground level from a designated paddock and analyzed for forage quality and yield estimates. These samples were dried in a 55°C oven for a minimum of 3 days and then weighed. To estimate yield, the weight of the dried sample in grams was converted to kilograms per hectare. A second set of ten, 0.25 m^2 quadrat samples was taken within 48 hours of the cattle leaving a paddock to estimate residual forage as well as to determine percent utilization.

Half of the dry samples that were clipped before cattle entered were utilized for measuring forage quality. These samples were ground to pass a 2 mm screen using a Wiley mill (Wiley, Model 4, Thomas Scientific, Swedesboro, NJ) and then ground to pass a 1 mm screen using a cyclone mill (Foss Cyclotec, Model 1093, Foss Corp., Eden Prairie, MN). Near Infrared Reflectance Spectroscopy (SpectraStar, Model XT 2600, Unity Scientific, Milford, MA) was used to analyze samples for crude protein (CP), in-vitro true dry matter digestibility (IVTDMD), acid detergent fiber (ADF), neutral detergent fiber (NDF), and digestible NDF (DNDF). The calibration that was utilized was for mixed grass hay (NIRS Forage and Feed Testing Consortium, 2017).

Botanical Composition and Basal Cover

Botanical composition and basal cover data were collected on May 8, 2018 as a baseline to determine potential shifts in forage mixtures over time using the modified step-point method (Owensby, 1973). This method requires a step-point frame with a pin that was lowered onto the soil surface at 100 random locations across a given experimental unit. The units sampled for botanical composition and basal cover were consistent with the units sampled for forage yield and quality (Fig.2). When the point of the frame is placed on the ground, it is recorded whether it makes contact with bare soil, litter, rock, or the base of a plant. If the frame hits the base of a plant, the species is recorded. If it does not hit the base of a plant, the nearest plant to the tip of the frame within a 180° arc is recorded. In this manner, information is obtained for basal cover and percent species composition.

Grazing Management

MiG systems require manipulating the length of time cattle graze and space allotted based on available forage resources to achieve objectives. For purposes of this project, cows were generally moved daily. In certain situations, depending on forage availability and herd size, cows were moved every 2-4 days. This allowed us to make daily adjustments to subdivision sizes, monitor cattle health and soil conditions, and maintain the electric fencing.

Paddocks were set up based on current forage availability using polywire and step-in posts. The goal for forage removal was approximately 50% of available forage for purposes of stand health and maintenance. By leaving approximately half of the available biomass, there was adequate plant material to perform photosynthesis, which allowed for efficient regeneration of above ground biomass while maintaining root carbohydrate reserves. The time, date and location of each herd move as well as the size of each paddock were tracked using the PastureMap mobile application (PastureMap, San Fransico, CA).

Decisions on paddock sizes were made based on forage availability and soil conditions. Biweekly assessments of forage yield were made and used to adjust future paddock sizes for the number of cattle currently grazing. Cattle numbers fluctuated at certain times due to events such as artificial insemination, embryo transfer, calf vaccinations, etc. For calculating paddock sizes, the following formula based on stocking density was used to obtain the estimated liveweight per hectare. Available forage was based on kilograms of dry matter per hectare estimated from the hand clipped samples, 0.50 was the utilization percentage desired, estimated daily intake was 2.6 to 3.0% of bodyweight, and length of the grazing period was the desired grazing duration before next move, generally one day.

$$\frac{\text{Available forage estimation (kg DM ha}^{-1}\text{) x .50 (utilization goal)}}{\text{Estimated daily intake (\% bodyweight) x Duration of grazing (days)}} = \text{kg of liveweight ha}^{-1}$$

$$\frac{\text{Total kg of liveweight for entire herd}}{\text{kg of liveweight ha}^{-1}} = \text{Size of paddock in hectares}$$

Animal Unit Days/Hectare

Animal unit days (AUDs) represent the number of days a single, 454 kg cow with calf consuming 11.8 kg of forage dry matter per day can be sustained on a given area. This value was adjusted based on weight of different animals throughout the grazing season. AUDs were calculated as a measure of performance of each individual seed mixture. This provided insight into the ability of each forage mixture to support grazing by the cowherd. Animal unit days of grazing per hectare was used as a surrogate estimate of the amount of dry matter produced over the season since growth and disappearance were constantly occurring. Throughout the season, time spent grazing in each species mixture was recorded using the PastureMap application. The total number of days a mixture could support grazing was compared across the four species mixtures.

2.2.4. Statistical Analysis

An analysis of variance (ANOVA) was performed on mean yields among species mixtures for each year and by rotation, individual forage quality parameters by species mixture and grazing rotation within each year and over the season, and ground cover among species mixtures within each year. The Tukey p-value adjustment method for comparing a family of 4 estimates was used for all results and the test significance was set at $p \leq 0.05$. Estimated marginal means and pairwise comparisons were used to distinguish differences among species mixtures when examining forage yields, forage quality parameters, and ground cover (RStudio Version 1.1.456, 2018). Animal unit days (AUDs) and rest days were reported without statistical analysis.

2.3 Results and Discussion

Forage Yield

Seasonal mean dry matter yields (kg ha^{-1}) when cattle grazed specified units from each species mixture were numerically greater in 2017 than in 2018 due to stockpiling of forage that occurred. The grazing season in 2017 did not begin until August 18th because project infrastructure construction (fences, waterers, etc.) had not been completed. The forage was hayed earlier in 2017 in units B, C, and D. This delayed grazing, allowing for regrowth to accumulate to as much as 5,130 kg ha^{-1} (Fig. 3). There were no significant differences among species mixture yields in 2017.

In 2018, grass/legume mix (A) was in its first year of production having been reestablished the fall before. During initial spring growth, the meadow brome in this mixture elongated early and created a stand that was tall and high yielding, but not very dense. Because of this, quarter A was hayed to promote vegetative regrowth. It produced 140 metric tons. This mixture was the highest yielding, even after removal of the first harvest as hay, which was not included in mean yield. Species mix A yielded significantly greater forage than species mixes B and D (Fig. 4). The higher mean seasonal yield of this mixture was most likely attributed to the homogenous removal of the growing points, which allowed for an even flush of dense vegetative growth which was maintained by grazing for the remainder of the season. Additionally, the Nunn clay soil type of this area could have provided greater nutrient availability than the other mixtures grown under differing soil types. It has been suggested by multiple investigators that forage productivity is a function of defoliation relative to the growth stage of the forage (Crawley, 1983; Maschinski and Whitham, 1989; Oates et al., 2011; Turner et al., 1993). Grasses in the other seed mixtures elongated and became slightly over-mature but were grazed through or mowed at about 25 cm instead of hayed. This resulted in slower vegetative regrowth, accounting for the slightly lower yields. The complex grass mix (B) had the lowest mean yield compared to the other mixtures (Fig. 4). From observations during the grazing season, cattle avoided relatively mature tall fescue plants and selectively grazed the other grasses, especially the Festulolium. This led to much shorter, overgrazed patches between tall fescue plants and reduced regrowth of the other species. The Festulolium also set seed earlier than the other species in the mix and was able to drop mature seed on the ground. Festulolium is known to establish easily from seed (OGTR, 2008) and numerous seedlings were observed. These seedlings were also grazed before they could mature, leading to some bare patches where reestablishment was occurring. In addition, the area around fresh manure piles that is avoided, also referred to as the "zone of repugnance," amplified selectivity effects in this mixture more so than the other mixtures. According to Dohi et al. (1991), this effect is caused by volatile chemicals resulting in an odor that is avoided by cattle. In future grazing seasons, it will be interesting to observe if this pattern of patchy grazing perpetuates.

The mean forage yield was significantly greater during the first rotation than the second grazing rotation in 2017. In 2018, mean yield was significantly decreased in the third and fourth rotations in 2018 (Table 7). Both years resulted in reduction of yield throughout the grazing season which is simply a function of season long grazing. Cool spring temperatures induce rapid forage growth which is optimal growth conditions for C3 species leading to greater yields. As cattle graze throughout the season, forage removal and regrowth is constantly occurring while temperatures began to rise throughout the summer. Forage does not grow back as quickly during these warming months leading to slightly reduced yields. Although yields do decrease throughout the season, forage was adequate to support the cattle without compromising the health of the forage stand.

Overall, the cool-season forage mixtures performed well in regard to supporting the cattle herd for the grazing season duration. With proper irrigation and grazing management, the biomass removal and regrowth balance supported the cattle from May – October in 2018 with no addition of chemical fertilizers. Multiple other studies have supported the hypothesis that herbivory at certain intensities can increase biomass production (McNaughton, 1983, 1979; Savory, 1983). Although this study did not compare varied intensities, it was observed that moderate biomass removal (~50% of present forage) allowed for a visually healthy forage stand that fulfilled the goal of sustaining 227 animal units (AUs) in 2018 while producing seasonal mean yields as high as 3900 kg ha^{-1}.

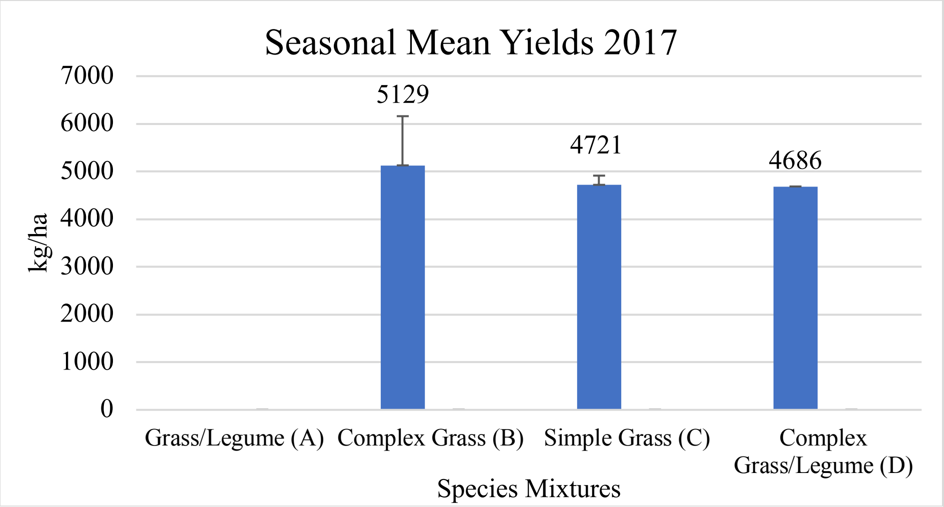

Figure 3: Seasonal mean yields by species mixture (n = 6) from August 18 – October 24 in 2017. There were no differences among means. Lines above bars indicate standard error.

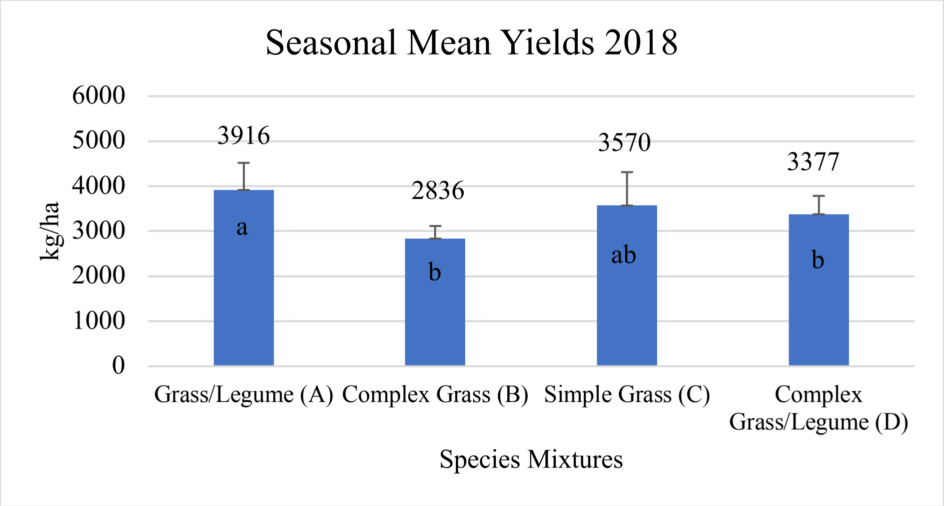

Figure 4: Seasonal mean yields by species mixture (n = 12) from May 4 – October 7 in 2018. Lines above bars indicate standard error. Letters on bars indicate significant difference ($p < 0.05$).

Table 7. Mean forage yield by round for 2017 and 2018 grazing season.

Mean Yield by Rotation

Rotation	2017	2018
1	5487.63 (a)	3826.86 (a)
2	4088.84 (b)	3653.02 (a)
3	NG	3294.13 (b)
4	NG	2926.53 (c)
Mean Seasonal Yield	4788.235	3425.135

Letters denote significance ($p < 0.05$).
NG = not grazed.

Forage Quality

In the 2017 grazing season, D was grazed first followed by C and B. Species mixture D had greater crude protein levels than the other two species mixtures in rotation 1 (Table 8). In the second grazing rotation, percent crude protein was not significantly different among mixtures. Species mixture C had significantly greater ADF and aNDF fiber in the first grazing rotation.

This species mix also had significantly greater digestible NDF as a percentage of dry matter (dNDF) than B and C in the first grazing rotation, leading to no significant difference for in-vitro true dry matter digestibility (IVTDMD). This was most likely due to the order of grazing that occurred in 2017, leaving species mixture C to be grazed last. There was a large portion of meadow brome in this mixture, which was trampled by cattle during grazing. The dead leaf matter from the meadow brome was hard to completely avoid during sampling and most likely contributed to the lower quality of this mixture.

In the first rotation of 2018, species mixture B was grazed first followed by C, D, and A. This resulted in B having significantly greater crude protein and in-vitro true digestibility as well as lower ADF and aNDF than the other mixtures (Table 9). This can be attributed to the presence of early-season vegetative growth while the other mixtures began entering the reproductive stage as the first grazing rotation proceeded. Forage quality optimization has been suggested to be a function of grazing timing relative to plant growth stage (Turner et al., 1993), which was most likely the case in this particular situation. During initial spring growth, the meadow brome in species mixture A elongated early and created a stand that was tall and high yielding, but not very dense. Because of this, quarter A was hayed to promote vegetative regrowth. It was grazed last in the first rotation after haying and regrowth had occurred. This allowed lignified, reproductive biomass to be homogenously removed. This resulted in mix A having significantly greater crude protein levels in the second grazing rotation as well as significantly lower ADF and aNDF than D and C, but no different than B (Table 9). By the third rotation, the majority of the lower quality, reproductive biomass had been grazed by the cows, encouraging vegetative regrowth that resulted in more similar forage quality values among mixtures (Table 9). Similar results were found by others. Schrick et al. (2015) conducted a grazing study evaluating the response of forage nutritive quality under varying intensities and seed-head suppression, noting that crude protein was consistently greater with seed-head suppression. They also found that in-vitro dry matter digestibility was greater with seed-head suppression, primarily late in the grazing season. Another grazing study reported that management-intensive rotational grazing, compared to continuous grazing or harvesting, consistently met moderate nutritional quality standards (allowing a lactating cow to produce 10 kg milk per day) due to defoliation maintaining vegetative plant growth (Oates et al., 2011).

A cow during lactation has the greatest nutritional demand. This is particularly true for crude protein and energy levels. A lactating cow requires approximately 10% crude protein and a 61% total digestible nutrients (TDN) which is generally met with high quality spring pasture and good quality summer pasture (Adams et al., 1996; Hall et al., 2009). Nutrient content of the forage from our study met and, in most cases, exceeded levels required for adequate livestock performance. In 2018, the lowest crude protein level was 10.6%, which was due to quickly maturing spring growth that was grazed towards the end of the first rotation (Table 11). As the season progressed, crude protein and dry matter digestibility levels increased as the result of reproductive growth removal stimulating vegetative regrowth in all mixtures. Inversely, 2018 ADF and aNDF tended to decline, reflected in lower lignin, cellulose, and hemicellulose levels and correspondingly greater digestibility. In 2017, there were no trends observed in quality due to early forage removal via haying which induced high quality vegetative regrowth (Table 8).

Overall forage quality for 2017 was similar across all mixtures, with no significance differences for any of the forage quality parameters measured (Table 10). Once again, this was most likely due to haying of all mixtures at the same point in time which induced vegetative regrowth. In 2018, species mixtures A and B had significantly greater average crude protein than mixtures C and D (Table 11). Soil type and grazing order could have been contributing factors to the difference between A and B and C and D. The area planted to mix D was comprised primarily of Kim loam soil while the area planted to mix A was dominated by Nunn clay loam. It was evident, based on visual observations, that there was moderate nitrogen deficiency and overall less vigorous plants within the Kim loam area of mix D. Soil N deficiency can have a substantial impact on crude protein content of the forage (Tiffany et al., 2000), resulting in lower overall seasonal crude protein measured for mix D. Species mixture B also had a significantly greater percentage of crude protein than C and D, most likely due to B being grazed first in 2018 resulting in early season vegetative growth that was high in protein (Tables 9 and 11). Greater seasonal ADF and aNDF means for species mix B reflect findings in the rotational comparisons, again likely as a function of grazing order.

Table 8. 2017 grazing season forage quality by rotation and species mixture in an irrigated MiG system at the Colorado State University Agricultural Research, Development, and Education Center.

Rotation	**Species Mix**	**Crude Protein**	**ADF‡**	**aNDF**	**dNDF48**	**IVTDMD48**
1	**A†**	NG#	NG	NG	NG	NG
	B	21.9 ± 0.51§(b)	33.7 ± 0.39(b)	53.2 ± 0.46(b)	26.0 ± 0.21(c)	79.8 ± 0.64$_{NS}$
	C	21.2 ± 0.25(b)	35.7 ± 0.25(a)	55.7 ± 0.36(a)	29.6 ± 0.28(a)	81.2 ± 0.39
	D	23.2 ± 0.33(a)	33.9 ± 0.33(b)	53.9 ± 0.35(a)	28.2 ± 0.30(b)	81.1 ± 0.41
2	**A**	NG	NG	NG	NG	NG
	B	22.2 ± 0.61$_{NS}$	32.7 ± 0.26(b)	52.2 ± 0.52(b)	24.1 ± 0.45(b)	78.4 ± 0.53$_{NS}$
	C	22.7 ± 0.53	35.1 ± 0.71(a)	54.4 ± 0.80(a)	25.6 ± 0.48(a)	77.9 ± 0.65
	D	22.51 ± 0.30	34.00 ± 0.39(a)	53.2 ± 0.60(a)	25.8 ± 0.22(a)	79.3 ± 0.75

Letters denote significance ($p < 0.05$).
† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume.
‡ ADF – acid detergent fiber, aNDF – α-amylase neutral detergent fiber, dNDF48 – 48 hour in-vitro digestible. neutral detergent fiber, IVTDMD48 – 48 hour in-vitro true dry matter digestibility.
§ Standard error.
# NG = not grazed.
NS = not significant

Table 9. 2018 grazing season forage quality by rotation and species mixture in an irrigated management-intensive grazing system at the Colorado State University Agricultural Research, Development, and Education Center.

Rot-ation	Species Mix	Crude Protein	ADF‡	aNDF	dNDF48	IVTDMD48
1	**A†**	13.2 ± 0.33§(b)	34.8 ± 0.55(a)	59.3 ± 0.76(a)	41.4 ± 0.30(a)	81.3 ± 0.86(b)
	B	17.6 ± 0.59(a)	21.4 ± 0.70(b)	42.4 ± 0.84(b)	36.3 ± 0.38(b)	90.5 ± 0.55(a)
	C	11.1 ± 0.33(ab)	32.0 ± 0.53(a)	54.7 ± 0.66(a)	33.1 ± 0.19(b)	80.0 ± 0.55(b)
	D	10.6 ± 0.28(b)	32.9 ± 0.72(a)	56.4 ± 1.04(a)	35.4 ± 0.75(b)	80.1 ± 0.56(b)
2	**A**	16.9 ± 0.47(a)	29.4 ± 0.63(b)	53.6 ± 0.74(b)	40.5 ± 0.34(b)	86.7 ± 0.48(a)
	B	12.3 ± 0.71(b)	31.2 ± 0.63(a)	54.8 ± 1.04(ab)	37.1 ± 0.46(b)	81.0 ± 0.83(b)
	C	11.5 ± 1.83(b)	32.5 ± 2.04(a)	57.5 ± 2.82(a)	47.2 ± 5.40(a)	86.8 ± 6.84(a)
	D	12.3 ± 0.63(b)	33.5 ± 0.89(a)	57.0 ± 1.09(a)	37.0 ± 0.24(b)	82.2 ± 0.82(b)
3	**A**	17.7 ± 0.71(a)	28.3 ± 0.77$_{\text{NS}}$	51.1 ± 0.89$_{\text{NS}}$	40.6 ± 0.44$_{\text{NS}}$	87.4 ± 0.55$_{\text{NS}}$
	B	15.5 ± 0.81(a)	28.4 ± 0.88	50.4 ± 1.28	36.8 ± 0.23	84.7 ± 0.87
	C	15.5 ± 0.87(a)	30.0 ± 0.97	51.8 ± 1.36	39.9 ± 0.32	87.4 ± 0.72
	D	14.7 ± 0.56(a)	30.6 ± 0.53	53.3 ± 0.78	38.9 ± 0.28	84.0 ± 0.48
4	**A**	19.1 ± 0.56(a)	25.8 ± 0.81$_{\text{NS}}$	49.2 ± 0.96(a)	39.6 ± 0.32$_{\text{NS}}$	86.8 ± 0.61$_{\text{NS}}$
	B	19.1 ± 0.78(a)	24.7 ± 0.66	44.5 ± 0.99(b)	37.2 ± 0.28	24.7 ± 0.59
	C	15.4 ± 0.62(b)	26.7 ± 0.57	48.9 ± 0.84(a)	39.5 ± 0.37	88.2 ± 0.84
	D	13.5 ± 0.73(b)	25.9 ± 0.69	47.5 ± 0.81(a)	36.2 ± 0.48	85.4 ± 0.68

Letters denote significance ($p < 0.05$).

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

‡ ADF – acid detergent fiber, aNDF – α-amylase neutral detergent fiber, dNDF48 – 48 hour in-vitro digestible neutral detergent fiber, IVTDMD48 – 48 hour in-vitro true dry matter digestibility

§ Standard error

NS = No significance

Table 10. 2017 mean forage quality from all grazing rotations in the grazing season by species mixture in an irrigated MiG system at the Colorado State University Agricultural Research, Development, and Education Center. There were no significant differences between forage quality parameters in 2017.

Species Mixture	Crude Protein	ADF	aNDF	dNDF48	IVTDMD48
A†	NG#	NG	NG	NG	NG
B	22.07 ± 0.56§	33.25 ± 0.32	52.76 ± 0.49	25.13 ± 0.33	79.15 ± 0.58
C	22.01 ± 0.39	35.46 ± 0.48	55.10 ± 0.58	27.65 ± 0.38	79.59 ± 0.52
D	22.85 ± 0.31	33.95 ± 0.36	53.60 ± 0.47	27.01 ± 0.26	80.24 ± 0.58

Letters denote significance ($p < 0.05$).

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

‡ ADF – acid detergent fiber, aNDF – α-amylase neutral detergent fiber, dNDF48 – 48 hour in-vitro digestible neutral detergent fiber, IVTDMD48 – 48 hour in-vitro true dry matter digestibility

§ Standard error

NG = not grazed

NS = not significant

Table 11. 2018 mean forage quality from all grazing rotations in the grazing season by species mixture in an irrigated MiG system at the Colorado State University Agricultural Research, Development, and Education Center.

Species Mix	Crude Protein	ADF	aNDF	dNDF48	IVTDMD48
A†	16.75 ± 0.52§(a)	29.60 ± 0.69(a)	53.34 ± 0.84(a)	40.57 ± 0.35 (a)	85.60 ± 0.62(a)
B	16.16 ± 0.72(a)	26.47 ± 0.71(b)	48.08 ± 1.04(b)	36.91 ± 0.34 (b)	70.28 ± 0.71(b)
C	13.43 ± 0.91(b)	30.35 ± 1.03(a)	53.26 ± 1.42(a)	39.95 ± 1.57 (a)	85.64 ± 2.24(a)
D	12.84 ± 0.55(b)	30.76 ± 0.71(a)	53.59 ± 0.93(a)	36.93 ± 0.44 (b)	82.98 ± 0.64(a)

Letters denote significance ($p < 0.05$).

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

‡ ADF – acid detergent fiber, aNDF – α-amylase neutral detergent fiber, dNDF48 – 48 hour in-vitro digestible neutral detergent fiber, IVTDMD48 – 48 hour in-vitro true dry matter digestibility

§ Standard error

NS = not significant

Animal Unit Days

Animal unit days (AUDs) represent the number of days the forage base was grazed by a single, 454 kg cow with calf consuming 11.8 kg of forage dry matter per day. The total AUDs were 13,767 in 2017 and 28,260 in 2018. The AUDs were greater in 2018 simply due to the length of the grazing season (Table 12 and 13). The 2017 grazing season was 67 days in length while it lasted for 154 days in 2018. No AUDs were calculated for grass/legume mixture A in 2017 because it was not grazed due to reseeding. The first growth in species mixture A in 2018 was hayed with a total yield of 140 metric tons prior to regrowth being grazed in the first rotation.

The complex grass-legume mixture (D) had the greatest AUDs for the 2017 season (Table 12). This could be due to the more homogenous grazing that was observed in this species mix creating more even regrowth. Although this was the most diverse forage mix, all species were very palatable including soft-leaved tall fescue variety, 'Baroptima plus E34'. This could have led to less selectivity during grazing. This same observation occurred in 2018 with species mixture D having the second greatest AUDs after B (Table 13). In 2018, the complex grass mixture B had the greatest AUDs. This mixture was grazed first in the rotation before many of the cool-season grasses attempted to set seed. Also, in the beginning of the 2018 grazing season, the full herd was not present due to calving. Some cows calved on the pivot while late calving cows were added post calving. Because there were less cows, the rotations were slower allowing greater utilization of early-season vegetative forage that perpetuated throughout the growing season due to the removal of the apical meristem. However, in 2018, species mixture B was not the highest mean seasonal yielding mixture yet still had the greatest AUDs. Mean seasonal yield was potentially lower due to being grazed first in the rotation. Being that B was first in rotation, clipped yield samples captured early season growth which had lower standing biomass potentially reducing the overall mean yield of this mixture. Differences in palatability among species, especially tall fescue, led to visually thin or bare patches that were concerning relative to the other mixtures. Overgrazed areas surrounded tall, more mature tall fescue plants. This led to the conclusion that most species, except tall fescue, were potentially over utilized in this mixture. Pasture unit 1 in the simple grass mixture C has a lower AUD value due to its smaller acreage. Less acreage in a pasture means less carrying capacity and shorter overall grazing periods. It was often grazed in conjunction with unit 2.

Table 12. Total mean animal unit days and AUDs per hectare from August 18 – October 24, 2017 per pasture unit, by species mixture, and total.

Species Mixture Total AUDs and AUDs ha^{-1}

Pasture Unit	**A†**	**B (Total)**	**B (ha^{-1})**	**C (Total)**	**C (ha^{-1})**	**D (Total)**	**D (ha^{-1})**
1	NG‡	607.40	34.6	112.95	24.1	538.96	29.9
2	NG	592.73	33.8	586.50	36.0	695.19	38.6
3	NG	556.58	31.7	790.93	41.1	817.90	45.4
4	NG	593.06	34.8	699.05	36.3	690.46	38.3
5	NG	560.87	37.2	579.18	39.1	621.20	43.4
6	NG	597.43	40.3	554.38	37.4	507.27	34.8
7	NG	561.43	37.9	566.48	38.9	569.20	39.1

8	NG	442.21	33.2	695.78	52.2	230.12	17.6
Total AUDs	***NG***	**4511.7**		**4585.2**		**4670.3**	

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume
‡ NG, not grazed

Table 13. Total mean animal unit days and AUDs per hectare from May 8 – October 9, 2018 per pasture unit, by species mixture, and total.

	Species Mixture Total AUDs and AUDs ha^{-1}							
Pasture Unit	**A† (Total)**	**A (ha^{-1})**	**B (Total)**	**B (ha^{-1})**	**C (Total)**	**C (ha^{-1})**	**D (Total)**	**D (ha^{-1})**
1	928	51.5	969.19	55.3	161.19	34.3	1179.02	65.4
2	844.88	46.9	900.78	51.4	1117.37	68.5	844.90	46.9
3	929.14	50.2	1034.33	59.0	1230.76	63.9	912.65	50.6
4	862.83	46.0	731.22	42.9	1095.25	56.8	1139.46	63.2
5	752.94	50.0	1039.74	70.2	875.23	59.1	867.53	60.6
6	622.87	41.3	836.53	56.4	844.51	57.0	842.58	57.8
7	1020.04	67.7	1080.30	72.9	844.16	57.9	669.90	46.0
8	438.79	32.9	901.84	67.6	823.40	61.7	919.12	70.2
Total AUDs	**6399.49**		**7493.93**		**6991.87**		**7375.16**	

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

Rest Periods

Rest days are integral to pasture recovery and regrowth potential. Studies have shown for cool-season pastures that are managed intensively, 20-30 days of rest is ideal for plant regrowth and recovery (Holland et al., 1992; Paine et al., 1999). Without adequate rest, root biomass reduces as grazing intensity and frequency increases (Dawson et al., 2000; Holland et al., 1992). Furthermore, repeated defoliations lead to roots growing more superficially (Chaieb et al., 1996). Moderate frequency defoliations (approximately once a month) resulted in deeper root growth, which is more ideal for avoiding water stress, particularly in semi-arid environments. Throughout the 2017 and 2018 grazing seasons, this ideal range of rest days was successfully met or exceeded in all species mixtures and rotations (Table 14). Maintaining this expectation in future grazing seasons will be important for continuing to foster root growth and vigor. This could increase stand longevity and capitalize on the initial investment in pasture establishment.

In addition, elongated roots from less intense and frequent grazing could improve water utilization deeper in the soil profile and more root biomass could lead to greater carbon sequestration and biological activity. Having plants that are more tolerant to water stress would be beneficial in a system that is water limited at times due to the limitation of being able to irrigate units (quarters) where cattle are grazing.

Table 14: Mean rest days by grazing rotation and species mixture from irrigated pasture under MiG.

	2017				2018			
Grazing Rotation	**GL† (A)**	**CG (B)**	**SG (C)**	**CGL (D)**	**GL (A)**	**CG (B)**	**SG (C)**	**CGL (D)**
1	-	-	-	-	-	-	-	-
2	-	26±7.5	42±10	32±1.0	45±0.8	46±0.3	46±1.8	46±3.3
3	-	-	-	-	33±0.5	47±4.0	36±1.0	36±2.3
4	-	-	-	-	27±2.5	31±0.6	33±2.8	31±3.2

† GL (A) – Grass/Legume, CG (B) – Complex Grass, SG (C) – Simple Grass, CGL (D) – Complex Grass/Legume

Botanical Composition

Grazing animals are selective by nature. Having a complex forage mixture could result in cattle selecting desired species more intensively and frequently, allowing other species a competitive advantage. Within a grass stand, species differ in growth rate, growth stage, and inherent size which can result in contrasting preferences by cattle (Dawson et al., 2000). Furthermore, cultivars express different morphologies when grazed. Theoretically, MiG can minimize selectivity and encourage more homogenous grazing habits (Shewmaker and Bohle, 2010). Baseline botanical composition data was collected to track any changes that potentially occurred over the grazing project duration. The percent of pure live seed (PLS) of each species that was seeded was compared to the baseline botanical composition to determine the success of establishment.

In species mixture A, the simple grass and legume mixture, meadow brome outcompeted orchardgrass to dominate this mixture (Table 15). Meadow brome, seeded at 29% of the total mix, made up nearly 55% of the established composition while orchardgrass seeded at 62% made up 38% of the composition. During the first full year of growth, it was visually observed that meadow brome was quick to shift into its reproductive phase; it was evident that the majority of the stand was meadow brome due to the ease of identifying seedheads. Additionally, meadow brome is known to perform better than orchardgrass in climates with little snow cover and spring frost occurrences (Ogle et al., 2012). The specific cultivar, 'Cache', was also bred for increased seedling vigor in irrigated settings, which might explain the competitive success of this species (Ogle et al., 2012).

In the complex grass mixture (mix B), the dominant species were tall fescue and smooth brome. Both of these species established at nearly double to triple the rate at which they were seeded. The percent of the mix seeded and percent establishment of tall fescue and smooth brome were 17% and 32% and 6% and 18%, respectively (Table 15). Meadow brome and creeping meadow foxtail both established at percentages relatively equivalent to the amount of seed that was planted. Orchardgrass, although planted at 27% of the mixture, only resulted in 13% of the botanical composition. Festulolium had the poorest establishment making up 20% of the seed mix composition but only 2.3% of the established forage. Festulolium is a hybrid between tall fescue and perennial ryegrass and, depending on its expression, can be misidentified for tall fescue.

Species mixture C, the simple grass mixture, showed successful establishment of orchardgrass and meadow brome with a very small percentage (0.10%) of creeping meadow foxtail. However, orchardgrass (58% of the seed mixture) only established at 30% of the composition while meadow brome (26% of the seed mixture) exceeded 60% of recorded forage species (Table 15). Otero sandy loam (excessively drained) and Garret loam (well-drained) are the main soil series where this species mixture was planted, and likely provided an environment more conducive to meadow brome than meadow foxtail. Meadow brome can perform under MiG with limited irrigation (Jensen et al., 2006). This suggests that meadow brome would establish more readily in sandy, well-drained soils, while species like meadow foxtail perform best in poorly-drained soils (Jensen et al., 2006; USDA-NRCS, 2013). Although meadow foxtail was planted and established as a minor percentage of the mixture, it has the potential to spread over time due to its rhizomatous, sod-forming growth habits.

Orchardgrass, tall fescue, perennial ryegrass, and Festulolium established relatively consistently with the percentage of pure live seed (PLS) planted in species mix D (complex grass/legume mix). However, meadow brome (only making up 11% of this seed mixture) established at over 27% (Table 15). Like species mixture C, the vast majority of the land area species mix D was planted on was well-drained (i.e. Kim loam). As stated above, meadow brome establishes well and thrives under these conditions. Meadow fescue only comprised 2% of the established botanical composition but made up 13% of the seed composition. Sources of error that may be present for meadow fescue could be poor establishment and misidentification. Meadow fescue is similar to other species in this mix and morphological plasticity in the field could have allowed it to be mistaken for Festulolium or tall fescue. According to the seed supplier from which the seed was purchased (insert company name here), meadow fescue (cv ‘Pradel’) should be harvested early during the first year of establishment to minimize competition within a mixture (Barenbrug, Tagent, OR). It was possible that other species in this complex mixture established quicker, outcompeting meadow fescue. Meadow fescue is also at a disadvantage due to the western U.S. climate of this system. This species has not been typically grown in the western U.S. but has been adapted to more humid, Northeastern U.S. climates (Fribourg et al., 2009).

Table 15: Percent species composition of the seed mixtures compared to each forage mixture post establishment and first grazing season (2017) under MiG.

Species	**Percent Composition of Seed Mix (%)**	**Percent Composition of Establishment (%)**
A†		
Meadow Brome	29	54.6
Orchardgrass	62	38
Creeping Meadow Foxtail	9	0.3
Other (non-planted species)	-	6
B		
Meadow Brome	19	22
Orchardgrass	27	13.6
Creeping Meadow Foxtail	12	14.3
Tall Fescue	17	32.6
Festulolium	20	2.3
Smooth Brome	6	18
Other	-	19
C		
Meadow Brome	26	63.3
Orchardgrass	58	34.3
Creeping Meadow Foxtail	16	0.1
Other	-	1.3
D		
Meadow Brome	11	27.3
Orchardgrass	34	29
Tall Fescue	14	19
Perennial Ryegrass	15	8.6
Meadow Fescue	13	2
Festulolium	13	11.6
Other	-	2.3

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

Ground Cover

The results of the modified step-point ground cover measurements are shown in Table 16. There were no significant differences among mixtures B, C, and D for any of the ground cover variables. However, species mixture A had significantly greater percentages of bare ground and lower percentages of litter compared to the other mixes, likely due to several factors. First, this was the first year of growth following establishment and the plants had not had time to produce enough biomass for adequate litter accumulation. Second, this mixture had not yet been grazed at time of sampling, so the cattle did not trample or otherwise waste growth that would have ended up on the ground as litter. It is interesting that there was not a difference in plant cover with this being the first year of growth for mixture A compared to the other 3 mixtures which were entering their second year of production. This illustrates that mixture A established well and plants were growing vigorously at time of sampling.

Table 16. Percentages of ground cover found in each species mixture under MiG.

Ground Cover (%)	**A†**	**B**	**C**	**D**
Plant	22	20	26	27
Litter	9.6*	60	63	61
Soil	68*	20	11	12

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

* $p < 0.05$.

2.4. Conclusion

In this irrigated, MiG system, manipulating plant growth stage with herbivores or haying, along with adequate regrowth periods, were the driving forces behind productivity and quality. Allowing approximately 26-46 rest days contributed to the productivity of the system and ability to sustain the cows over the grazing season. I hypothesized that there would be no significant difference in forage quality between the species mixtures due to similarities among the cool-season species. In both 2017 and 2018, species mixtures that were either hayed or grazed first in the rotation induced vegetative regrowth resulting in the greatest quality and production. This evidence does not support my hypothesis and suggests that although species with similar high-quality potential were planted, management plays a larger role than anticipated. I also hypothesized that mean seasonal forage yield would be greater in the complex mixtures due to the diversity of cool-season species. Again, data did not support this hypothesis. Management seemed to be a larger contributing factor to seasonal mean yield over diversity. The simple grass/legume mixture (A) had a greater seasonal mean yield than the most diverse mixture (D). Stand age and soil quality may also have played a role in the differences between these mixtures. Mean forage yield decreased throughout the growing season due to increases in temperatures that slowed the regrowth of biomass removed through grazing. Also, forage in a vegetative state has less overall biomass than early season forage with stem material.

Bare patches in species mix B were observed around large patches of non-soft leaf tall fescue (Texoma MaxQ II). It was evident that selectivity against tall fescue played a large role in patchiness. However, in the other three species mixtures, visual observations suggested that MiG with proper stocking densities resulted in homogenous utilization of forage. This suggests that when species with relatively equal palatabilities exist in the mixture, more homogenous grazing can be achieved. Although MiG is known for potential benefits of decreased selectivity, this is still dependent on species present in the mixture.

Soil conditions, plant phenology, and competitive advantages likely contributed to the differences between seeded and established mixture compositions. Future botanical composition will be necessary to understand how long-term MiG impacts grazing behavior, ultimately impacting the species in these mixtures. This information is needed to provide insight on MiG and its role in reducing selectivity to allow complex mixtures to remain diverse.

Litter present on the soil surface was similar among species mixtures that were grazed and planted at the same time compared to the species mixture that was not. Trampling from grazing and natural accumulation of plant matter through growth cycles both contributed to surface cover and, over time, could likely lead to increased soil organic matter.

As an entire functioning grazing system, forage quality and AUDs met the ultimate goal of the system: to sustain 227 AUs for the duration of the grazing season while maintaining a well-managed forage base. Forage quality exceeded nutritional requirements of cow-calf pairs and produced enough forage to sustain the cattle herd in both 2017 and 2018. Although individual components of the research are important, it is ultimately the functionality of the entire system that is of interest in this MiG project. This information is of utmost importance to producers in Colorado (and other irrigated semi-arid systems) interested in adopting these practices in their own enterprises.

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CHAPTER 3: SOILS

3.1 Introduction:

Management-intensive grazing (MiG) is often defined as "a flexible version of rotational grazing that balances forage supply with animal demand (Stout et al., 2000)". Over the past decade, interest in MiG on irrigated pastures in the western U.S. has increased steadily due to the prospects of reduced production costs, increased animal output, land use efficiency, and environmental benefits. This system is being considered as an option by many farmers and ranchers due to pressure to reduce public land grazing and the declining space available for pasture (Cox et al., 2017). Adoption of this practice has the potential to bring the benefits of intensively managed, improved pastures into the already established irrigated crop infrastructure that exists on many ranches. However, there are still many unknowns about the implications of an intensive cattle grazing system on a limited parcel of irrigated land, particularly in terms of soil quality. One would imagine that studying changes in soil quality would be integral for improving the understanding of how MiG affects the overall function and viability of cropland converted to pasture grazing systems.

Converting cropland to a perennial pasture system enhances soil quality by increasing microbial and enzymatic activity, building soil organic matter, and sequestering carbon (Acosta-Martínez et al., 2008; Carter et al., 1994; McCallum et al., 2004; Paudel et al., 2011; Veum et al., 2015). Acosta-Martinez et al. (2008) showed that microbial biomass carbon was up to 6.6 times greater under pasture compared to corresponding vegetable production sites. Intimately correlated to microbial biomass carbon is the ability of microorganisms to degrade soil organic matter via enzymatic activity (Turner et al., 2002).

Enzymes are integral to all soil biological activity, including organic matter decomposition.

Specifically, the β-glucosidase (BG) enzyme plays an important role in the process of cellulose degradation. As a group, the enzymes referred to as "glucosidases" release significant energy sources in the form of sugars that are important for sustaining soil microbial populations (Bandick and Dick, 1999). Bandick and Dick (1999) found that a permanent pasture site had greater β-glucosidase activity and overall enzyme activity than in cultivated annual vegetable production or winter wheat-summer fallow. Turner et al. (2002) found that β-glucosidase activity was positively correlated to concentrations of soil carbon and microbial carbon under pasture soils. Soil microbial and enzymatic activity undoubtedly are linked to soil physical properties that affect soil water and air relations.

In terms of physical soil properties, perennial pasture plants establish root systems that improve overall physical properties such as increased aggregate stability, water-infiltration, and sub-soil macroporosity (Carter et al., 1994; McCallum et al., 2004; Milne and Haynes, 2004), all of which are likely affected by improvements in both soil organic matter and microbiological activity. McCallum et al. (2004) found that perennial pasture improved soil macroporosity and infiltration in the dense B horizon of the soil profile, as well as increased the number of 0.3-0.03 mm pores. Adding herbivory in perennial plant systems can further enhance these positive improvements. Herbivory addition increases plant root exudation (Bardgett et al., 1998; Macduff and Jackson, 1992; Shand et al., 2006), with root exudates playing a major role in binding soil particles together to create greater aggregate stability. Aggregate stability can be further via greater organic matter accumulation simply by eliminating tillage in perennial systems (Tisdall and Oades, 1982). A study by Milne and Hayes (2004) further supported this contention, finding greater aggregate stability in perennial grazing systems compared to annual ryegrass grazing systems. Improving soil microbial habitats and physical attributes through the use of perennial pasture systems likely leads to improvements in nutrient cycling.

These aforementioned soil properties, in conjunction with climate, management, and residue quality, all effect the rate at which nutrients are released from organic forms (Drinkwater et al., 1996; Mikha et al., 2006). Precipitation in particular, has been positively correlated with potentially mineralizable nitrogen (PMN) soil levels (Doran, 1987), with PMN an indicator of a microbial population's capacity to mineralize nitrogen from organic to plant-available forms. Thus, managed irrigation could provide an advantage to irrigated MiG pasture systems over dryland pastures in terms of how quickly manure N is mineralized; no-till managed systems may further enhance this advantage. Doran (1987) found that in a no-till system, soil microbial biomass and PMN distributions were similar, with both being greatest in the top 7.5 cm of soil. In long-term grazing systems, manure and plant litter decomposition are the main fertility sources, yet are only found on the soil surface and are not incorporated. Thus, having proportionately more MBC and PMN in the top few cm of soil is advantageous for nutrient cycling and breakdown of plant material in these systems.

Grazed pastures also tend to accumulate more potassium (K) and phosphorus (P) in the top several cm of soil than in systems that remove forage by hay harvest (Mathews et al., 1994). When passing through the animal, approximately 96% of P is excreted in manure (Eghball et al., 2002). The availability of the P excreted in cattle manure reaches and often exceeds 70%, primarily in inorganic forms (Eghball et al., 2002). The remaining P availability is largely controlled by microbial mineralization, which is influenced by soil temperature, moisture, and the manure characteristics such as species origin and diet (Eghball et al., 2002; Slavich and Petterson, 1993). About 73% of K is excreted by cattle in urine and is often 100% bioavailable; this is not a large environmental concern in pasture systems (Eghball et al., 2002) because K is generally considered immobile and only leaches in extreme cases of low soil pH and cation exchange capacity. In a study determining the fate of potassium under irrigated pasture, K losses through leaching was negligible (0.99 g m^{-2} yr^{-1}; Early et al., 1998).

Managed grazing appears mostly positive. However, the addition of grazing, particularly in irrigated systems, raises concerns about adverse effects on soil properties and thus overall soil quality. Specifically, bulk density is the primary concerns in perennial pasture, managed grazing systems because of compaction caused by hoof-to-soil contact; bulk density can be exacerbated with increased soil moisture within irrigated perennial pasture systems, higher stocking densities, and amount of surface litter (Da Silva et al., 2003; Drewry et al., 2008; Greenwood and McKenzie, 2001). Bulk density is a concern in these systems due to the low success rate in remediation and impact on forage yields. Methods such as aeration, deep-ripping via tillage, and natural recovery have been studied to alleviate compaction (Greenwood et al., 1998; Greenwood and Mckenzie, 2001; Malhi et al., 2011). Aeration and deep-ripping studies have had extremely variable responses most likely due to being soil and system dependent. Natural recovery by removing grazing from a system has been shown to return bulk density levels comparable to ungrazed soils (Greenwood et al., 1998). Da Silva et al. (2003) showed that decreasing amounts of post graze residue correlated to higher penetrometer resistance, an indirect measure of soil bulk density. Positive and negative grazing impacts in perennial pasture systems can make or break livestock enterprise viability, with the primary driver behind yields, forage quality, and profitability the ability of soils to function properly. Proper soil functionality may be correlated to soil quality quantification.

The Soil Management Assessment Framework (SMAF) is a soil quality assessment program that utilizes 11 soil quality indicators (SQI) in conjunction with soil taxonomy as a foundation (Andrews et al., 2004). The individual indicators are grouped into nutrient, chemical, physical, biological and overall soil quality indices. Soil quality is dependent on the soil's inherent properties, climatic conditions, crops present, and management practices performed. These points are considered within the SMAF to create an output that reflects the specific limitations and needs of the analyzed soil. These details allow output values to be relative to input values, allowing the program to be transferable across climates and locations. This program has been used similarly in previous research to measure soil quality changes in native pasture, perennial vegetation systems, and cropland converted to pasture. For example, Veum (2015) utilized the SMAF to assess soil quality for different annual and perennial cropping systems. They concluded that of the SQI categories, biological and physical were the most sensitive to change in management (Veum et al., 2015). Paudel (2011) found that grazed pasture systems had greater beta-glucosidase activity, water stable aggregation, soil organic carbon, and total nitrogen. They concluded that because there is minimum disturbance, more organic matter can accumulate resulting in ecological benefits to the system (Paudel et al., 2011).

The research mentioned above, although in ecologically similar systems, does not recognize a livestock component. To date and as far as we are aware, there has been no research using SMAF to study irrigated, management-intensive livestock grazing systems. Based on current literature, I hypothesized that: 1) converting irrigated cropland to perennial, management-intensively grazed pasture would cause negative changes in the physical SQI due to increases in bulk density exerted from hoof pressure. Increasing bulk density can be expressed as increased penetrometer resistance; 2) biological SQI will increase due to microbial biomass carbon and enzymatic activity being stimulated from perennial grass roots and lack of tillage; and 3) nutrient SQI will increase due to P and K levels from manure accumulation during the grazing season. These hypotheses are supported by research by Veum et al. (2015) that concluded that biological and physical SQI's were most sensitive to change in management practices, and by Greenwood and McKenzie (2001) who discussed the impacts cattle grazing can have on soil physical properties. Thus, the objective of this study was to quantify soil quality changes caused by land-use change and cattle grazing on an irrigated, perennial pasture using the SMAF.

3.2. Materials and Methods

3.2.1. Site Description

This study was conducted at the Colorado State University Agriculture Research, Development and Education Center, located 13 km northeast of Fort Collins, CO (40°39’30.40” N, 104°59’11.24” W). The 82-ha research area was under center pivot irrigation. Climatic conditions were mid-latitude dry, cold, semi-arid steppe (Kottek et al., 2006), with average low and high temperatures of 1.0 °C to 16.8 °C and average annual rainfall of 38 cm (WRCC, 2018) at an elevation of 1,554 m. For our study period, 2017 and 2018, mean temperatures ranged from 6.90 to 22.7 °C and 10.7 to 27.5 °C, respectively (CoAgMet, 2018). The amount of irrigation water applied to each species mixture along with growing season precipitation can be found in table 17. The following soil series are found in the study area: Aquepts, Connerton-Barnum complex, Garrett loam, Kim loam, Nunn clay loam, Otero sandy loam, and Thedalund loam (Table 18).

Prior to project establishment, the study area was managed for about a decade as a tilled cropping system with crops including corn silage (*Zea mays* L.), dry beans (*Phaseolus vulgaris* L.), and alfalfa (*Medicago sativa* L.). In September 2016, the area was converted to four forage mixtures planted on each quarter of the project area, including a simple grass-legume mix, a complex grass-legume mix, a simple grass mix, and a complex grass mix (Table 19). Each forage mixture comprised approximately 20 hectares (Figure 1). Prior to planting and establishment, a deep-ripper was used to alleviate a plow pan that had formed due to the clay soil type and previous management. Following deep ripping, the field was moldboard plowed, disked twice, cultipacked twice, and then rolled with a heavy steel roller to break up large soil aggregates and firm the soil surface prior to stand establishment. Cool-season grasses were planted in early September 2016 and legumes were cross-drilled in March 15-16, 2017.

Unfortunate climatic circumstances in the spring of 2017 led to multiple issues in establishment. Species mixture A failed due to winds that moved loose soil and damaged small seedlings. Oats were planted in this quarter on March 23, 2017 in response to avoid further wind erosion. The planned mixture was re-planted in August 2017. Most of the legumes that were cross-drilled in early March were killed due to a hard frost that occurred shortly after germination. Success rates for the legume mixtures were approximated at less than 5%. Legumes were again interseeded in early August of 2018. Thus, the forage mixtures with legumes contained few if any for the duration of this research.

Table 17. Irrigation applied by species mixture and total precipitation that occurred from April to October.

	2017			**2018**		
Species Mixture	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**
A†	9.75	32.5	**22.55**	14.1	38.3	**29.1**
B	12.35	32.5	**25.15**	15.45	38.3	**30.5**
C	11.9	32.5	**24.7**	13.85	38.3	**28.9**
D	11.6	32.5	**24.4**	15.45	38.3	**30.5**

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

Table 18. Soil series present within the project area with descriptions and percent of the project area.

Soil Series	Description		Percent of Project Area
Nunn clay loam	Fine, smectitic, mesic Aridic Argiustolls	Somewhat poorly drained; restrictive layer > 200 cm	56.3
Thedalund loam	Fine-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer 50-100 cm	0.5
Connerton-Barnum complex	Fine-loamy, mixed, superactive, mesic Torriorthentic Haplustolls	Well-drained; restrictive layer > 200 cm	2.6
Otero sandy loam	Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents	Somewhat excessively drained; restrictive layer > 200 cm	13.6
Garrett loam	Fine-loamy, mixed, superactive, mesic Pachic Argiustolls	Well-drained; restrictive layer > 200 cm	9.2
Kim loam	Fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer > 200 cm	11.7
Aquepts loamy	Inceptisol with a water table near the surface	Poorly drained; restrictive layer greater than 200 cm	6.1

Table 19. Forage species planted in each 20-ha portion of the 82-ha project area.

Forage Mixture	Species
A - Grass/Legume Mix	Meadow brome (*Bromus biebersteinii Roem. & Shult.),* Orchardgrass (*Dactylis glomerata L.),* Creeping meadow foxtail (*Alopecurus arundinaceus* Poir.*),* Birdsfoot trefoil (*Lotus corniculatus L.),* Strawberry clover (*Trifolium fragiferum L.),* White clover (*Trifolium repens L.)*
B - Complex Grass Mix	Meadow brome, Orchardgrass*,* Creeping meadow foxtail, Tall fescue (*Festuca arundinacea* Shreb.), Festulolium (*xFestulolium*), Smooth brome (*Bromis inermis L.*)
C - Simple Grass Mix	Meadow brome*,* Orchardgrass*,* Creeping meadow foxtail
D - Complex Grass/Legume Mix	Meadow brome*,* Orchardgrass, Tall fescue, Perennial ryegrass (*Lolium perenne),* Meadow fescue (*Festuca pratensis),* Festulolium (*xFestulolium),* Red clover (*Trifolium pretense L.),* Alsike clover (*Trifolium hybridum L.)*, White clover*,* Birdsfoot trefoil

3.2.2. Project Design

Three random grazing experimental units (paddocks) were selected per seed mixture (i.e., per quarter section of the field) and consistently sampled throughout the grazing season for forage yield, quality, and penetrometer measurements (Fig. 5). Units containing minor soil types were avoided.

In 2017, approximately 171 cow-calf pairs were grazed from August 18 until October 24. The grazing season was delayed due to fencing and water infrastructure being constructed. The herds were separated by breed (Angus and Hereford) for breeding purposes. The herds were then combined on September 21 and grazed until October 24. In 2018, approximately 136 cow-calf pairs, 49 replacement heifers, and 5 steers were grazed from May 4 to October 7. The entire cow herd was not initially present on the pivot at the beginning of the grazing season. A portion of the cows calved on the pivot and the remainder were added post calving. Throughout the remainder of the grazing season, up to 3 herds were grazed at one time. Groups were rearranged for breeding purposes throughout the grazing season, but the number of animals remained relatively constant.

Figure 5: Diagram of pre-determined 8 paddocks along with the 2 designated experimental units within each cool season mixture (A, B, C, D).

3.2.3. Grazing Management

MiG systems require manipulating the length of time cattle graze and space allotted based on available forage resources to achieve management goals and objectives (Shewmaker and Bohle, 2010). For this project, cows were generally moved daily. In certain situations, depending on forage availability and herd size, cows were moved every 2-4 days. This management method allowed for making daily adjustments to subdivision sizes, monitoring of cattle health and soil conditions, and maintaining the electric fencing.

Paddocks were set up based on current forage availability using polywire and step-in posts. The goal for forage removal was approximately 50% of available biomass for purposes of stand health and performance. By leaving approximately half of the available biomass, there was adequate plant material to perform photosynthesis, which theoretically allowed for efficient regeneration of above ground biomass while maintaining carbohydrate reserves in the roots. The time, date and location of each move, as well as the size of each paddock, were tracked using the PastureMap mobile application (PastureMap, San Francisco, CA).

Decisions on paddock size were made based on forage availability and soil conditions. Biweekly assessments of forage yield were made and used to adjust future paddock sizes for the number of cattle currently grazing. Cattle numbers fluctuated at certain times due to events such as artificial insemination, embryo transfer, and calf vaccinations. For calculating paddock sizes, following a formula based on stocking density was used to obtain the estimated liveweight per acre. This equation can be found in Appendix A. Available forage was based on kilograms of dry matter per hectare estimated from hand clipped samples, 0.50 was the desired utilization percentage, estimated daily intake was 2.6 to 3.0% of body weight, and day length was the desired grazing duration before next move, generally one day.

3.2.4. Soil Sampling and Processing

Although seven soil series comprised the project area (Table 18), only the major soil series in each quarter was sampled. Soil samples were collected for analysis before grazing in May 2017 and after the initial grazing season in May 2018. Sampling locations were randomly plotted using ArcMap (Version

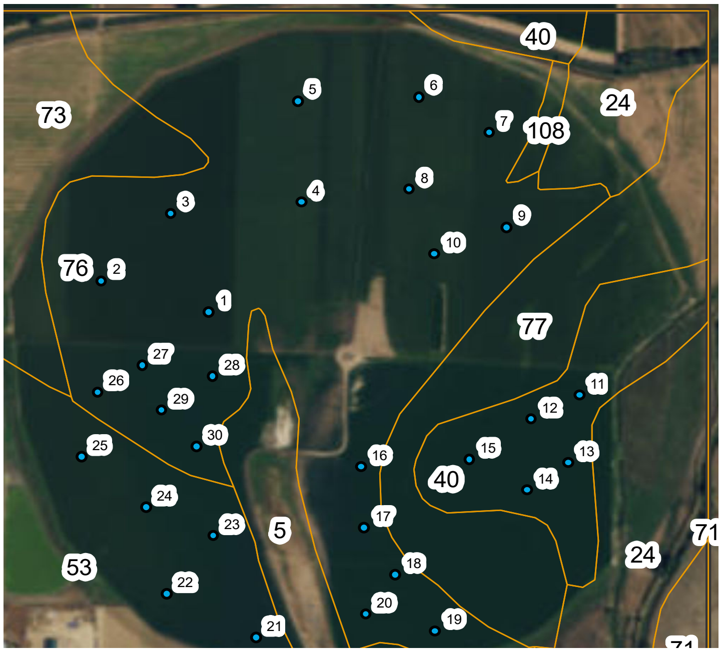

Figure 2. Soil sampling map created with ArcMap GIS program utilizing NRCS Soil Survey shapefile. Blue dots depict sampling replicates within each soil series.

10.5.1, ArcMap GIS) and located using Avenza Maps (Version 3.6, 96.17; Figure 2). Areas of extreme variability were excluded from soil sampling (e.g., wet areas, small sections of extraneous soil types). Soil sampling within each major soil series and each quarter were comprised of 5 replicates and 30 soil cores per replicate, collected from the 0 to 5 and 5-15 cm depths. Soil samples were collected using a soil probe with an inner diameter of 3.2 cm. Samples were immediately placed in plastic bags, sealed, and placed in coolers. Also, an extra core was obtained from both depth increments for each replicate and placed in a metal can for gravimetric soil moisture and bulk density determination.

Once returned to the laboratory, samples were stored in a refrigerator at 4 º C before processing. Sub-sample cores for moisture content and bulk density were weighed, then immediately dried at 105 º C for at least 24 hours, then weighed again. The bulk soil samples were passed through an 8-mm sieve, removing large pieces of organic material and rock. A representative sub-sample of ~150 g of field-moist, 8-mm sieved soil was placed immediately in a plastic bag ziplock bag, labeled and stored at 4º C for subsequent microbial biomass carbon analysis. Another sub-sample of 150 g of 8-mm sieved soil was passed through a 2-mm sieve and then air-dried, while the remaining 8-mm of sieved soil was allowed to air-dry for subsequent analyses.

3.2.5. Soil Analyses

Microbial biomass C

The microbial biomass protocol used was a modified version of the fumigation method by Allison (Allison, 2008). For each sample, two 10 g samples of 8-mm field moist (oven-dry equivalent) were utilized for fumigation and non-fumigation extractions. Non-fumigated samples were shaken for one hour with 50 ml of 0.5 M K_2SO_4, and then filtered through Whatman 2V folded filter paper. Fumigated samples were placed in 50 ml glass beakers and placed in a vacuum desiccator along with a 200-mL beaker containing 20 ml of non-ethanol containing chloroform and several boiling chips. A vacuum was attached to the desiccator, and the desiccator evacuated until the chloroform boiled; the desiccator was then vented. This process was repeated three more times with no venting after the last boiling. The desiccators were covered with a black garbage bag for four days to keep light out in order to prevent chloroform degradation. Afterward, the desiccators were vented, and a vacuum was drawn for 2 minutes to remove excess chloroform. This process was repeated 5-10 times. Following the chloroform evacuation step, the samples were extracted following the same protocol as above. A 4 mL subsample of the (non) fumigated filtrate was diluted with 36 ml of deionized (DI) water and then analyzed for total dissolved carbon using a Shimadzu TOC-L (Shimadzu Scientific Instruments, Inc). The difference between C in the fumigated and non-fumigated samples was considered the chloroform-labile C pool (EC), and is proportional to microbial biomass C (C): $C=EC/kEC$ where kEC is soil-specific but was (and often is) estimated as 0.45 (Beck et al., 1997).

Water stable aggregates

This procedure was based on the method of Kemper and Rosenau (1986) using the 8-mm sieved, air-dried soil. A 100 g soil sample was placed on top of a nest of sieves comprised of 2.0, 1.0, 0.5, and 0.25-mm screen sizes stacked on top of each other. The sieves were locked into a metal holder, completely immersed in a water column, and the holder connected to a modified Yoder sieving machine. The machine was set to 30 strokes per minute for 5 minutes, after which the sieves were removed, the soil removed from each sieve with water, and collected in pre-weighed 23 x 33 cm Al pans. The pans were placed in an oven at 105 ^{o}C until all the water evaporated, and then the pans were weighed for aggregate percent determination.

Potential mineralizable N (PMN)

Potentially mineralizable nitrogen was determined using a 28-day aerobic incubation (Curtin and McCallum, 2004). Briefly, a 10 g sample of the air-dry, 2-mm sieved soil was shaken for 30 minutes with 2 M KCl then filtered. These results represented baseline inorganic N (e.g., NH_4-N + NO_3-N) and were determined colorimetrically using a Lachat Flow Injection System (QuikChem 8500 Series 2 FIA). Another 30 g sub-sample of air-dried soil was placed into a 50 ml beaker, the soil gently packed down to a uniform bulk density of 1.0 g cm^{-3} and adjusted to 60% water-filled pore space with DI water (see calculations in Appendix A). The beaker was then placed in a quart-sized glass mason jar to which a small amount of water was added at the bottom to maintain 100% relative humidity. Jars were incubated in the dark at room temperature for 28 days, opening every seven days to allow for air exchange. After the 28-day incubation period, a 10g sub-sample was removed, extracted with 2 M KCl, filtered, and analyzed for inorganic N as above. Soil moisture content was determined on a separate sub-sample to correct for weight. Potentially mineralizable N was calculated by subtracting the baseline from 28-day mineralized inorganic N concentrations.

pH and EC

Soil pH and electrical conductivity (EC) were determined using a 1:1 (soil:solution) extraction (Rhoades, 1996; Thomas, 1996). Briefly, 20 g of air-dried, 2-mm sieved soil, and 20 mL of DI water were placed into 50 mL centrifuge tubes and shaken for 2 hours. Afterward, the pH was directly measured in the mixture. Mixtures were then centrifuged to separate the solution from the solid phase. The solution was gently poured into an EC meter for EC determination.

Soil-Test P and K

Olsen-extractable P and K were determined by shaking 2 g of air-dried, 2 mm sieved soil with 40 ml of 0.5M $NaHCO_3$ (adjusted to pH 8.5) solution for 30 minutes (Olsen et al., 1954). The solutions were filtered through Whatman 2V folded filter paper, allowed to sit overnight to allow for loss of CO_2, and then diluted ten-fold with DI water before analysis via inductively-coupled plasma-optical emission spectroscopy (ICP-OES).

Total C, Inorganic C, and Organic C

A 15 g sub-sample of 2-mm sieved soil was placed in a 20 mL plastic scintillation vial containing two metal rods. The vials were tightly packed into a 2 L plastic bottle and placed on a roller mill (Bailey Mfg., Inc., Norwalk, IA) for five days to allow metal rods to pulverize soil and create a fine powder. This powder was analyzed for total soil C content using a dry combustion method LECO Tru-SPEC Elemental Analyzer (Leco Corp., St.. Joseph, MI). The powder ground soil was then analyzed for inorganic C, determined via the modified pressure calcimeter method (Sherrod et al., 2002). Soil organic C (SOC) was indirectly determined by subtracting inorganic carbon from the total carbon content.

Soil Texture

This analysis was outsourced to the Colorado State University Soil, Water, and Plant Testing Laboratory (Fort Collins, CO). The laboratory utilized the hydrometer method to determine the percentage of sand, silt, clay, and subsequently texture classification (Ashworth et al., 2001).

ß-Glucosidase Activity

The procedure used was a modified method published by Green et al. (2007). Briefly, 1 g of air-dried, 2-mm sieved soil was added to a 50 mL Erlenmeyer flask; each sample was duplicated once along with an equal set of controls and a single blank. Next, 4 mL of modified universal buffer (MUB) adjusted to pH 6.0, 0.25 mL of toluene, and 1 mL of 0.05 M ρ-nitrophenyl-ß-D-glucopyranoside (PNG) solution was added to the flasks. It is important to note that the PNG was not added to the set of controls until after the incubation process (i.e., the next step). The sample was swirled, stoppers were placed on the flasks, and the samples were incubated at 37°C for 1 hour. The reaction was stopped by adding 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.1 M Tris (hydroxymethyl) aminomethane (THAM) buffer solution (pH ~12) followed by flask swirling. The soil suspension was filtered through Whatman No. 2 filter paper. The samples were diluted five-fold using 1 mL of filtrate and 4 mL of 0.1 M THAM prior to analysis. A standard curve was created using solutions of increasing *p*-nitrophenol (1 g p-nitrophenol L^{-1}) concentrations (0, 10, 20, 30, 40, and 50 ug L^{-1}). These standards also contained 1 mL of 0.5 M $CaCl_2$ and 4 mL of 0.1 M THAM buffer solution to mimic the sample solution matrix. A yellow color was developed, with color intensity measured on a Genesys 10S UV-VIS spectrophotometer at 410 nm.

3.2.6. Statistical Analysis

An analysis of variance (ANOVA) using Kenward-Roger degrees of freedom method with test significance level of $p < 0.05$ in RStudio was performed on all indicator raw data, all indicator scores, and for the physical, chemical, biological, nutrient, and overall SQI for the 0 to 5 and 5 to 15 cm depths (RStudio Version 1.1.456, 2018). The linear mixed effect model utilized was created with the Lmer package in RStudio. Comparisons were made between year 2017 and 2018 data sets to determine if there was significant change in each parameter as well as an interaction between depth and year.

3.3. Results & Discussion

Effects on Soil Physical Indicators and Physical Soil Quality

A significant bulk density increase was observed between 2017 to 2018 (Table 20). This led to a significant bulk density index score decrease between years, from 0.80 to 0.37 and from 0.59 to 0.34 in the 0-5 cm and 5-15 cm depths, respectively (Table 21). Bulk density in surface soils would be lower post tillage and planting due soil mixing during establishment and would likely increase when cattle exert hoof force on the soil due to grazing activities. The minimum and maximum bulk densities measured after the first grazing season in 2018 were 0.77 and 1.89 g cm^{-3}. Previous studies have shown that when soils reach or exceed a bulk density of 1.7 g cm^{-3}, root growth is impeded (Bruand and Gilkes, 2002). Although mean bulk density levels have not reached 1.7 g cm^{-3}, future monitoring of this indicator will be important from a soil health and perennial forage stand perspective.

Water stable aggregates (WSA) did not show significant changes between pre- and post-grazing (Table 20). However, the data showed a significant difference in depths for the indicator values and the WSA index score (Tables 20 and 21, respectively). Greater aggregation was present at the 5-15cm depth than the 0-5 cm depth. In 2018, mean WSA percentages were 45.7% at 0-5 cm and 59.6% at 5-15 cm. Factors that could have contributed to this difference include the lack of tillage from 2017 to 2018, the addition of perennial grasses with fibrous root systems, and microbial activity (e.g., increased MBC, discussed below) related to these management changes. Soil aggregate formation relies heavily on the microbial activity which is often greater in grazed, improved pasture systems than in native or tilled systems, due to the level of production present in improved pasture systems (Sparling, 1992; Warren et al., 1986a). The lower WSA in the 0-5 cm depth could also be attributed to the physical pressure of grazing. Warren et al. (1986) found that soil aggregate size was negatively correlated to trampling rate. Although perennial vegetation and microbial activity can aid in aggregation, grazing pressure may have an adverse effect on aggregation.

Soil bulk density and water stable aggregate data both comprise the physical soil quality index value in SMAF. Changes in bulk density primarily caused a significant negative change in the physical soil quality index (Table 22) from 2017 to 2018.

Effects on Soil Biological Indicators and Biological Soil Quality

Microbial biomass C significantly increased from 2017 to 2018 (Table 20) resulting in an increased MBC index between 2017 and 2018 (Table 21). There was a significant difference in the year by depth interaction, revealing a greater increase at the 0-5 cm depth than the 5-15 cm over time. Other studies have shown that MBC levels are often greater in the surface soils in systems without tillage due to surface residue acting as a carbon (i.e., energy) source for microbial populations (Doran, 1987). Converting from a tilled, minimal residue system to a permanent, grazed system has likely provided an influx of carbon material responsible for the increase in MBC. In addition, the grazing strategies employed in this study aimed to utilize only 50% of the forage biomass present in a grazing period. According to multiple studies, partial plant defoliation has been found to increase the exudation of soluble exudates from the roots (Bardgett et al., 1998; Holland et al., 1996). This rhizodeposition, in turn, would be expected to stimulate soil microbial activity. Synthetic N was not added to this system once converted to a perennial pasture. Reduced nitrogen and overall fertility conditions have been found to stimulate the release of organic root exudates in grasses as well as foster a greater microbial community (Bardgett et al., 1998; Hodge et al., 1996). Studies have shown that cool-season, managed grasses (like those present in the current study) tend to exude quickly decomposed C substrates which can stimulate microbial activity (Grayston et al., 1998). Easily decomposable C substrates are likely present in this grazing system due to cattle manure inputs and the fast-growing nature of modern cool-season grass varieties (Dawson et al., 2000).

SOC remained unchanged from 2017 to 2018, resulting in no significant change to the SOC index value ($p > 0.05$; Tables 20 and 21). Changes in MBC and BG have been detectable earlier than changes in SOC because of the rapid turnover rate, with MBC and BG being early indicators of long-term soil carbon accumulation (Sparling, 1992; Turner et al., 2002). Soil organic carbon has been shown to increase along with WSA under pasture, leading to physical improvements in the soil and hydrological processes (Martens et al., 2004). Although no changes have been detected in the first year of the grazing system, future monitoring will be necessary to track possible SOC changes and correlations with other indicators over time.

Potentially mineralizable nitrogen was significantly greater in 2018 than in 2017 (Table 20). This result caused a significant increase in the PMN index score from 2017 to 2018 at both depths (Table 21). The soil indicator values for PMN were greater in the 0-5cm depth, similar to MBC. Similar to our findings, Doran (1987) observed identical MBC and PMN distributions in the top 7.5 cm of soil in a no-tillage system.

β-Glucosidase activity significantly increased from 2017 to 2018 (Table 20). This was likely attributed to the land-use change from a tilled, cropping system to a perennial pasture system. Bandick and Dick (1999) concluded that BG levels reflect soil management effects due to its role in the carbon cycle. The authors mentioned that an uninterrupted rhizosphere and greater organic matter additions harbors greater levels of enzymatic activity; the concept of an uninterrupted rhizosphere supports our findings. Martens et al. (2004) concluded that the upper soil profile contained more β-glucosidase-type enzymes as long as management practices contribute plant biomass and avoids tillage. The increase in BG led to a significant increase in the BG index score from 2017 to 2018 in the 0-5cm and 5-15 cm depths (Table 21). Bandick and Dick (1999) suggested that enzymes in the soil may be early indicators of biological change when management practices are altered. Future monitoring and analysis will be needed to observe if additional changes in soil biological activity occur over time.

The changes that occurred in three out of the four biological indicators caused an increase in the biological soil quality index score from 2017 to 2018 (Table 22). From pre-grazing samples taken in 2017 to post-graze in 2018, the biological soil quality index increased from 0.290 to 0.433 and 0.256 to 0.372 in the 0-5 and 5-15 cm depths, respectively. The land-use change from a tilled, annual system to a no-till perennial system has imparted positive changes on soil biological activity and thus the biological soil quality index.

Effects on Soil Chemical Indicators and Chemical Soil Quality

There was no significant change in pH or the pH index value from 2017 to 2018 (Tables 20 and 21). Due to alkalinity, clay content, and CEC, the soil at this site likely has a greater buffering capacity that resists change in pH. This result could mean that pH, even over the future long-term of this grazing project, may not significantly change.

Electrical conductivity significantly decreased from 2017 to 2018 at both 0-5 and 5-15 cm depths, resulting in a significant increase in the EC indicator score (Tables 20 and 21). Electrical conductivity is an important indicator of soil quality in agroecosystems and can be impacted by management changes in a relatively short amount of time. Inherent soil properties, such as texture and parent material, as well as management practices like irrigation, fertilization, and land-use, all influence EC (USDA-NRCS, 2014).The lack of fertilizer inputs since the land-use change, combined with irrigation, could explain the EC decrease simply due to flushing of fertilizer salts below the 15 cm soil depth. The EC reduction led to a significant increase in the chemical soil quality index between depths (Table 22).

Effects on Soil Nutrient Indicators and Nutrient Soil Quality

Extractable K concentrations significantly increased from 2017 to 2018, with greater concentrations in the 5-15 than the 0-5 cm depth (Table 20). The extractable K index values were significantly different between years and between depths with a higher indicator score for the 0-5 cm portion (Table 21). The increase in soil K concentration was likely due to manure application from cattle grazing. Approximately 73% of K consumed by cattle is excreted in urine and is often 100% bioavailable (Eghball et al., 2002). Early et al. (1998) studied the fate of K in simulated urine patches under irrigated grazing of dairy cattle using lysimeters, finding that ~20% of K that was applied remained within the top 0-5cm of soil.

Olsen-extractable P significantly decreased in the 0-5 cm depth from 2017 to 2018, but no significant change occurred in the 5-15cm depth (Table 20). The decrease in Olsen-extractable P concentrations led to a decrease in the extractable P index value between years (Table 21). The 2018 Olsen P soil samples were analyzed twice due to suspect, below-detection-limit concentrations occurring in multiple soil samples; below detection results were similar between both extractions. These below detection Olsen P concentrations, ultimately lowering the nutrient indicator score, could have been a result of greater plant P uptake or to instrumental error. Approximately 96% of P intake by cattle is excreted in manure, 70% of which is primarily in inorganic forms (Eghball et al., 2002). Because of this, extractable P concentrations were expected to increase due to cattle manure accumulation. The decrease in soil extractable P content led to a significant reduction in the nutrient soil quality index (Table 22). If the low values did not occur within the 2018 data analysis, SQI values likely would have risen as expected with manure application.

Effects on Physical, Biological, Chemical, and Nutrient Soil Quality on Overall Soil Quality

There was not a significant change in the overall soil quality index from 2017 to 2018 (Table 22). Although there was not a significant change at the present time, as soil parameters shift over years of grazing management, they may cause future, significant shifts in this indicator.

Table 20. Mean Soil Management Assessment Framework individual soil indicator values (2017 and 2018 at 0-5 and 5-15 cm depths), analysis of variance (ANOVA), and significance within a management-intensive, irrigated grazing system.

	0-5 cm		**5-15 cm**				
	2017	2018	2017	2018	ANOVA (between years)	ANOVA (between depths)	ANOVA (Year: Depth)
ρ_b (g cm^{-3})	1.15	1.52	1.31	1.53	**	NS†	NS
WSA (g kg^{-1})	43.1	45.6	57.1	59.5	NS	**	NS
BG (mg pnp kg^{-1} soil h^{-1})	72.1	88.1	69.8	75.9	**	NS	NS
PMN (mg g^{-1})	15.6	18.3	12.7	16.8	**	NS	NS
SOC (%)	1.55	1.40	1.40	1.45	NS	NS	NS
MBC (mg g^{-1})	117.6	315.9	131.7	245.3	**	NS	*
pH	7.98	8.11	7.93	8.03	NS	NS	NS
EC (dS m^{-1})	2.18	1.34	2.91	2.44	**	NS	NS
K (mg kg^{-1})	203.6	414.8	194.8	253.2	**	**	**
P (mg kg^{-1})	16.0	13.2	11.7	11.1	**	NS	NS

* $p < 0.05$.

** $p < 0.01$.

† NS, not significant.

‡ SOC, soil organic carbon; WSA, water-stable aggregates; MBC, microbial biomass C; P, phosphorus; K_{ext}, extractable K; ρ_b, bulk density; EC, electrical conductivity; BG, -glucosidase, PMN, potentially mineralizable N.

§ pnp = *p*-nitrophenol.

Table 21. Soil Management Assessment Framework individual soil indicator index scores (0.00 to 1.00; greater is better; 2017 and 2018; 0-5 and 5-15 cm depths), analysis of variance (ANOVA), and significance within a management-intensive, irrigated grazing system.

	0-5 cm		**5-15 cm**				
	2017	**2018**	**2017**	**2018**	ANOVA (between years)	ANOVA (between depths)	ANOVA (Year:Depth)
ρ_b (g cm^{-3})	0.80	0.37	0.59	0.34	**	*	NS†
WSA (g kg^{-1})	0.78	0.73	0.90	0.88	NS	**	NS
BG (mg pnp kg^{-1} soil h^{-1})	0.05	0.06	0.05	0.05	**	NS	NS
PMN (mg g^{-1})	0.82	0.97	0.68	0.90	**	NS	NS
SOC (%)	0.18	0.16	0.16	0.16	NS	NS	NS
MBC (mg g^{-1})	0.09	0.53	0.11	0.36	**	NS	*
pH	0.01	0.01	0.01	0.01	NS	NS	NS
EC (dS m^{-1})	0.53	0.82	0.29	0.45	**	NS	NS
K (mg kg^{-1})	0.96	0.99	0.94	0.93	**	**	**
P (mg kg^{-1})	0.94	0.60	0.75	0.38	**	NS	NS

* $p < 0.05$.
** $p < 0.01$.
† NS, not significant.
‡ SOC, soil organic carbon; WSA, water-stable aggregates; MBC, microbial biomass C; P, phosphorus; K_{ext}, extractable K; ρ_b , bulk density; EC, electrical conductivity; BG, -glucosidase, PMN, potentially mineralizable N.
§ pnp = *p*-nitrophenol.

Table 22. Soil Management Assessment Framework physical, chemical, biological, nutrient, and overall soil quality index (SQI) scores (0.00 to 1.00; greater is better; 2017 and 2018; 0-5 and 5-15 cm depths), analysis of variance (ANOVA), and significance within a management-intensive, irrigated grazing system.

	0-5 cm		**5-15 cm**				
	2017	**2018**	**2017**	**2018**	ANOVA (between years)	ANOVA (between depths)	ANOVA (Year x Depth)
Physical	0.79	0.55	0.75	0.61	**	NS	NS
Biological	0.29	0.43	0.25	0.37	**	NS	NS
Chemical	0.27	0.41	0.16	0.23	NS	*	NS
Nutrient	0.95	0.80	0.84	0.65	**	**	NS
Overall	0.52	0.52	0.45	0.45	NS	NS	NS

* $p < 0.05$.
** $p < 0.01$.
† NS, not significant.

3.4. Conclusion

This study showed that soil physical, biological, and nutrient SQI values significantly responded to grazing and management changes from tilled, irrigated row crops to an irrigated perennial grazing system. Positive soil quality effects were observed with increases in the biological SQI, and in particular increases in microbial and enzymatic activities; these could be early indicators of future carbon sequestration. Soil organic carbon remained relatively unchanged but will be an important indicator to monitor over the long-term. Negative impacts occurred to the soil physical SQI, driven primarily by increasing bulk density. This result was likely caused by initial hoof compression during grazing. Bulk density is an indicator that should be monitored closely in the future due to its potential impacts on hydrology and root health. The nutrient SQI value declined due to the observed reduction in extractable soil P. Cattle manure inputs caused a significant increase in available K, which would also be expected for P due to high P concentrations in cattle manure (Eghball et al., 2002). However, the opposite was observed, ultimately reducing the mean P concentrations from 2017 to 2018, and ultimately the nutrient SQI. Although these are only initial findings in the scope of the project, the effects of this grazing system on soil quality will be essential to monitor over the long term. Long-term monitoring will increase the understanding of how MiG impacts can promote and sustain soil health for the environmental and economic sustainability of irrigated, managed grazing systems.

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CHAPTER 4: SOIL PENETRATION RESISTANCE

4.1. Introduction

Perennial pasture plants establish root systems that increase the structural stability of soils and improve overall physical properties such as aggregate stability, water-infiltration, sub-soil macroporosity, and organic matter (McCallum et al., 2004). However, grazing, particularly in irrigated systems, raises concerns about potential adverse effects on soil physical properties. At some level, compaction is present in most grazed pastures. As the soil surface is compacted from grazing, soil pore space decreases which increases soil bulk density; this process may be exacerbated when grazing occurs on wet soils (Tate et al., 2004; Warren et al., 1986a).

Negative changes in physical properties can impede root growth and water movement through the soil, subsequently reducing pasture yields (Greenwood and McKenzie, 2001). Reports indicate that plant root growth is impeded when soil penetration resistance reaches 2000-2500 kPa (Huyssteen, 1983). In multiple studies, soil physical health degradation has been shown to depend on cattle management such as stocking density (animals per unit of area), grazing duration, soil type, and soil moisture content (Chanasyk and Naeth, 1995; Chiavegato et al., 2015; Drewry et al., 2008).

Warren et al. (1986) found that increases in compaction are reversible with adequate recovery time. This may explain why shorter duration rotational grazing systems often have lower soil bulk density values than continuous grazing, simply due to the period of recovery given to an area in which animals are not present (Warren et al., 1986a). Freeze-thaw cycles over the winter months also have a regenerative impact on soils affected by increased bulk density. Pardini et al. (1996) found that freeze-thaw cycles modified the soil physical structure, increasing its bulk volume and creating irregular and rounded pore spaces, leading to bulk density decreases.

Based on the above research, soil compaction is an issue that is influenced by many environmental and management factors that can compound over time. Thus, I hypothesized that soil resistance would increase from spring to fall due to compression after a first full, irrigated perennial pasture grazing season in a previously tilled agroecoystem. I also hypothesized that soils that were grazed when they were beyond field capacity moisture content, following precipitation events, would have greater penetrometer resistance than pastures that were grazed when drier.

4.2. Materials and Methods

4.2.1. Site Description

This study was conducted at the Colorado State University Agriculture Research, Development and Education Center located 13 km northeast of Fort Collins, CO (40°39’30.40” N, 104°59’11.24” W) at an elevation of 1,554 m. The 82-ha research area was under center pivot irrigation. Climatic conditions were mid-latitude dry, cold, semi-arid steppe (Kottek et al., 2006), with average low and high temperatures of 1.0 °C to 16.8 °C and average annual rainfall of 38 cm (WRCC, 2018). For our study period, 2017 and 2018, mean temperatures ranged from 6.90 to 22.7 °C and 10.7 to 27.5 °C, respectively (CoAgMet, 2018). Yearly growing season precipitation and irrigation applied by species mixture can be found in table 23. The following soil series are found in the study area: Aquepts, Connerton-Barnum complex, Garrett loam, Kim loam, Nunn clay loam, Otero sandy loam, and Thedalund loam (Table 24).

Prior to project establishment, the study area was managed for about a decade as a tilled cropping system planted to crops including corn silage (*Zea mays* L.), corn grain, dry beans

(*Phaseolus vulgaris* L.), and alfalfa (*Medicago sativa* L.). In September 2016, the area was converted to four perennial forage mixtures consisting of a simple grass-legume mix, a complex grass-legume mix, a simple grass mix, and a complex grass mix (Table 25). Each quarter of the project area was planted to one of the previous mixtures (Fig. 6). Each forage mixture comprised approximately 20 ha. Prior to planting and establishment, a deep-ripper was used to alleviate a plow pan that had formed due to the clay soil type and previous management. Following deep ripping, the field was moldboard plowed, disked twice, cultipacked twice, and then rolled with a heavy steel roller to break up large soil aggregates and firm the soil surface prior to stand establishment. Cool-season grasses were planted from late August to early September 2016 and legumes were cross-drilled on March 15-16, 2017.

Unfortunate climatic circumstances in the spring of 2017 led to multiple issues in establishment. Species mixture A failed due to winds that moved loose soil and damaged small seedlings. Oats were planted in this quarter on March 23, 2017 to avoid further wind erosion. The planned mixture was re-planted in August 2017. Most of the legumes that were cross-drilled in early March were killed due to a hard freeze that occurred shortly after germination. Success rates for the legume mixtures were approximated at less than 5%. Legumes were again interseeded in early August of 2018. Thus, the forage mixtures with legumes contained few if any for the duration of this experiment.

Table 23. Irrigation applied by species mixture and total precipitation that occurred from April to October.

2017				**2018**		
Species Mixture	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**	Irrigation applied (cm)	Precipitation (cm)	**Total (cm)**

A†	9.75	32.5	**22.55**	14.1	38.3	**29.1**
B	12.35	32.5	**25.15**	15.45	38.3	**30.5**
C	11.9	32.5	**24.7**	13.85	38.3	**28.9**
D	11.6	32.5	**24.4**	15.45	38.3	**30.5**

† A - Grass/Legume, B - Complex Grass, C - Simple Grass, D - Complex Grass/Legume

Table 24. Soil series present within the project area with descriptions and percent of the project area.

Soil Series	Description		Percent of Project Area
Nunn clay loam	Fine, smectitic, mesic Aridic Argiustolls	Somewhat poorly drained; restrictive layer > 200 cm	56.3
Thedalund loam	Fine-loamy, mixed, superactive, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer 50-100 cm	0.5
Connerton-Barnum complex	Fine-loamy, mixed, superactive, mesic Torriorthentic Haplustolls	Well-drained; restrictive layer > 200 cm	2.6
Otero sandy loam	Coarse-loamy, mixed, superactive, calcareous, mesic Aridic Ustorthents	Somewhat excessively drained; restrictive layer > 200 cm	13.6
Garrett loam	Fine-loamy, mixed, superactive, mesic Pachic Argiustolls	Well-drained; restrictive layer > 200 cm	9.2
Kim loam	Fine-loamy, mixed, active, calcareous, mesic Ustic Torriorthents	Well-drained; restrictive layer > 200 cm	11.7
Aquepts loamy	Inceptisol with a water table near the surface	Poorly drained; restrictive layer > 200 cm	6.1

Table 25. Forage species planted in each ~20 ha portion of the 82-ha project area.

Forage Mixture	**Species**
A - Grass/Legume Mix	Meadow brome (*Bromus biebersteinii* Roem. & Shult.), Orchardgrass (*Dactylis glomerata* L.), Creeping meadow foxtail (*Alopecurus arundinaceus* Poir.), Birdsfoot trefoil (*Lotus corniculatus* L.), Strawberry clover (*Trifolium fragiferum* L.), White clover (*Trifolium repens* L.)

B - Complex Grass Mix	Meadow brome, Orchardgrass, Creeping meadow foxtail, Tall fescue (*Festuca arundinacea* Shreb.), Festulolium (*xFestulolium*), Smooth brome (*Bromis inermis* L.)
C - Simple Grass Mix	Meadow brome, Orchardgrass, Creeping meadow foxtail
D - Complex Grass/Legume Mix	Meadow brome, Orchardgrass, Tall fescue, Perennial ryegrass (*Lolium perenne* Boiss & Hohen.*),* Meadow fescue (*Festuca pratensis),* Festulolium (*xFestulolium),* Red clover (*Trifolium pretense L.),* Alsike clover (*Trifolium hybridum* L.), White clover, Birdsfoot trefoil

4.2.2. Project Design

Permanent infrastructure that was installed included an electrified perimeter fence with two concentric inner fences constructed using high-tensile wire (Fig. 1). Ten permanent water blocks were located around the pivot with 8 within the outer concentric high-tensile fence line and two in the center (Fig. 1). The 8 water blocks within the outer concentric fence had four sides with electrified rope gates for controlling access to paddocks. Paddocks were generally created every 1-3 days using polywire and step-in posts and the fences that delineated paddocks were re-constructed in the same locations throughout each grazing rotation using the GPS and paddock drawing tools on the mobile application PastureMap™ (PastureMap, San Fransico, CA). Further subdivisions to these paddocks were also made on an as-needed basis using additional polywire and step-in posts to adjust for forage availability and animal numbers. These fences were not placed in the same location each grazing rotation. Three random grazing experimental units (paddocks) were selected per seed mixture (i.e., per quarter section of the field) and consistently sampled throughout the grazing season for forage yield, quality, and penetrometer measurements (Fig. 1). Units containing minor soil types were avoided.

In 2017, approximately 171 cow-calf pairs were grazed from August 18 until October 24. The grazing season was delayed due to fencing and water infrastructure being constructed. The herds were separated by breed (Angus and Hereford) for breeding purposes. The herds were then combined on September 21 and grazed until October 24. In 2018, approximately 136 cow-calf pairs, 49 replacement heifers, and 5 steers were grazed from May 4 to October 7. The entire cow herd was not initially present on the pivot at the beginning of the grazing season. A portion of the cows calved on the pivot and the remainder were added post calving. Throughout the remainder of the grazing season, up to 3 herds were grazed at one time. Groups were rearranged for breeding purposes throughout the grazing season, but the number of animals remained relatively constant.

Figure 6: Diagram of pre-determined 8 paddocks along with the 2 designated experimental units within each cool season mixture (A, B, C, D).

4.2.3. Grazing Management

MiG systems require manipulating the length of time cattle graze and space allotted based on available forage resources to achieve management goals and objectives (Shewmaker and Bohle, 2010). For this project, cows were generally moved daily. In certain situations, depending on forage availability and herd size, cows were moved every 2-4 days. This management method allowed for making daily adjustments to subdivision sizes, monitoring of cattle health and soil conditions, and maintaining the electric fencing.

Paddocks were set up based on current forage availability using polywire and step-in posts. The goal for forage removal was approximately 50% of available biomass for purposes of stand health and performance. By leaving approximately half of the available biomass, there was adequate plant material to perform photosynthesis, which theoretically allowed for efficient regeneration of above ground biomass while maintaining carbohydrate reserves in the roots. The time, date and location of each move, as well as the size of each paddock, were tracked using the PastureMap mobile application (PastureMap, San Francisco, CA).

Decisions on paddock size were made based on forage availability and soil conditions. Biweekly assessments of forage yield were made and used to adjust future paddock sizes for the number of cattle currently grazing. Cattle numbers fluctuated at certain times due to events such as artificial insemination, embryo transfer, and calf vaccinations. For calculating paddock sizes, following a formula based on stocking density was used to obtain the estimated liveweight per acre. This equation can be found in Appendix A. Available forage was based on kilograms of dry matter per hectare estimated from hand clipped samples, 0.50 was the desired utilization percentage, estimated daily intake was 2.6 to 3.0% of body weight, and day length was the desired grazing duration before next move, generally one day.

4.2.4. Sampling Methods

Soil resistance (kPa) measurements were taken using a cone penetrometer with a 1.27 cm cone (Field Scout SC900; ASABE, 1999). Measurements were taken in two experimental units (approximately 2-2.8 ha in size) in each of the four cool-season species mixtures. The units selected for measurement in each species mixture were one unit grazed during wet conditions and one that was not impacted from grazing during wet conditions. Measurements were taken in the spring of 2018 before grazing began and in the fall 2018 post-grazing. In each experimental unit, 30 random penetrometer readings were taken to a depth of 45 cm unless a compaction layer inhibited penetration to that depth. The penetrometer recorded data in 2.5 cm increments.

Soil resistance increases as soil moisture decreases as reported by others (Bradford, 1980; Huyssteen, 1983). This made it essential to sample when the soil was close to field capacity, as suggested by Bradford (1980). Samples were taken 48 hours post irrigation or precipitation to ensure ideal moisture conditions. Soil moisture samples were taken in the spring of 2018 using a handheld digital moisture sensor with 3” probes (TDR 100, Spectrum Technologies, Aurora, IL) to obtain volumetric water content (VWC) and ensure adequate moisture for sampling. The mean %VWCs for forage mixtures B, C, and D in spring and fall of 2018 were 32, 30, and 31%, and 28, 26, and 27%, respectively.

In fall of 2018, gravimetric soil core samples were taken to 20 cm in addition to TDR measurements to obtain additional data on soil moisture. The moisture sampling depth was selected based on prior compaction research. The soil depth at which impact occurs below the given pressure increases with the width of applied stress (Greenwood and Mckenzie, 2001). A cattle hoof, being relatively narrow, tends to cause compaction at shallower depths (Greenwood and Mckenzie, 2001). Compaction due to grazing generally does not surpass 15 cm unless the soil is saturated and grazing persists for an extended period of time (Greenwood and McKenzie, 2001; Tanner and Mamaril, 1959).

Above average precipitation occurred for approximately two weeks during September 2017 that resulted in the soil surface being visually damaged in specific units due to hoof action from grazing on wet soils. Penetrometer measurements were taken in units that were grazed during precipitation events and units that were only grazed in dry conditions to quantify any potential compaction that may have occurred. One unit in species mixtures B, C, and D experienced grazing during rain events. These units were penetrometer sampled in addition to the regular sampling units to collect data on any possible damage that may have occurred.

Species mixture D, unit 2, received approximately 2.95 cm of rain within 24 hours followed by poor drying weather. The unit was grazed 24 hours after this rain event. Visual pugging and plant damage was severe in areas by fences and watering areas and moderately impacted throughout the rest of the paddock. Species mixture C, unit 7, was grazed 72 hours after the precipitation events in species mixture D that totaled 1.27 cm of rain in combination with overcast, humid weather. Species mixture B, unit 4, was grazed a few weeks later during an overnight snow (~ 4.5 cm) event that melted within 24 hours, creating saturated soils and visual pugging comparable to the other 2 units.

4.2.5 Statistical Analysis

The penetrometer used in this study recorded soil resistance (kPa) from 0-45 cm in 2.5 cm increments. The focus of this research was the 0-20 cm depth based on prior research in this subject area (Greenwood and Mckenzie, 2001; Orr, 1960; Tanner and Mamaril, 1959). In addition, deeper layers of the soil profile on this project area contain legacy effects from tillage that were excluded for the purposes of this research. The mean was calculated for each 2.5 cm depth increment for all 30 random measurements taken per experimental area. The mean maximum resistance was selected along with the depth at which it occurred. The maximum resistance for sampling units grazed when wet and grazed while dry were compared using a paired t-test ($p < 0.10$). Statistical analysis could not be performed on the data comparing spring and fall of 2018 because the measurements occurred at two separate points in time and lacked the correct soil moisture data for spring 2018. To make proper statistical comparison between samplings, both sampling events would need to include gravimetric soil samples to depth of the penetrometer sampling to include in the model as a covariate. Although our visual observations and volumetric water content measurements using the TDR moisture meter indicated the soil moisture was comparable, we failed to collect gravimetric soil cores to penetrometer depth to include in our model.

4.3. Results and Discussion

Penetrometer resistance for paddocks grazed wet in 2017 was significantly greater compared to those grazed dry when measured in the spring of 2018. Paddocks grazed wet and grazed dry had maximum resistance means of 825 and 594 kPa ($p = 0.056$; Table 26). Paddocks grazed wet as compared to dry, when measured in the fall of 2018, showed no significant difference with maximum resistance means of 1293 kPa for pastures grazed while wet, and 1169 kPa when grazed dry (Table 27). The above data shows a greater spread in penetrometer values between paddocks grazed wet and dry in the spring as compared to the fall sampling period. The spring sampling period was temporally closer to the wet grazing events (September 2017). Warren et al. (1986) found that increases in compaction are reversible with adequate recovery time, which suggests that from September 2017 to October 2018 recovery may have occurred in paddocks that were grazed when wet. In both the spring and fall sampling, maximum soil resistance consistently occurred at the 5, 7.5, and 10 cm depths. Many cattle grazing studies have found similar results, showing compaction or physical soil alteration at relatively shallow depths not exceeding 20 cm (Greenwood and McKenzie, 2001; Orr, 1960; Tanner and Mamaril, 1959).

Overall, mean maximum resistance values from the fall tended to be greater than in the spring; Chanasyk and Naeth (1995) found similar results. This could be attributed to freeze-thaw, snowmelt, and recovery time over the winter season (Pardini et al., 1996). Although an analysis could not be done to statistically decipher a difference between spring and fall, fall values being consistently greater could suggest a possible overall impact from grazing. Future studies with gravimetric soil moisture samples to depth of the penetrometer sampling will be needed to retrieve the proper information to perform this analysis. Collecting additional soil bulk density samples with depth could also further support future data quality, as suggested by Chanasyk and Naeth (1995). Penetrometer and bulk density samples together would be a more powerful assessment of soil strength and density, particularly at the shallow level of impact in a perennial grazing system.

Table 26. Maximum soil resistance (kPa) and depth from the mean of 30 aggregated penetrometer measurements in sampling units in May 2018 that were grazed during wet and dry conditions in September of 2017.

Species Mix	Soil Conditions for Grazing Event	Depth (cm)	Maximum soil resistance (kPa)
D	Dry	7.5	550.57
D	Wet	7.5	840.50
B	Dry	15	673.77
B	Wet	10	1012.00
C	Dry	10	558.87
C	Wet	10	621.67

Mean (Dry)	**594**
Mean (Wet)	**824***

* p < 0.10

Table 27. Maximum soil resistance (kPa) and depth from the mean of 30 aggregated penetrometer measurements in sampling units in May 2018 that were grazed during wet and dry conditions in September of 2017.

Species Mix	Soil Conditions for Grazing Event	Depth (cm)	Maximum soil resistance (kPa)
D	Dry	5	1168.40
D	Wet	7.5	1278.73
B	Dry	7.5	1241.97
B	Wet	7.5	1542.87
C	Dry	10	1097.66
C	Wet	10	1058.07
Mean (Dry)			**1169**
Mean (Wet)			**1293**

* p < 0.10

4.4. Conclusion

The results of this study provide evidence to support the hypothesis that paddocks grazed during wet conditions have greater soil resistance. Unfortunately, due to moisture sampling inconsistencies, we cannot statistically determine if penetrometer resistance increased from the spring to the fall. The depth at which maximum soil resistance occurred from grazing in this study (0-10 cm) coincides with the findings of previous studies (Greenwood and McKenzie, 2001; Orr, 1960; Tanner and Mamaril, 1959) and generally supports findings from presented in chapter 3. It has been generally reported that plant root growth can be impeded when soil penetration resistance reaches 2000-2500 kPa (Huyssteen, 1983). The maximum mean resistance in pastures grazed while wet and dry in September 2017 when measured in spring of 2018 was 824 and 594 kPa, respectively (Table 1). Results from the fall 2018 sampling had maximum mean resistances of 1293 kPa (wet) and 1169 kPa (dry) (Table 2). Although not statistically evaluated, this data shows a general trend of increasing soil resistance over time, but it has not reached levels that could impede root growth. Future monitoring will be necessary to observe if soil resistance continues to increase or plateaus below the impedance threshold. Continuation of this research will be necessary to better understand the impacts of irrigated, MiG on soil physical properties. The information from monitoring over time could be informative for producers regarding issues that may arise in this type of grazing system and what management decisions can be made for mitigation.

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CHAPTER 5: SUMMARY

5.1. Pasture and Forage Management

Management is the key player

In this irrigated, MiG system, management played the ultimate role in determining the outcome of the forage results. The manipulation of plant growth stage with cattle or haying, along with adequate regrowth and rest periods, were the driving forces behind productivity and quality. Although similar species with relative high-quality potential were planted, management played a larger role in determining quality than I had anticipated. Management also seemed to be a larger contributing factor to seasonal mean yield than species diversity in the mixtures. Although the data collected on botanical composition is in its early stages, management will impact grazing behavior, ultimately impacting the species in these mixtures over time. Simple versus diverse mixtures are often debated when it comes to planting pastures. It will be interesting to see how management either sustains or changes these mixtures. Litter present on the soil surface was also impacted by management, with similar litter amounts among species mixtures that were grazed and planted at the same time compared to the species mixture that was planted later in time. Trampling from higher density stocking rates (compared to a continuous system) and natural accumulation of leaf matter through growth cycles both contributed to surface cover. Over time, litter added to the system could lead to increased soil organic matter and a host of other associated benefits. The interesting conclusion, based on the above information, is that the overall results of the forage studies could have easily changed with any small alteration in project/grazing management. I think that sometimes in research we often don’t pay enough attention to the human factor that influences the outcome of our results. In this type of system there are hundreds of small decisions that could be made each day and each of those decisions could influence different aspects of this complex system. It is important that we understand that the potential of this system is dependent on our ability to manage complexities.

The overall management allowed forage quality and AUDs to meet the ultimate goal of the system: to sustain 227 AUs for the grazing season duration, meet cattle nutritional needs, and maintain a healthy forage stand. Forage quality exceeded nutritional requirements of cow-calf pairs and produced enough forage to sustain the cattle herd in both 2017 and 2018. Although individual components of the research are important, it is ultimately overall system functionality that is of interest in this (hopefully) long-term MiG project. This information is vitally important to producers in Colorado, and in other similar systems globally, that are interested in adopting these practices in their own enterprises.

Unfortunately, this system cannot be directly compared to other grazing systems (e.g., continuous, mob grazing, rotational, etc.) because those systems were not included in the study. Yet, comparisons between grazing system types is common and seems to be valued in this field of research. There is value in comparative methods but I also believe there is greater applicability in extracting one type of grazing system that producers are interested in, and performing research while managing at full-scale. How a system measures up to the expectations and goals of itself is legitimate for assessing how a system will perform under real-world conditions. I personally think the agricultural industry could benefit from more research of this type and I believe many producers would agree. Discussions at field days and interactions with industry representatives has enlightened me to some of the true needs of research and how much of academia is not catering to implementation and on-the-ground solutions. Our system was tasked with not only performing multi-faceted systems research, but simultaneously providing a feed source for ~230 AUs (entire CSU cow/calf herd). This system exceeded nutritional requirements for the cows and provided forage for a grazing season lasting from April/May-October for both years, while also contributing ~140 metric tons of hay. In a real-life scenario, I would conclude that this system (over this period of time) was successful at meeting the operational needs. It sustained the entire cattle operation for a full-length grazing season while providing an additional winter feed that was not originally anticipated. I will be interested to see how this system compares to others when the economic analysis is performed. After all, system economics and feasibility are just as important for adoption of these practices.

I would be interested in how this system would perform under a stocker operation. In terms of functionality, a stocker system might be a less complicated route for this system. A cow-calf operation requires the access of the herd for artificial insemination, vaccinating, and other associated activities which can become complicated bringing the herd on and off the pivot. Although our grazing area was very close to the facility in which these activities were performed, it still required extra labor, time, and likely stress on the animals. The effort and time needed for moving fence and herds is minimal compared to moving the cattle on and off the pivot for breeding related activities. My experience moving cattle on this project has truly opened my eyes to how little labor could be required for this system. If moving the herds and routine health checks was the only labor necessary for a stocker system, the time allotted could be as little as 30 minutes per day. This is less time than running a feed truck and less fuel, not to mention that once the pasture is established, there should be minimal upkeep costs.

Unexpected concerns and recommendations

Concerning bare patches in species mix B were observed around large patches of tall-fescue. Selectivity against tall-fescue was the primary issue; however, avoidance of manure patches seemed to exacerbate this issue. This was an issue that arose unexpectedly and was not discussed as a common issue in this type of system in the literature or from experience of others. Most information I found stated that manure began to break down generally in 20 to 30 days, which is the length of one of our grazing rotations. That is what I would also expect, particularly in a system that is irrigated as compared to a dryland system. However, what we observed was manure patches persisting for over a year. Grass would begin to grow through manure, but growth was extremely slow and these areas still seemed to be avoided by cattle. Although none of these observations are measured or included in my thesis, I think it is a legitimate concern for this system that most likely has a solution. Holter et al. (1993) concluded that dung from animals treated with Ivermectin inhibited the larvae of dung beetles. They also conclude that the decomposition rates of treated cattle manure were drastically decreased. The other questions I had were 1) is this a microbial issue?, and 2) has this system not reached an equilibrium from previous management? Many of the grazing advisors I've learned from over the past two years discuss the elimination of synthetic fertilizers to allow microbial populations to shift, becoming more efficient at nutrient cycling and organic material decomposition. Lovell and Jarvis (1996) found that when NH_4-N was applied, it was used preferentially by microbes which can stimulate or induce a functional shift in microbial communities. The authors discussed how high nutrient availability promoted copiotrophs while nutrient-limited soil environments favor slow-growing oligotrophs. According to this study, microbial richness and diversity were both negatively affected by immediate N availability and community composition. They cite multiple other studies that observed greatly reduced bacterial diversity following long-term N, P, and K fertilization. The study concludes with recommendations to utilize manure in combination with NPK or simply manure alone (or any other organic fertility source) reduces associated impacts on microbial communities. After reading these studies, I think this topic is worth pursuing as a small plot experiment within the system. It would be interesting to see how plots with zero NPK application (only cattle manure via grazing) compared to manure/low NPK application, and higher NPK rates over time. Would the manure only plots begin to improve over time with biological adjustment or is there still merit to low NPK additions? Do the differences in yield between the plots justify the cost of fertilizer application? Those would be the main questions I would be curious to answer in such a study.

5.2. Soil Quality and MiG

Predicting soil carbon with supplementary analyses

Positive soil quality effects were observed with increases in the biological SQI, and in particular increases in microbial and enzymatic activities; these could be early indicators of future carbon sequestration according to previous research. This increase was most likely caused by drastic changes in management which include increases in litter, manure, living/sloughing roots, and eliminating tillage. Soil organic carbon remained relatively unchanged from 2017 to 2018. However, over time it will be important to measure these two parameters to see if the spike in microbial biomass equates to future carbon sequestration. An additional analysis of soil fungal:bacterial (F:B) ratios would supplement the biological data, allowing more detailed conclusions to be drawn concerning microbial biomass carbon and future carbon sequestration. This insight could further predict the system's ability to sequester carbon. According to a study by Malik et al. (2016), litter additions caused an increase in the abundance of fungi leading to a greater F:B ratio. Mesocosms with greater F:B ratios had greater soil organic matter and lower CO_2 respiration rates. This evidence supported the conclusion by Malik et al. (2016) that greater

F:B ratio was linked to a greater carbon sequestration potential. Supplementing our biological soil quality data with this analysis could help better predict the potential of our system to sequester carbon and improve soil quality over the long-term.

Bulk density vs. penetrometer

Negative impacts occurred to the soil physical SQI, driven primarily by increasing bulk density. This result could be a short-term effect caused by initial hoof compression from grazing post tillage and forage establishment. Bulk density is a vital indicator that will need to be monitored closely in the future due to its potential impacts on hydrology and root health. The bulk density samples obtained for this research were calculated from the same soil cores for the rest of the soil analysis. Upon doing further research and meeting with other soil scientists, I now realize there is a better method that reduces error involved in bulk density sampling. Soil corers have a tapered end and tend to compress the soil profile when pushed through the profile. The proposed future method for bulk density would be using a Madera probe (Precision Machine Company Inc., Lincoln, NE). This method is wider, not tapered, and is tapped into the ground reducing compression. It also has slots for cutoff knives at varying depths within the core. This type of bulk density would be an ideal measurement to have for a grazing system to understand how MiG is impacting soil physical properties. Based on labor, time, and supplementary data needed for penetrometer resistance measurements (moisture to depth, bulk density), this type of bulk density sampling could replace the penetrometer measurements entirely. Compaction research in grazing systems has concluded that the impacts from cattle remain in ~ the 0-15 cm soil depth, a zone easily measured via bulk density sampling.

The Soil Management Assessment Framework, combined with some of the recommended methodologies and complementary data listed above would be very effective at describing the soil quality of this grazing system. The results of this soil quality assessment are only initial findings in the scope of the project, but give a starting point for future issues to be cognizant of and alter manage based on. Long-term monitoring will increase the understanding of how MiG impacts can promote and sustain soil health for the environmental and economic sustainability.

5.3. Conclusion

The results of the forage and soil quality data do not necessarily determine the success or failure of this management method, but more-so make recommendations for future management. Management-intensive grazing is hyphenated because the system is not “intensive grazing”, it is about intensive management of the system as a whole. This requires constant assessment of results and alterations in management based on those results. Because this is the beginning of a (hopefully) long-term project, there is a steep learning curve in understanding how to recognize key elements, make decisions, and trouble-shoot issues. Over time, in theory, management of the cattle and forage could potentially improve, ultimately improving the overall health of the system. So I find myself asking, is the research question how will MiG impact forage and soil resources? Or is it how will we as managers influence them?

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APPENDIX

Soil Calculations:

$$Field\ Water\ Content(\%) = \frac{weight\ of\ moist\ soil - weight\ of\ ovendried\ soil\ *\ 100}{Weight\ of\ ovendriedsoil}$$

$$Field\ Moisture(\%) = \frac{\text{weight of moist soil} - \text{weight of ovendried soil}\ *\ 100}{\text{Weight of wet soil}}$$

$$Bulk\ Density\ = \frac{\text{field moist weight of soil} * [1 - \text{field water content}]}{\text{Volume of soil collected}}$$

Volume of soil collected is calculated using: pi * r^2 * h * N cores or 3.1414 * $(1.59\ \text{cm})^2$ * 10 cm * 20 cores = **1588 cm^3.**

Soil Porosity (% $\text{cm}^3\ \text{cm}^{-3}$) = [1 – (BD/PD)] * 100

$$\%Water - filled\ Pore\ Space\ (WFPS) = \frac{\%\text{Volumetric water content} * 100}{\%\text{soil porosity}}$$

where PD, particle density, is taken as a constant equal to 2.65 g cm^{-3}.

where % volumetric water content = % gravimetric water content * BD.

Soil Organic Matter(%) = % Soil organic carbon * 1.72

~ 58% of soil organic carbon exists in organic matter, 1/.58 = 1.72

Sample Analysis:

Water Content & Percent Moisture

For consistency in reporting analytical data, a sub-sample of the air-dry soil will be dried at 104º C for 24 to 48 hours or until it reaches a constant weight. All weights are to be recorded in a spreadsheet so that both the water content and percent moisture of the air-dry samples can be calculated using the formulas shown below (all weights measured in grams):

$$\%\mathit{Airdried\ Water\ Content} = \frac{\textbf{weight of airdried soil} - \textbf{weight of ovendried soil} \ * \ \textbf{100}}{\textbf{weight of ovendried soil}}$$

$$\%\mathit{Airdried\ Moisture} = \frac{\textbf{weight of airdried soil} - \textbf{weight of ovendried soil} \ * \ \textbf{100}}{\textbf{weight of airdried soil}}$$