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Impact of Virtual Fence Technology on Yearling Steer Behavior, Performance, and Energetic Expenditure

Logan Riley Vandermark
South Dakota State University, logan.vandermark@sdstate.edu

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IMPACT OF VIRTUAL FENCE TECHNOLOGY ON YEARLING STEER BEHAVIOR, PERFORMANCE, AND ENERGETIC EXPENDITURE

BY

LOGAN RILEY VANDERMARK

A thesis submitted in partial fulfillment of the requirements for the

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THESIS ACCEPTANCE PAGE

Logan R Vandermark

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Jameson Brennan
Advisor Date

Bob Thaler
Department Head Date

Nicole Lounsbery, PhD
Director, Graduate School Date

This thesis is dedicated to my father, K.J. You have taught me so much over the past 24 years, without your guidance I would not be the man that I am today.

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ABSTRACT

IMPACT OF VIRTUAL FENCE TECHNOLOGY ON YEARLING STEER BEHAVIOR, PERFORMANCE, AND ENERGETIC EXPENDITURE

LOGAN RILEY VANDERMARK

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Beef cattle production in the U.S. is largely dependent upon extensive rangelands like the Northern Great Plains. Solutions are needed to meet both the demand of animal-based protein products for a growing world population and the desire for producers to manage for several different ecosystem functions. Virtual fencing (VF) is an emerging precision technology that has the potential to revolutionize livestock management on extensive rangeland systems. However, the need to quantify animal behavior and performance differences using emerging precision technologies, like Vence^{TM}, is ever growing. Thus, the objective of this research was to determine the impact of virtual fencing on steers in the Northern Great Plains. Steer behavior, performance, and energetic expenditure was compared between virtually fenced rotational grazing and season long continuous grazing. Global positioning systems (GPS) and daily weight data collected were used to create and validate a precision system model to determine Net energy for activity (NEmr_act) for rangeland cattle. We found that animal behavior (grazing and resting time), performance (average daily gain, ADG), and energetic expenditure (Mcals/hd/d) was not significantly impacted by treatment group. However, treatment group did affect walking time per day, with those in the VFR walking 0.03 hours more per day than those in the CG. Our findings match aspects of previous research

on animal behavior and performance based on stocking rate. This would indicate that VF technology does not negatively impact animal production. This technology is a feasible tool for managers to use in many production settings to increase efficiency, reduce labor cost, and reduce time for meeting grazing objectives.

CHAPTER 1. LITERATURE REVIEW

Introduction

Rangelands exist in arid and semiarid regions and are composed primarily of grasses, grass-like plants, forbs, or shrubs (Stoddart et al., 1975). Grazing lands cover approximately 25% of the Earth's surface, which equates to 32 million km^2 (Reid et al., 2008). In the Northern Great Plains (NGP; Montana, Nebraska, North Dakota, South Dakota, and Wyoming), livestock production accounts for approximately 40% of the land in the region, equivalent to a grazing area of 314,000 km^2. In addition, numerous wildlife species utilize and depend on NGP plant communities that interact to create a functional ecosystem for both livestock and wildlife (Geaumont et al., 2019). Environmental factors impacting these rangelands include the introduction of cool season invasive grass species (Kral-O'Brien et al., 2019) and frequent droughts (Heitschmidt et al., 2005). Rangelands are also impacted by grazing management, with light or periodic grazing having little effect on forage quantity (Heitschmidt et al., 2005), and long-term continuous heavy grazing resulting in rangeland degradation and a decline in productivity (Bolo et al., 2019).

Rangeland Degradation

Overexploitation and overstocking caused rangeland degradation in the late 1800s. Degradation is a reduction in the natural landscape to provide services for livestock (Behnke and Scoones, 1992). European settlement brought widespread heavy livestock use to the NGP in the mid- to late 1800s. Starting in the mid-1800s and continuing into the early 1900s, there was significant damage to rangeland health in the NGP and western states due to excessive livestock grazing (Rowley, 1985). The concern for restoring these natural areas grew so great that it became the justification for creating the U.S. Department of Agriculture Soil Conservation Service (now the Natural Resources Conservation Service, NRCS) (Rowley, 1985). Inappropriate grazing practices including heavy stocking rates can result in significantly higher levels of runoff, sediment, and nutrient losses (Park et al., 2017). Highly degraded rangelands have limited forage production due to soil loss, thereby greatly reducing the ability to graze livestock.

In the early to mid-1900s considerable efforts were made to improve grassland conditions. Early ecologists Frederic Clements (1916) and Arthur Sampson (1919) began studying the dynamics of plant community succession, which later became the foundation for modern-day rangeland science. Clements (1916) developed the concept of plant successional theory, which stated that temporal shifts within community composition can be attributed to changes in the presence and abundance of a species within an environment. The rate of succession can vary depending on the intensity of the disturbance (e.g., grazing), and succession eventually leads to a climax community – a community that is at equilibrium with its climate and is considered stable (Laycock, 1991). Climax communities are defined as the idealized endpoint of succession. Regression from the climax community was viewed as a reversible process. Clements believed that a plant community lacking disturbance would trend towards its climax community once again (Clements, 1916). Clements stated, “The most rational and reliable way to detect overgrazing is to recognize the replacement of one type of plant cover by another” (Dyksterhuis, 1949). These early concepts of range science led to a focus on climax communities and how to return degraded rangelands back to their former state. Clements created a range condition class tool that had four classes (poor, fair, good, excellent) and were based on how much of a departure the existing plant community was from the climax community (Westoby et al., 1989). All range condition classes can be viewed as one continuum, with range condition being a singular point on the continuum. Trends within a given rangeland are indicated by shifts between range condition class (Westoby et al., 1989).

Early recommendations on land management based on range condition class only accounted for plant species composition and ignored other factors such as soil erosion, forage production, ecosystem processes, and seral state (Smith, 1988). The incorporation of successional theory has resulted in improved rangeland conditions and management of grazing lands; however, aspects of Clements' range succession model lack applicability on arid and semiarid rangelands since it was created for grassland systems with highly productive grasses. In contrast, the adoption of state and transition models allows for plant communities to exist in alternative states that differ from the climax community (Westoby et al., 1989). States indicate the current plant community, while transitions are actions that can often be associated with management such as grazing or fire that can modify the current plant community (Westoby et al., 1989). State and transition models can aid in quantifying rangeland ecosystems' response to disturbances by organizing current knowledge of ecosystem processes (Stringham et al., 2003). The use of state and transition models serves as a reminder that rangelands are dynamic systems, and not static models, and change over time (Briske et al., 2005).

Grazing Systems and Stocking Rates

Other early work in range science focused on proper grazing management through stocking rates and grazing systems. Sampson introduced the idea of deferment into proper land management; deferment is defined as the delay in grazing until plant regrowth is adequate to graze again (Kothmam, 1974). Deferment is when a pasture is grazed intensively and not returned to until at least the following year. Rest occurs between two grazing events and allows a pasture to be grazed again the same year if there is adequate regrowth. Along with rest or deferment, there was an emphasis on stocking rates. Stocking rate is the number of animal units per unit of land for a set amount of time (Dyksterhius, 1949). As range science progressed, recommendations shifted from season long (continuous grazing) within pastures to instead allowing for periods of rest or deferment to allow for recovery from grazing.

Stocking rate calculations are commonly reported as animal unit months or AUM/acre (Reece et al., 2008). Van Poollen and Lacey (1979) argued that adjusting livestock numbers is more important when analyzing forage production than the grazing system used. More importantly, stocking rates are not a static strategy, but should be periodically adjusted for current conditions of a local area (Steffens et al., 2013). Appropriate stocking rates would ideally be set at a conservative value to maximize livestock and forage production within pastures (Steffens et al., 2013). A study conducted in the late 1980s analyzing stocking rate and grazing systems concluded that steers spent more time grazing in a heavy stocking rate than those in a moderate stocking rate, who spent significantly less time grazing and more time resting (Hepworth et al., 1991). Stocking rate can also impact grazing efficiency, the proportion of forage consumed by cattle compared to the total forage quantity that disappears because of other activities such as trampling, insect consumption, and forage that is urinated or defecated on (Smart et al., 2010). In juxtaposition, some research suggests that grazing efficiency has been shown to increase at high grazing pressures and decrease at low grazing pressures (Smart et al., 2010), in response to reduced selectivity of available forage. This indicates that smaller pasture sizes would allow for higher grazing efficiency. Grazing efficiency in combination with stocking rate dictates how much of the available forage cattle are consuming, and consequently influences animal performance.

In addition to calculating appropriate stocking rates and considerations for grazing efficiency, land managers can also utilize a variety of grazing systems to achieve desired land management goals such as forage production and utilization using livestock (Kothmam, 1974). Land managers often must balance how many acres are allocated to livestock and the impact the cattle will have on rangeland health (DeFries et al., 2004). The simplest solution is a continuous grazing system, as it requires a single unit of land with a perimeter fence only; this allows the livestock to have unrestricted movement within the pasture (Kothmam, 1974). The drawbacks are that the pastures can be grazed unevenly resulting in areas of relatively heavy and light use, and unequal distribution of manure and therefore leading to soil nutrient deficiencies in non-preferred grazing areas (Peterson and Gerrish, 1995; Jones, 2015). Further, cattle are selective grazers – as they graze in a continuous grazing system, more desirable forages may become reduced in pastures due to overuse while undesirable species may persist as they are selected against (Pinchak et al., 1990).

Differences between rotational and continuous grazing systems have been studied extensively. There is an ongoing debate surrounding the differences of animal behavior and animal performance with cattle in rotational and continuous grazing systems (Briske et al., 2008). Simple rotational grazing systems use multiple pastures and allow for periods of rest and deferment following grazing (Kothmam, 1974). Intensive time-controlled rotational grazing consists of multiple paddocks, high stocking densities, and rest periods that increase in duration as forage growth rate decreases (Hart et al., 1993). When in a larger pasture, cattle gains and pasture utilization decrease compared to cattle in a smaller pasture size regardless of the grazing system; daily distance traveled in a larger system was also significantly greater in large pastures (Hart et al., 1993). A study comparing rotational to continuous grazing showed that there was an increase in forage consumed in the rotational system after the first two years of implementation and an increase in animal performance, specifically weight gain (Walton et al., 1981). There is also evidence that rotational grazing systems provide ecosystem services that continuous grazing systems cannot achieve (Teutscherova et al., 2021). However, research has found that rotational grazing has negatively impacted average daily gains (ADG) compared to continuous grazing (Briske et al., 2011; Augustine et al., 2020). In contrast to Walton et al. (1981), Derner and Briske (2008) conducted an extensive review of continuous versus rotational grazing and found no additional benefits of rotational grazing when analyzing plant production, animal production per head, or animal production per area. While this review suggests that rotational grazing is a viable grazing strategy on rangelands for animal production, the perception that rotational grazing is superior to continuous grazing is not supported by most experimental investigations (Briske et al., 2008). Further, cattle gains and grazing utilization were found to be similar between continuous and rotational systems when cattle were on similarly sized pastures (Smoliak, 1960).

Factors that Influence Range Management

The perceived benefits of rotational grazing among producers might be attributed to several factors. First, cattle are handled more often in a rotational grazing system, which allows producers to monitor health concerns (Olson, 1999; Teague et al., 2013). Second, research trials studying rotational grazing are not at a production scale. Likewise, the duration of scientific studies does not adequately capture long-term benefits of rotational grazing. Finally, there are possibly too few paddocks in the trials that have been conducted, which again limits inferences to simpler two- to three pasture rotations. A rotational grazing system can have potential benefits such as an increase in forage utilization, increased stocking rates, improved grazing distribution, and improved soil quality (Kothmam, 1974; Teutscherova et al., 2021). However, these benefits come at a cost – implementing a rotational grazing system requires increased inputs such as fencing and labor, and additional water and shelter infrastructure needed in each pasture (Wang, 2020).

The implementation of intensive or rotational grazing systems is variable in the NGP. Survey results indicate that intensive rotational grazing is used on less than 10% of rented or owned land, but simple rotational grazing is used on approximately 50% of owned/leased land; both systems have few producers who revert to continuous grazing (Wang, 2020). A survey of 760 ranchers in Wyoming and California found that 66% of respondents have implemented a rotational grazing system within their management plan

(Roche et al., 2015). Roche et al. (2015) further state that 93% of respondents using a rotational system used an extensive rotational system with moderate grazing period durations, stocking rates, and rest periods during the growing season. The slight increase in producer adoption in the latter survey could be attributed to three factors, 1) the differences in ecosystems between surveys, 2) producers who use a rotational system influencing their nearby neighbors, and 3) the variation in sample size between surveys (Roche et al., 2015). A survey of 4,500 producers across South Dakota, North Dakota, and Texas found the top three barriers to improving their grazing system were capital, labor, and infrastructure (i.e., water and fence) (Wang, 2016).

In addition to implementation costs, other variables besides stocking rate influence range management, resulting in an emphasis on adaptive management. Factors such as soil, climate, topography, and vegetation can be highly variable across systems (Anderson et al., 2014). These same external biotic and abiotic factors can influence the foraging behavior of livestock, which is also affected by the physiology of the animal or animals that inhabit the area (Provenza et al., 2007; Finger et al., 2014). For example, the topography of pastures has a large impact on livestock grazing selection and behavior (Raynor et al., 2021). To fully comprehend plant-animal interactions pasture size should be considered since it drives livestock behavior, which translates to the feasibility to adopt management intensive grazing practices (Anderson et al., 2014). Thus, adaptive management – a decision-based system that is implemented using detailed monitoring data (Augustine et al., 2020) – is useful in determining range management decisions. Land managers are often asked to balance a variety of ecosystem services and livestock production practices. This could pose challenges to land managers wanting to implement rotational grazing systems or intensive management systems using traditional barb wire fence or electric poly wire fence. Virtual fencing (VF) may provide the flexibility to achieve a variety of land management objectives that would be difficult to implement otherwise.

Virtual Fencing

Adaptive management can be implemented through the advancement of new precision land management technologies that enable producers to manage the landscape with their animals in ways that can improve grassland health and sustainability. Simultaneously, adaptive management can improve the value of grazed forage as a source of nutrition for grazing livestock. Among the more novel technologies is the use of VF – borders without physical barriers – to implement precision grazing management (Umstatter, 2011). VF systems operate via a GPS-enabled collar that is placed around each animal's neck. There is a three-way interaction between the collars, a base station in the field, and a computer or tablet which allows users to 'draw' their pasture boundaries. These boundaries transmit to the base station (operated by cellular and solar), which 'pushes' the virtual fence to the collars. Livestock are controlled within the virtual pasture with an auditory cue followed by an electrical cue if the animal goes beyond the virtual boundary.

The benefits of implementing VF to establish a rotational grazing system can help livestock producers improve grassland management, improve animal performance, and reduce the need for additional fence and water infrastructure. The adoption of VF technology can change manual labor to cognitive labor by reducing labor costs associated with rotating animals and checking fence (Anderson et al., 2014). The potential applications of VF are vast and include the introduction of VF on leased ground, crop-livestock integration, co-op fencing programs, fire-fuel load reductions, and riparian restoration. Barriers to VF adoption have not yet been studied extensively, but likely include the capital to invest in VF technology and the skills required to learn and implement it. Despite VF technology existing over the past 40 years, there are few commercial options available for producers (Umstatter, 2011). The few options that are available include NoFence^{TM}, eShepHERD^{TM}, and Vence^{TM}. As time advances, the costs of VF technology will likely decrease and lead to more widespread adoption by land managers.

Research on VF technology is limited and has primarily focused on the functionality of the collars to move and contain animals within target areas. A study conducted in 2015 using collars worn by cattle and an above-ground induction cable determined that the induction cable as a visual deterrent was the main determining factor in containing cattle (Umstatter et al., 2015). VF has been proven to have high efficacy in a variety of scenarios including deterring animals from feed, containing livestock within desired areas of grazing, and moving animals across the landscape all without substantial animal behavior or welfare impacts (Campbell et al., 2018, 2020, 2021). Suggestions for further research include analyzing the impact of herd pressure on individual behavior (Campbell et al., 2018). One benefit to utilizing VF and precision livestock management technology is the ability to generate real-time data on individual animals that can be integrated into animal nutrition models and utilized to inform management decisions (Menendez et al., 2022)

Energetic Expenditures

Livestock health and production are often tied to ADG, which is the traditional primary metric in determining animal performance in rangeland systems. However, there is potential to derive other metrics to quantify animal performance using precision technology data for pasture-based systems. One example is real time daily energetic cost associated with activity for cattle traveling. The basis for energetics in determining animal performance is found in previous works of calculating animal energetics through comparative slaughter, direct calorimetry, and indirect calorimetry work that the animal science community uses to this day (Garrett et al., 1959; Lofgreen, 1965; Lofgreen and Garrett, 1968; Reynolds et al., 2019).

The development of energetic equations for beef cattle began in the 1960s with foundational work by Lofgreen and Garrett, leading to the development of the California Net Energy System, CNES (Owens and Hicks, 2019). The goal of the CNES was to calculate the energetic requirements of beef cattle (NRC, 1976) and later sheep (NRC, 1984). Lofgreen and Garrett began calculating heat production from animals through the difference of metabolizable energy and retained energy. The calculations of heat production in beef cattle were made possible with the use of the comparative slaughter technique (Lofgreen, 1965). Through this work, researchers attained an estimate of net energy for maintenance (NEm) based on the values of heat production at zero feed intake; later creating the equation known as $NEm = 0.077 \cdot W^{0.75}$, where “W” is full body weight (kg) (Lofgreen and Garrett, 1968). In 1984, revisions were made to how NEm was calculated, most importantly the adjustments for frame size. Frame size was broken down into yearling, medium, and large. Further research noted that NEm requirements could vary based on breed type and emphasized the importance of accounting for unshrunk body weight (BW), shrunk BW, and empty BW (NRC, 1984).

Recent advancements in understanding energetic equations have used respiration calorimetry, with a focus on indirect calorimetry (Gerrits, 2023). Respiration calorimetry is a non-invasive form of calculating the same values that Lofgreen and Garrett were calculating through comparative slaughter. Energetic expenditure is calculated by the difference of heat production (HP) and metabolizable energy (ME). Indirect calorimetry is a method where heat production and both the type and rate of substrate utilization are estimated by recording gas exchange measurements from animals (Gerrits, 2023). Researchers use "chambers" or "head boxes" that cattle are kept in for 24 hours to calculate HP. This has allowed researchers to measure retained energy (RE) and net energy for growth (NEg) indirectly. Overall, most research conducted to date on energy expenditure in cattle is based on feedlot systems (Tedeschi and Fox, 2020). This research has also been largely used to calculate net energy for growth (NEg) and net energy for maintenance (NEm) requirements. NEg is the energy from the animal's diet that goes towards growth after NEm requirements have been met. NEm is the energy required by the animal to sustain life and includes activities such as ruminating and breathing (NRC, 2016). Net energy maintenance requirements for activity (NEmr_act) accounts for the energy spent beyond basal metabolic needs such as walking or foraging within pastures.

NEmr_act is critical to the discussion of energy expenditure in rangeland cattle that have the additional challenge of navigating heterogeneous landscapes to capture their dietary requirements (Caton and Olson, 2016).

Factors Influencing Net energy for Activity

Energy expenditure for the physical activity of grazing is influenced by various aspects, including but not limited to forage quality and availability, topography, weather, water distribution, and animal genotype (NRC, 1996). As forage quality and abundance is reduced animal grazing time drastically increases, in some cases by up to 200% (Scarnecchia et al., 1985). Weather, specifically heat, can result in reduced productivity due to the energetic expenditure (EE) of acquiring homeostasis; especially in *Bos taurus* compared to *Bos indicus* (Blackshaw and Blackshaw, 1994). Cattle behavior is variable among individuals which could lead to differing amounts of time spent grazing within the same herd, possibly attributed to genetics (Stephenson and Bailey, 2017). All these variables lead to differences in EE, which is the amount of energy that goes towards net energy for growth or net energy for maintenance.

Rangeland Energetics

There is limited knowledge on EE for beef cattle grazing extensive rangelands. The seminal paper that first evaluated EE of rangeland cattle was by Osuji (1974). His findings suggest that on average, energy requirements can increase from 25-50% for grazing cattle compared to cattle in confined systems – approximately 0.072 Mcals. Other work by Brosh et al. (2006) quantified energetic expenditure by using heart rate monitors. They measured heart rate multiple times a day and multiplied it by O_2 consumption and heat production to calculate total EE; their results suggest that grazing EE ranged from 13 to 48 kJ/(kg of BW0.75 · d) (Brosh et al., 1998, 2002). More recently, EE equations developed by Tedeschi and Fox (2020) calculate EE for physical activity through static models with empirically derived values. One of the unique challenges in determining energetic expenditure for activity (NEmr_act) in rangeland cattle production is the energetic equations that are in use were designed for confined systems, namely feedlots and drylots.

The quantification of rangeland energetics leads to various challenges depending on the methodology implemented (Jorns et al., 2022). Recent efforts have utilized animal metrics using heartrate monitors coupled with GPS collars to determine animal performance (Brosh et al., 2006; Aharoni et al., 2013). In these trials, EE was determined for certain behaviors such as standing, grazing, and walking. The EE values that Brosh et al. (2006) and Aharoni et al. (2013) are within the range of expected energetic costs, which suggest that the cost for activity would equate to a 20% increase in NEm (Tedeschi and Batista, 2021). Researchers have also tried to determine animal movement and subsequently the EE of animals with pedometers, with the recent integration of accelerometers (Walker et al., 1985; Funston et al., 1991; Jorns et al., 2022). Jorns et al. (2022) calculated EE using step-energy relationships based on the number of cattle steps and distance equivalents determined by Test et al. (1984). In this study, the mid-season grazing weight was used for calculating EE on a subsample of animals within the herd of yearlings. Overall, further research is needed to understand EE of grazing animals in extensive systems such as rangelands. The adoption of precision technologies such as VF and in-pasture daily weighing will allow researchers to capture data at an unprecedented level leading to an enhanced understanding of livestock energetics for cattle grazing on rangelands. To our knowledge, there are currently no studies that have tried to determine an individual animal's EE in extensive rangeland systems based on GPS and real time weight data.

Livestock on extensive rangeland systems convert unusable forage into high quality animal-based protein sources, creating a valuable contribution for a growing need for human food production. Despite the increasing knowledge of energy and metabolism for cattle in confined systems, little is known about the EE of grazing animals within continuous and rotational grazing systems. Thus, there is a knowledge gap on the impacts of activity and grazing management strategy on EE. The need exists to develop precision system models for NEmr activity that can account for individual animal energetic expenditure and differences within management system to improve beef cattle production.

Summary

Although most previous studies have focused on the efficacy of VF technology to move and control animals within targeted areas, limited research exists to quantify the impact of VF technology on animal behavior, performance, and models for calculating NEmr_act costs on extensive rangeland settings. The goal of this thesis was to determine the difference between a VF rotational (VFR) grazing system and a continuous graze (CG) system on animal behavior, performance, and EE within a NGP beef production operation. Objectives of this study were to 1) determine the impact of a VFR and a CG system on daily distance traveled, resting, and grazing time, 2) compare the impact of a VFR grazing system and a CG system on animal performance, specifically ADG, 3) develop and validate a precision system model that calculates daily NEmr_act on an individual animal, and 4) determine the impact of a VFR grazing system versus a CG system on NEmr_act expenditure. We hypothesized that 1) cattle within the VFR will have increased daily distance traveled and resting time, and decreased grazing time compared to the CG system due to confinement in a smaller pasture, 2) cattle within the VFR will have decreased ADG due to the increase in activity and walking time, as they are rotated through the course of the trial, and 3) cattle within the VFR will have an elevated NEmr_act measured on a daily basis compared to the CG system due to the increased time spent walking at the epoch of each new rotation. The results of this study will create opportunities for managers to implement grazing systems that can benefit both livestock production and rangeland health.

The successful implementation of precision livestock technology is dependent on its effect on livestock production. Emerging technologies should only be deemed worthy of producer adoption if it does not impede livestock production, and instead increases production efficiency or at least maintains production efficiency. The quantification of individual animal EE for activity can have direct management implications for both researchers and producers. Real time data collection and analysis will allow for data informed management actions. In addition to aiding producers in livestock management, increased adoption of these technologies may allow for unprecedented data collection that researchers can use to answer producer questions surrounding animal performance and energetics and range management.

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CHAPTER 2. IMPACT OF VIRTUAL FENCING ON STEER PERFORMANCE AND BEHAVIOR BETWEEN GRAZING SYSTEMS IN THE NORTHERN GREAT PLAINS

ABSTRACT

Virtual fencing (VF) is an emerging precision technology that has the potential to revolutionize livestock management on extensive rangeland systems. It involves the use of GPS enabled collars to create a virtual boundary around a designated area, such as a pasture or paddock. When an animal wearing the collar approaches the virtual boundary, it receives an auditory cue, and if it continues to approach the boundary, it receives an electrical cue. VF has several advantages over traditional physical fencing, including increased management flexibility and reduced labor costs. Key to the adoption of this technology is determining the impact on animal behavior and performance. We evaluated the effect of traditional season long grazing and rotational grazing with three different stocking rates. In the summer of 2021 and 2022, steers equipped with VF collars grazed native summer pastures from May to August. Animals were managed under two systems, continuous graze (CG) and virtual fence rotational (VFR) grazing. GPS data was used to estimate daily distance traveled, grazing, resting, and walking time. Grazing and resting behavior had no observed differences between treatment groups. However, there was an observed interaction for walking behavior that was significantly impacted by stocking rate and treatment, depending on year. VFR steers in 2021 in the heavy and light stocking rates spent the most time walking (0.42 hr ± 0.02 and 0.47 hr ± 0.2, respectively).

Average daily gain (ADG) was calculated using C-Lock SmartScales^{TM} over the course of the trial. ADG results suggest that stocking rate and treatment significantly impacted steers from year to year. Observed ADG differences match current knowledge of grazing management strategy and stocking rate impact on animal performance. Overall, VF had little impact on animal behavior and performance suggesting that its' implementation into production settings is warranted.

INTRODUCTION

Concerns over rangeland health and restoration in the past century have led to a focus on grazing systems and stocking rates (Kothmann, 1974). In the mid-20th century, livestock and range management focused heavily on developing grazing systems based on the concept of rest-rotations compared to traditional, continuously grazed systems. Several variations on the timing and duration of rest-rotation within these grazing systems exist such as deferred rotation, short duration grazing, high intensity-low frequency, and adaptive multipaddock (AMP) grazing (Holechek, 1983; Bork et al., 2021). Many of these grazing strategies have persisted into contemporary range management, with emphasis on greater control over grazing distribution on the landscape and an enhanced focus on improving ecological objectives (Derner et al., 2009). In addition, grazing management systems have the potential to maximize livestock production through more even utilization of forage resources; however, previous research indicates that there is no singular factor that exclusively dictates animal performance and behavior, and suggests multiple variables should be accounted for when managing livestock on rangelands (Bailey et al., 2015; Raynor et al., 2021; Jorns et al., 2022).

Comparisons between continuous and rotational grazing have resulted in varying outcomes. Proponents of rotational grazing suggest that it increases stocking rate and decreases animal impact on the landscape compared to a continuous grazing system (Savory, 1983). Past research has indicated that rotational grazing allows for greater standing forage availability, while maximizing forage quality and yield (Sanderman et al., 2015). Furthermore, pastures with equivalent forage availability had higher nutritive values under rotational grazing (Paine et al., 2013). Within tall grass plant communities, multi-paddock grazing has resulted in improved soil organic matter, enhanced soil microbial activity, and increased water-holding capacity over light and heavy continuous grazing pastures (Teague et al., 2011). Furthermore, rotational grazing can reduce both soil temperature and the amount of bare ground present compared to traditional continuous grazing practices (Teague et al., 2010). One study investigated rotationally grazing steers through cultivated pastures – commonly referred to as crop-livestock integration – and found potential in increased soil health metrics; however, this did not occur with steers that rotationally grazed native pastures (Harmel et al., 2021). A review on the impact of rotational grazing on animal production per head and per unit of area found no additional benefits from rotational grazing over continuous grazing (Jung et al., 1993; Briske, 2008). Given this research, there is a lack of agreement on which grazing system outperforms another with respect to impacts on both ecosystems and livestock performance.

Ultimately, a grazing system is a product of the livestock producer’s desired goals and limitations. Limitations such as the lack of capital, increased labor demands, and additional infrastructure resources have been cited as primary barriers to adopting rotational grazing practices are (Wang et al., 2020). Fencing in rotationally grazed systems can be 40% greater compared to systems that do not rotationally graze; consequently, there’s a need for flexible options for producers to implement their grazing management strategies (Wind et al., 2019). Installation of five-strand barbed wire in South Dakota can cost a minimum of $15,000 per mile with labor and materials considered in the total cost (Moriarty, 2023; *Personal communication*). Recently, there has been an emphasis on implementing precision technologies on extensive rangelands to increase livestock distribution and improve animal efficiency. Emerging precision technologies include livestock welfare concern detection, remote disease detection, parturition detection, water system monitoring, and VF (Bailey et al., 2021).

The development of new precision land management technologies is entering the consumer market, including VF. The concept of VF for livestock first originated in 1987 with the development of Peck’s Invisible Fencer Co. (Fay et al., 1989). Later, researchers used Tri-tronics A1–90 remote dog training collars to manage four Hereford steers using electrical stimulation (Quigley et al., 1990). Modern VF technology utilizes a three-way interaction among a GPS enabled collar worn by the animal, software to control the movement of steers on the landscape, and a base station to facilitate communication between the collar and the user (software). Past research on VF technology is limited and has primarily focused on the efficacy of the technology including effectiveness of exclusion and containment rate within desired areas, and the ability to rotate steers between paddocks using VF; other research has focused on applications of VF for management objectives. (Umstatter et al., 2015; Campbell, 2017; Campbell et al., 2019, 2021; Ranches et al., 2021; Boyd et al., 2022). VF has successfully excluded cattle from environmentally sensitive areas, specifically riparian areas and sapling growths (Campbell et al., 2018, 2020). In addition, previous research found no difference in stress or animal behavior between VF (eShepherd^{TM}) to polytape fence in Australia (Campbell et al., 2021). Additional studies indicate that there is no difference in cortisol level between physical fencing and VF, warranting VF as a viable and ethical management tool (Jeffus et al., 2021). Although numerous applied applications for VF exist to more precisely manage animal distribution on the landscape, it is essential to understand how VF impacts animal behavior and performance compared to traditional management, to further the adoption of this technology. The objective of this study is to assess the impact of VF on daily distance traveled (DDT), ADG, grazing time, walking time, and resting time compared with a CG system across three stocking rates. We hypothesized that CG steers will have higher ADG, and VF will not negatively impact animal behavior.

MATERIALS AND METHODS

Institutional Animal Care and Use Approval

The animal care and handling procedures used in this study were approved by the South Dakota State University Animal Care and Use Committee (Approval Number: 2104-021E).

Study Area

This experiment was conducted at the South Dakota State University (SDSU) Cottonwood Field Station (CFS), located in western South Dakota. The trial period was conducted over two summer grazing seasons from May to August in 2021 and 2022. The

CFS is located within a mixed grass prairie ecosystem and is composed primarily of native C3 green needlegrass (*Nassella viridula* Trin.) and western wheatgrass (*Pascopyrum smithii* Rydb.), needle-and-thread (*Hesperostipa Comata* Trin. & Rupr) grasses, and C4 blue gramma (*Bouteloua gracilis* Willd. Ex Kunth), buffalograss (*Bouteloua dactyloides* Nutt.) with the inclusion of sedges (*Carex* spp.). There are also recent introductions of non-native grasses, such as Kentucky blue grass (*Poa pratensis* Boivin & Love) and Japanese brome (*Bromus japonicus* Thunb.). Soil in the study area is predominately Kyle clay and Pierre clay (NRCS, 2022). The topography is gently sloping with rolling hills and relatively flat-topped ridges with elevation that ranges from 710 m to 784 m. The climate is semi-arid with hot summers and cold winters; annual precipitation for 2021 and 2022 was 278 mm and 267 mm, respectively (South Dakota Climate and Weather, 2023).

A long-term grazing study implemented in 1942 has been conducted at the CFS on six pastures ranging in size from 31 to 73 ha (Dunn et al., 2010). The long-term experimental design has been a randomized complete block with three levels of stocking rate in two replicate blocks. Pastures have been stocked with steers to maintain pasture treatments with different stocking rates: light, moderate, and heavy, that have created three distinct plant communities found within Northern Great Plains (NGP) rangelands. Lightly grazed pastures consist of diverse plant communities predominantly composed of western wheatgrass (*Pascopyrum smithii* Rydb.) and green needlegrass (*Nassella viridula* Trin.), while heavily grazed pastures are dominated by buffalograss (*Bouteloua dactyloides* Nutt.) and blue grama (*Bouteloua gracilis* Willd. Ex Kunth.) The moderately grazed pastures have an intermediate plant community, consisting largely of native species found in the NGP. When the study was initiated, pasture boundaries were situated to uniformly allocate topographic features (hills, draws, ecological sites) across all treatments.

Grazing Management Treatments

Steers in 2021 and 2022 were allocated into two treatment groups. The groups were a CG treatment and a VFR grazing treatment steers were managed in a rotational grazing system using Vence^{TM} collars worn by the animal. Primarily cross-bred black angus yearling steers (n=127 and n=135, in 2021 and 2022, respectively) were sorted into pastures based on initial body weight ranging from 256 to 444 kg. Each pasture was grazed separately by steers at stocking rates comparable to the long-term grazing study (Dunn et al., 2010). Steers within CG had free access to the entire pasture for the duration of the grazing season. Steers within the VFR treatment were rotated among virtual ‘paddocks’ within the pastures for the duration of the grazing season. Across both grazing management scenarios, VF collars were used to track all animal locations at 5-minute intervals; only steers within the VFR were managed with VF boundaries and auditory and electrical cues from the collars. The days spent in each paddock for the VFR treatment were determined based on bi-weekly clip plots for biomass estimation. Peak biomass for each pasture based on the year shown in Table 2.1.

Calculations of grazing days in these paddocks were calculated using the SDSU Extension Grazing Calculator (Ehlert and Brennan, 2021). Three stocking rates were used and replicated for both treatment groups, CG and VFR; the light stocking rate was 0.32

AUM/ac, the moderate stocking rate was 0.40 AUM/ac, and the heavy stocking rate was 0.72 AUM/ac (Dunn et al., 2010). Our experimental design was randomized complete block design, with a treatment structure is a 2 x 3 factorial design.

ADG were estimated using SmartScales^{TM} (C-Lock Inc., Rapid City, SD). SmartScales^{TM} were placed in each of the pastures at the stock tanks. Steers steer weights were downloaded from C-Lock^{TM} through an application programming interface (API). A 3-day rolling average for daily weights was calculated to minimize variations in rumen fill and number of trips taken to the scale. ADG was calculated using a linear model to develop a regression equation for each individual animal with weight as the dependent variable and day of trial as the independent variable. The slope of the regression line was used for the ADG estimate.

Collar Efficacy

In 2021, 127 version 2 collars (Vence^{TM}, Figure 2.1) were outfitted on steers. Of these collars, 98 were retained on the animal for the duration of the trial in 2021, resulting in a 77% retention rate. In 2022, 137 version 3 collars (Vence^{TM}, Figure 2.2) were outfitted on steers. Of these collars, 61 were retained on the animal for the duration of the trial, resulting in a 44% retention rate. The containment for each pasture and year can be found in Table 2.2. Containment rate was calculated as the number of GPS fixes in the correct paddock divided by the total number of GPS points. Only collars that remained on for the full duration of the grazing season were used in the behavior analysis. Fallen collars were reattached approximately 1 week after they fell off.

Statistical Analysis

Raw data was downloaded from Vence^{TM} Herd Manager^{TM} through an API. Downloaded data was cleaned by removing messages that failed to transmit correctly or were outside the bounds of study site pastures. Data was cleaned based on previously reported methods (Knight, 2016) to remove potentially bad GPS fixes. Within Program R, the animal behavior metrics of DDT, daily grazing time, daily resting time, and daily walking time were calculated for each individual animal. DDT was calculated by summing the distance between successive GPS fixes for each day. Determination of grazing, resting, and walking GPS points were based on existing methods for classifying livestock movement behaviors (Ungar et al., 2005; Augustine and Derner 2013; Cibils et al., 2013; Brennan et al., 2021). Individual daily behavior metrics were averaged by week for analysis. The experimental unit was individual animal (Tobin et al., 2020; Brennan et al., 2021; Raynor et al., 2021; Jorns et al., 2022). The animal behavior metrics were analyzed using a mixed model analysis of variance (ANOVA) to compare the impact of stocking rate (heavy, moderate, or light), treatment (VFR, CG), year (2021, 2022), and all interactions on DDT, grazing time, resting time, walking time, and ADG. Fixed effects in the model were stocking rate, treatment, and year; the random effect was an individual animal. For behavior metrics, week was treated as a repeated measure. Interactions significant at $P < 0.05$ were compared using the lsmeans package to summarize the effects of factors, both fixed and random (Lenth, 2018). Tendencies in the model were indicated at p-value of $P < 0.10$.

RESULTS

DDT was significantly impacted by year ($P = 0.02$), with steers traveling less in 2022 (5129 m ± 70.3) than those in 2021 (5621 m ± 55.8) (Figure 3). Steers in 2021 traveled approximately 482 m more per day than those in 2022. There were no other observed differences in DDT for steers based on treatment group (P = 0.42), stocking rate (P = 0.25), or any interaction between stocking rate, treatment, or year.

There was a significant stocking rate by year interaction for grazing time (stocking rate x year, P = 0.009) (Figure 4), with steers in 2022 spending approximately 1 hour less per day (9.53 hr ± 0.11) grazing than those in 2021 (10.6 hr ± 0.09). In 2021, steers in the heavy stocking rate spent significantly more time grazing (11.21 hr ± 0.154) compared to the light or moderate stocking rates (10.42 hr ± 0.140 and 10.16 hr ± 0.154, respectively). In 2022, steers in the heavy, moderate, and light stocking rate pastures spent the same amount of time grazing (9.56 hr ± 0.199, 9.61 hr ± 0.192, and 9.42 hr ± 0.181). Resting behavior was not significantly impacted by treatment (P = 0.93), stocking rate (P = 0.45), year (P = 0.55), or any interaction between the variables. On average, steers spent 13.85 hr ± 0.41 resting per day.

There was a significant three-way interaction for walking behavior. Walking behavior was significantly impacted by stocking rate and treatment, depending on year (stocking rate x treatment x year, P = 0.003) (Figure 2.5). VFR steers in 2021 in the heavy and light stocking rates spent the most time walking (0.42 hr ± 0.02 and 0.47 hr ± 0.02, respectively), while the time spent walking in the moderate stocking rate was 0.34 hr ± 0.02.

There was a significant two-way interaction for stocking rate by year (P < 0.01) and for treatment by year (P < 0.01) for ADG. Steers in the light stocking rates, 2021 moderate, and 2021 heavy stocking rate had the highest ADG (Figure 2.6). Steers in the

202 heavy stocking rate and moderate stocking rate had the lowest ADG (Figure 2.6). ADG was significantly impacted by treatment, depending on year (treatment x year, $P < 0.01$) (Figure 2.7). Continuously grazed steers had higher ADG compared to VFR steers in 2021. In 2022 VFR steers had higher ADG than those in the CG treatment (Figure 2.7). Lastly, ADG was significantly impacted by stocking rate, depending on treatment (stocking rate x treatment, $P = 0.03$). There were no observed differences in ADG in 2021 and 2022 for steers in the light stocking rate, nor for 2021 for steers in the moderate stocking rate. In 2022, VFR steers in the heavy stocking rate gained the least (0.65 kg/hd/d ± 0.03); in 2021, CG steers in the moderate stocking rate and CG steers in the heavy stocking rate gained slightly more than VFR steers in 2022 (Figure 8).

DISCUSSION

Stocking rate and treatment did not impact DDT, with the only significant effect being a year effect. This contrasts with previous research that reported heifers in continuously grazed systems traveled 1.6 km more per day than heifers under a high intensity low frequency grazing system (Anderson and Kothmann, 1980); difference in this study were attributed to changes in crude protein and digestible energy. Other research has shown that DDT was approximately 1 km more per day in short duration grazing compared to season long grazing, but differences observed may be due to differences in tightness of the pedometer case around the animal's leg (Walker et al., 1985). Differences in our results for DDT between treatments may be due to pasture design/layout. Specifically, the CG pastures had centrally located water sources, which could impact overall travel distance to water (Porath et al., 2002). In the VFR pastures, the rotations pivoted around the water source for all paddocks within the pasture. The location of water features can have a significant impact on the distance traveled for water, leading to the need to strategically design rotational grazing systems with water access being centrally located to minimize the impact on animal behavior and performance (Ganskopp, 2001). Thus, this could be an explanation for the lack of observed differences in DDT, resulting in less distance traveled for water events.

Stocking rate can impact grazing efficiency, the proportion of forage consumed by cattle compared to the total forage quantity that disappears because of other activities (e.g., insect and wildlife consumption, soiled forage due to urine and defecation) (Redfearn and Bidwell, 2017). Grazing efficiency tends to increase at high stocking rates and decrease at lower stocking rates (Smart et al., 2010), due to increased social herd pressure to capture nutritive requirements before forage becomes limited. This suggests that smaller pasture sizes would allow for greater grazing efficiency, resulting in less grazing time per day. However, we did not observe this – as stocking rate increased (and pasture size decreased), grazing time increased in 2021 and there was no difference in grazing time in 2022. A possible explanation for our observations is a consequence of weather, mainly precipitation, resulting in decreased forage quantity and quality. Early spring drought can cause a 20-40% reduction in forage production, with cool season perennials being most susceptible to drought within the NGP (Heitschmidt et al., 2005). Furthermore, drought causes changes in forage quality with lower plant neutral detergent fiber (NDF), leaf protein, and higher stem protein (Pecetti et al., 2016). In addition, drought may impact C3 and C4 grasses differently, with C3 grasses potentially increasing in quality (Grant et al., 2014) and C4 grasses decreasing in quality, because drought events can inhibit tillering and branching while also undergoing senescence; ultimately resulting in the relocation of nutrients from the leaves to the roots of the plant. With lower forage quantity and quality, the number of hours spent grazing would need to increase to meet rumen requirements, which could explain why steers within the high stocking rate had higher grazing times due to lower forage production and increased prevalence of C4 grasses. Furthermore, drought can impact forage quality negatively through the lack of growth, but it is possible that forage quality increases in some plants as a result of increased leaf to stem ratio (Peterson et al., 1992). Rotational grazing at higher stocking rates limits the amount of time spent grazing because there is less dead and live forage mixed together, decreasing the amount of time cattle need to find the current year’s growth (Walker and Heitschmidt, 1989). This was not witnessed in our study, which may be a byproduct of limited reduction in forage quality of C3 grasses due to drought years in 2021 and 2022.

Resting behavior was not impacted by treatment or stocking rate. This mirrors other research, where resting behavior was not impacted by grazing management strategy in late season grazing (Sprinkle et al., 2020). In our study, walking behavior was significantly impacted by stocking rate and treatment, depending on year. Observed differences in walking behavior from year to year could be a result of increased grazing time. Specifically, differences in observed walking behavior are likely attributed to the location of higher quality, specific forages within respective pastures, or placement/locations of water within the pasture (Anderson and Kothmann, 1980). Our observed increases of walking time for steers in the VFR grazing system in the heavy and light stocking rates could potentially be a function of forage quality degradation as the growing season progressed. Early in the growing season cattle travel less to obtain forage for consumption; however, walking increases later in the growing season walking potentially as a result of searching for clusters of high-quality forage within a paddock or pasture (Jorns et al., 2022). The lack of differences in resting and grazing behavior between treatment groups, CG and VFR, matches previous research suggesting that animal behavior is not modified based on grazing management strategy (Venter et al., 2019). Our lack of observed differences is crucial to the use of VF technology as a viable tool for producers.

Animal performance, specifically ADG, varied by treatment and stocking rate depending on year. Steers in the light stocking rate performed the most consistently from year to year. Long-term stocking rate studies have shown that with increasing stocking rate and grazing pressure, ADG can decrease up to 16%, with steers in lighter stocking rates performing the best (Derner et al., 2008). Derner et al. (2008) also noted that performance tended to be reduced by up to 6% in short duration grazing compared to traditional season long grazing systems. These findings match the animal performance in our study; except for the 2022 CG steers, with the lowest ADG at 0.68 kg/hd/d. This difference is likely attributed to the reduction in forage quality from two successive drought years (Teague et al., 2004; Grant et al., 2014). We observed differences between treatment groups and stocking rates with steers performing better under the CG regime in 2021 and the VFR regime in 2022. This contradicts previous literature suggesting that CG results in the highest performance (Briske et al., 2008; Augustine et al., 2020). However, there is a lack of consensus on how grazing management strategy (i.e., continuous versus rotational) impacts animal performance with some research suggestion no difference in animal performance (Hawkins, 2017) and some literature indicates there are animal performance benefits in smaller pasture sizes (Hart, 1993).

MANAGEMENT IMPLICATIONS

The implementation of precision technology such as VF into rangeland cattle production has some potentially impactful outcomes. Our study demonstrated no observable differences due to treatment or stocking rate on DDT, which demonstrates that animal behavior is not affected by VF. We found there is likely no difference of VF technology on ADG, rather it was dependent upon the year and stocking rate. These results demonstrate the applicability of VF technology, and the associated benefits of reduced labor construction, and maintenance of fencing can make VF a viable option for livestock production on extensive grasslands.

The management opportunities with VF are numerous. First, VF can be implemented – and is being implemented – on public land across the U.S. This can benefit both the producer and the government agency that issues these grazing permits, as producers may be limited in their ability to implement grazing management practices due to the expense of investing in infrastructure on land that is not owned. VF can be used to protect environmentally sensitive areas, including riparian areas, critical wildlife habitat, and aid in wildfire mitigation practices that would otherwise be labor intensive. As with any new technology or management strategy, the key for producer adoption is understanding the impact on animal production and behavior, as this ultimately impacts the economic viability of the producer's operation.

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TABLES AND FIGURES

Figure 2.1. Vence^{TM} collar (Version 2) used in the summer of 2021. This collar is a nylon strap design with a dive weight to counterweight the collar for proper orientation. This collar has an auditory and electrical cue.

Figure 2.2. Vence^{TM} Collar (Version 3) used in the summer of 2022. This collar is a chain design with a plastic bridge (not pictured) that the chains loop through. Collar has both an auditory and shock cue.

Table 2.1 Peak biomass availability for each pasture over the course of both trial years, 2021 and 2022.

Peak Biomass Availability (lbs./acre)		
	2021	2022
Pasture 1	867	636
Pasture 2	835	921
Pasture 3	993	1165
Pasture 4	855	563
Pasture 5	1399	951
Pasture 6	1529	1086

Table 2.2. Containment rate of steers for both field seasons, 2021 and 2022. V2 collars, Figure 1, were used in the 2021 field season. V3 collars, Figure 2, were used in the 2022 field season. Containment rates were similar among years and stocking rates except for 2022 heavy VFR which was significantly lower than 2021 and other stocking rates.

2021	**Stocking Rate**	**Containment Rate**
	Light	69%
	Moderate	78%
	Heavy	70%
2022		
	Light	72%
	Moderate	73%
	Heavy	54%

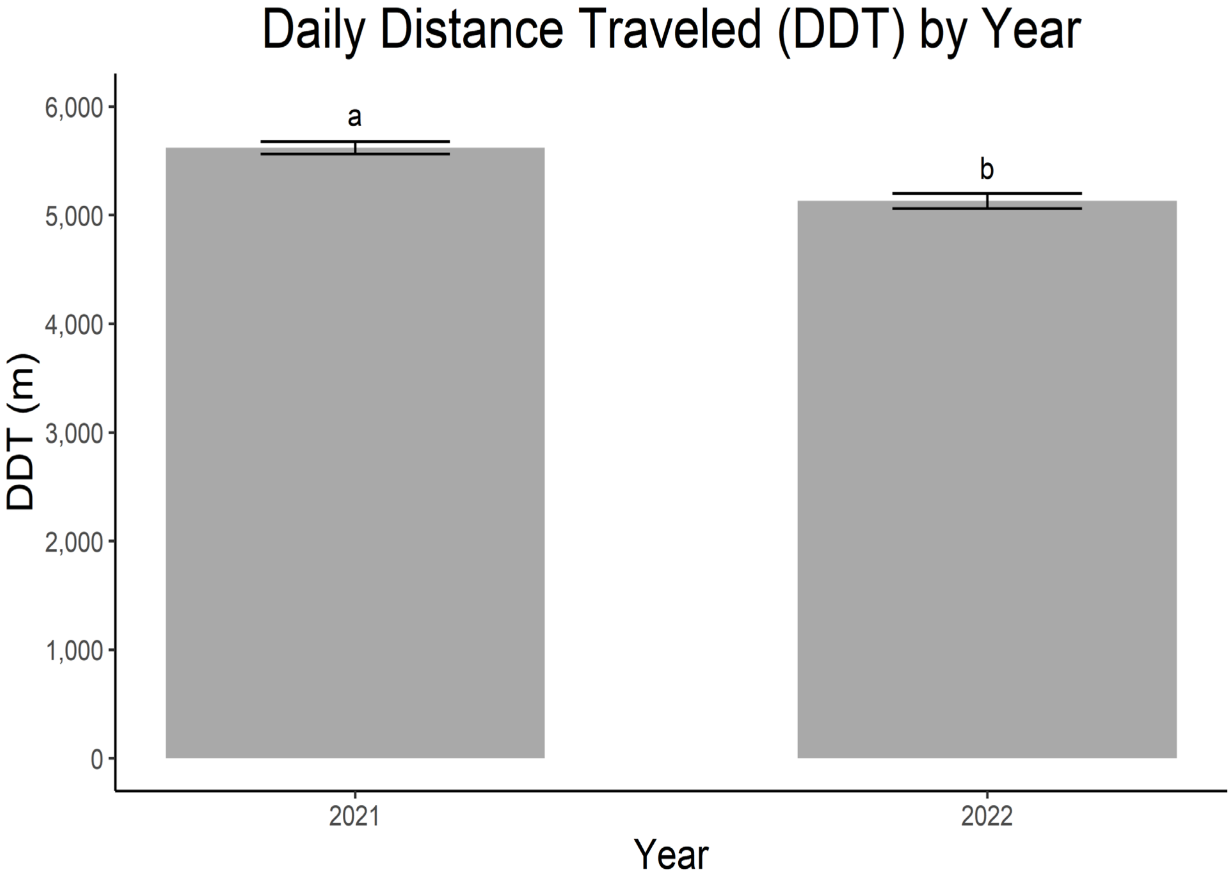

Figure 2.3. Daily distance traveled (DDT) in meters in 2021 and 2022.

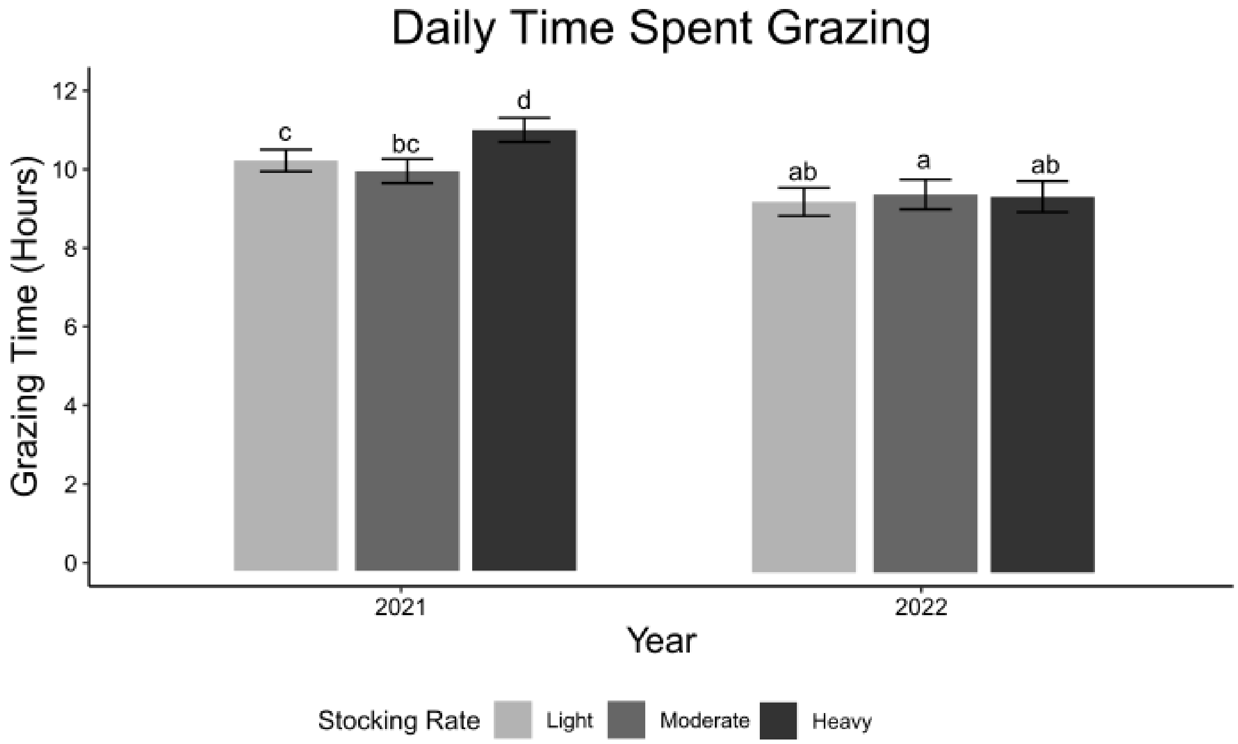

Figure 2.4. Daily time spent grazing reported in hours per day, by stocking rate (light, moderate, heavy).

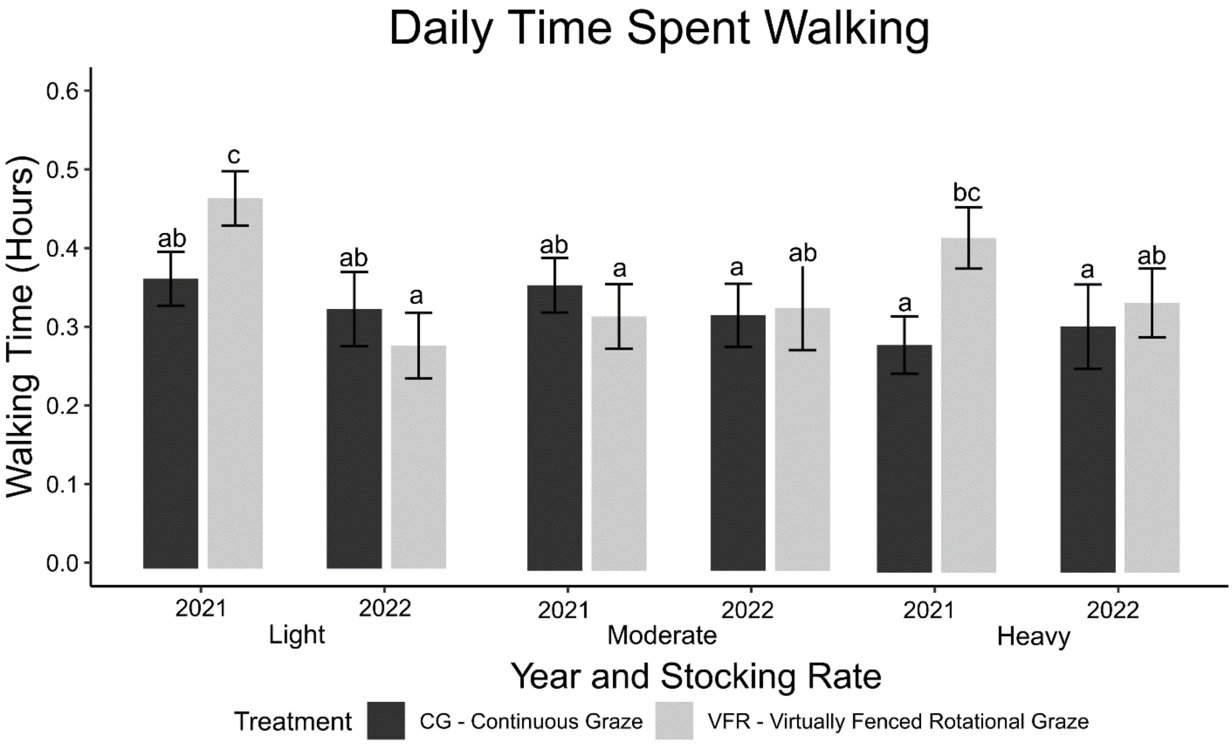

Figure 2.5. Daily time spent walking reported in hours per day per head, by year and stocking rate (light, moderate, heavy).

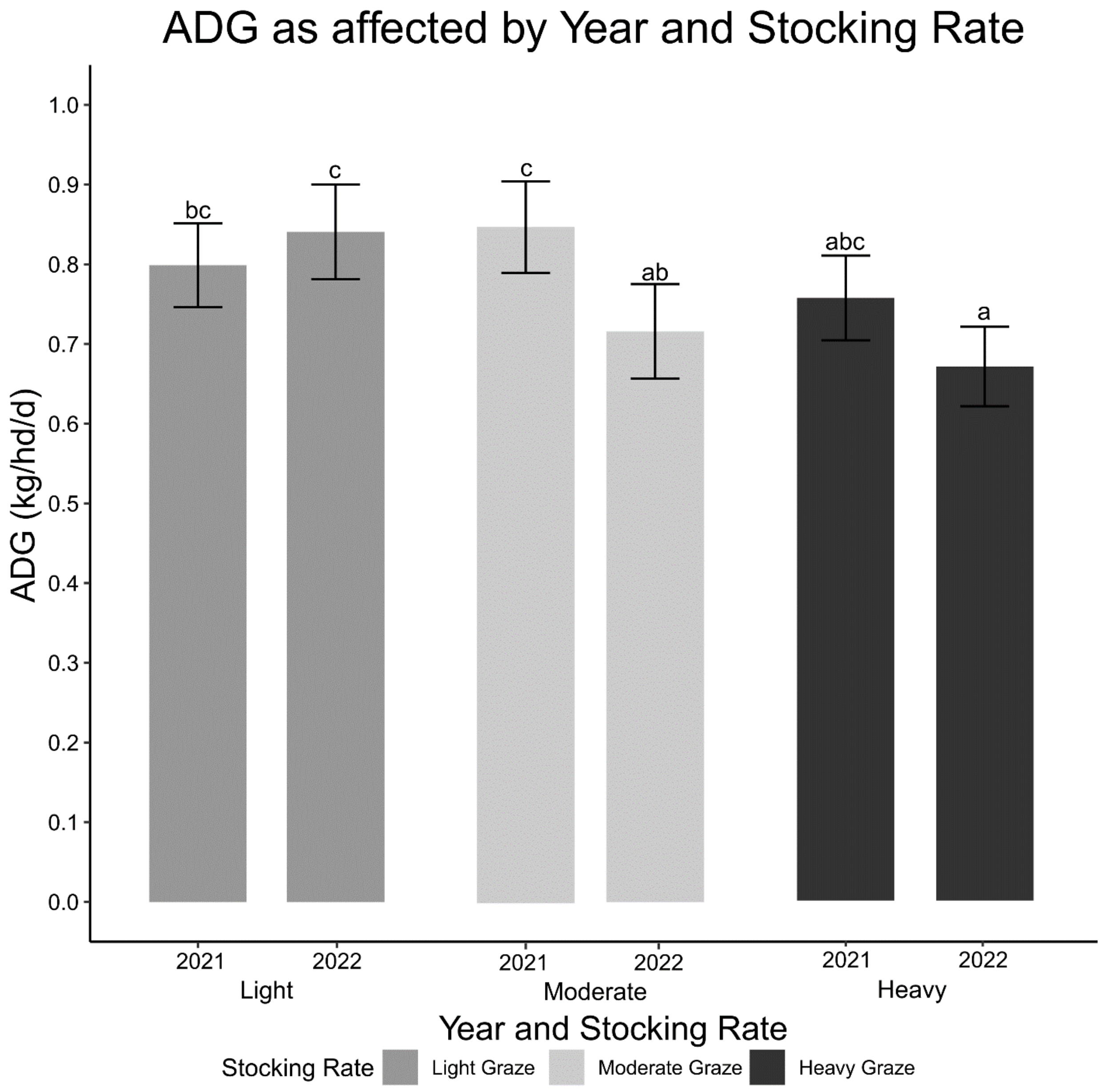

Figure 2.6. ADG (kg/hd/d) for steers by stocking rate (light, moderate, heavy)and year.

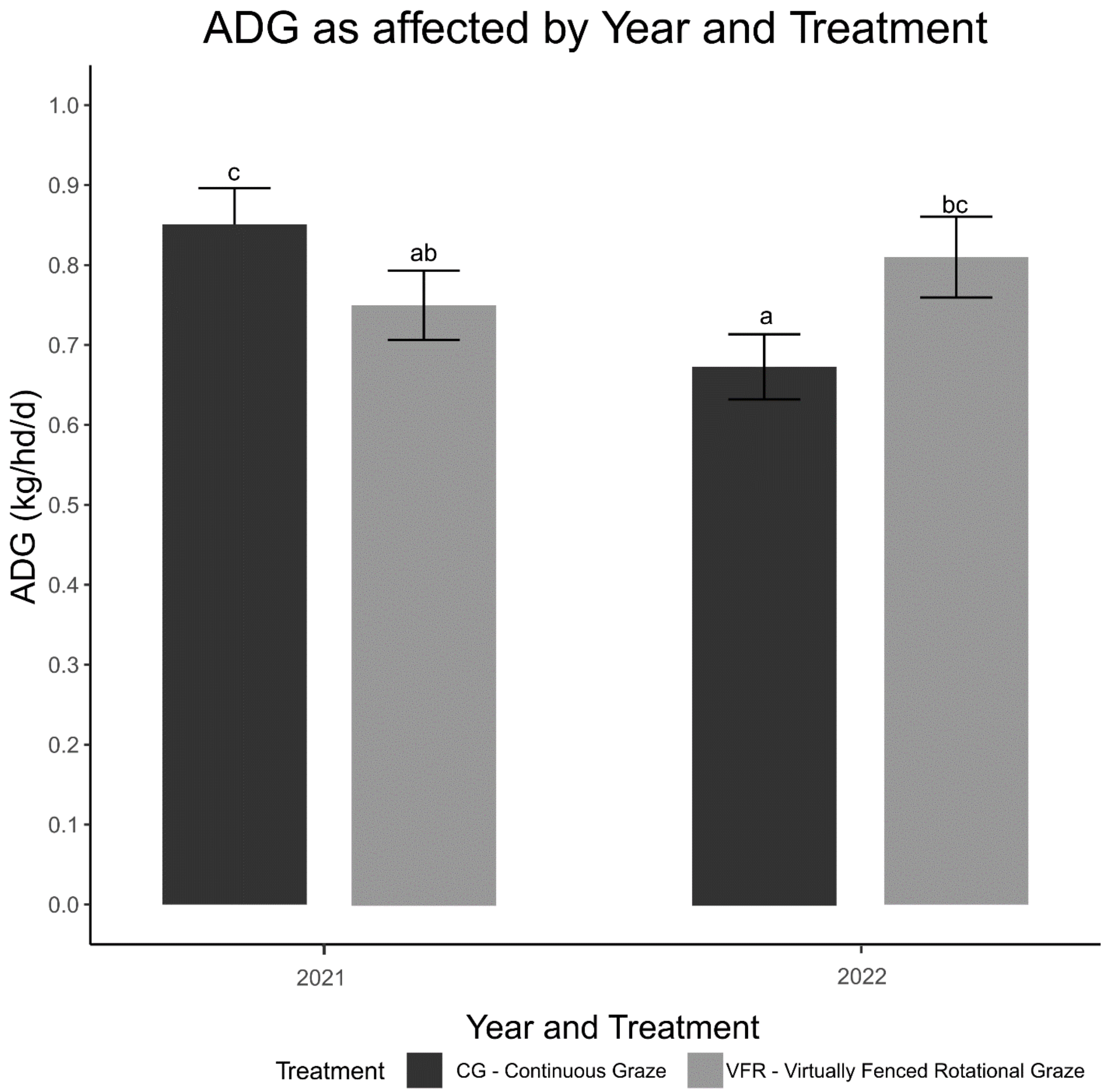

Figure 2.7. ADG (kg/hd/d) by treatment (CG, VFR) and year.

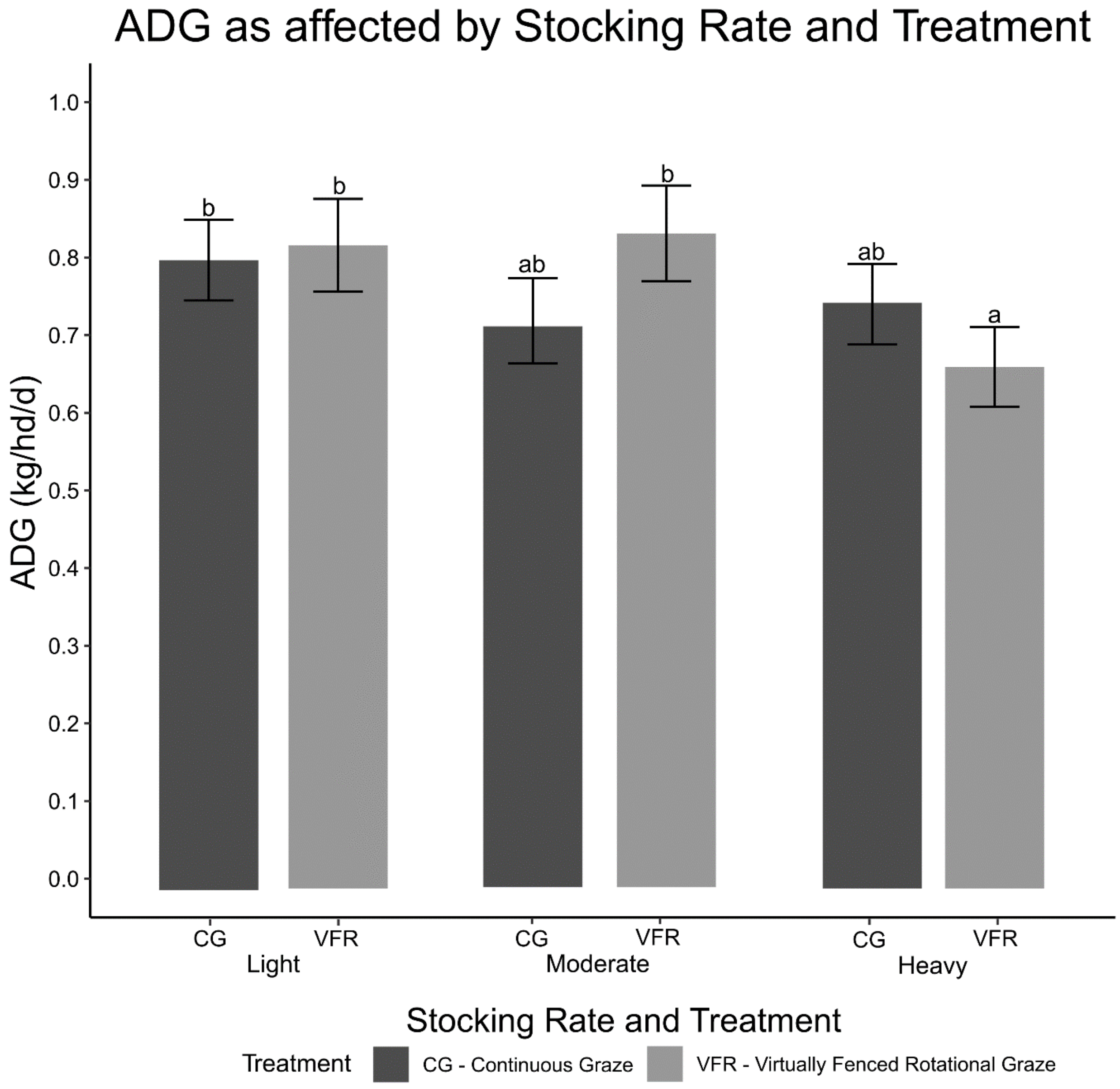

Figure 2.8. ADG (kg/hd/d) by stocking rate (light, moderate, heavy) and treatment (CG, VFR).

CHAPTER 3. PROPOSAL TO CALCULATE INDIVIDUAL ANIMAL NET ENERGY FOR ACTIVITY COSTS IN BEEF CATTLE ON EXTENSIVE RANGELANDS WITH PRECISION TECHNOLOGY

ABSTRACT

Beef cattle production is largely dependent upon rangelands for cattle to convert unusable plant-based fiber in the form of forage into an animal-based protein source for human consumption. Solutions are needed to meet both the growing demand for animal-based protein products by a growing world population and the desire for managers to produce energetically efficient cattle. Previous research has largely focused on increasing cattle efficiency within confined systems; however, there is little research focused on rangeland cattle. We created a precision systems model (PSM) to account for net energy for activity of beef cattle on extensive rangeland systems using daily weights, GPS data, and virtual fencing (VF) technology. Our results indicate a relationship of stocking rate and net energy for activity, with cattle in high stocking rate pastures expending less energy than those in light stocking rate pastures. There may be potential benefits of high stocking rates in continuous grazing systems, resulting in less energetic expenditure. Producers and managers could take energetic expenditure (EE) into account to increase their sustainability and efficiency of beef cattle production within the Northern Great Plains (NGP).

INTRODUCTION

Beef cattle production in the western United States is largely dependent on rangelands. Cattle operating within these systems often need to spend more time and energy traversing extensive landscapes to reach daily nutritive requirements through forage consumption. Animal behavior varies among each individual within a herd; however, research has shown cattle will on average travel approximately 7 km per day (Walker et al., 1985; Sprinkle et al., 2019). Additionally, cattle will graze approximately 7-9 hours a day to meet dietary needs (Aharoni et al., 2009; Quirino et al., 2022) and rest approximately 11 hours a day (Quirino et al., 2022). Numerous factors can influence livestock grazing distribution (e.g., distance to water). Topography can play an important role in the daily movements and behavior of grazing cattle. Previous research indicates some cattle breeds are more likely to graze and travel to areas with steeper slopes (Bailey and Welling, 2007). However, livestock behavior can be modified through placement of lick tubs and water resulting in the increase of pasture use efficiency (Bailey and Jensen, 2008).

All these behaviors ultimately result in varying expenditures of energy not only between individual animals but also daily variations from the same animal. The daily EE of beef cattle can be categorized into two categories, a NEm requirement and NEm required for activity, NEmr_act (Petersen et al., 2014). NEm is a measure of the amount of energy that an animal needs to maintain its body weight, body temperature, and other basal metabolic functions while at rest (heat and cold stress). NEmr_act, is the amount of energy that an animal needs to expend to capture resources through daily travel to food, water, and shelter across the landscape. Animal energetics has largely focused on animals in confined systems such as feedlots or pens in dry lots for beef and dairy cattle. Consequently, rangeland cattle energetics are lesser known than those in confined systems. Limited data are available regarding efficiency of metabolizable energy use for muscular work; however, cattle grazing on extensive systems likely expend more energy than animals in confined systems (Caton and Olson, 2016) due to the difference in daily distance traveled (DDT). This can influence animal performance as some animals are acclimatized or at a higher fitness level than others within a herd (Caton and Olson, 2016). There are unique challenges to determining EE for animals grazing on extensive rangeland systems largely due to environmental factors such as location relative to the thermal neutral zone and variations in topography (Osuji, 1974).

Technological advancements in agriculture allow the opportunity to apply precision technology in rangeland cattle production systems (Bailey et al., 2021). The implementation of radio frequency identification (RFID) tags, daily weight collection, and GPS collars on cattle in extensive pasture-based systems can provide a higher granularity of data that can be used to quantify animal energetics. Previously, researchers have tried to determine animal performance on rangelands. However, this has resulted in challenges from technology failures, costs of measuring individual animals at the herd level, or behavior misclassification (Walker et al., 1985; Ungar et al., 2005; Ungar et al., 2018). As these technologies become more widely adopted for livestock production, there are opportunities to utilize the resulting big datasets to improve animal efficiency.

EE of grazing and walking was evaluated by Fox et al. (1988) and later adapted in the NRC (1996) to account for activity cost based on forage quality and quantity. Recent work by Tedeschi and Fox (2020) have proposed an equation to quantify NEm_act based on animal movement metrics such as distance traveled on flat or ascending terrain, body weight, and time spent resting. Although the model has been used to estimate EE at the herd level, no study has sought to incorporate weight and movement data to quantify NEm_act at the individual level and to estimate daily variations among individual animals within a herd . Thus, the objectives of this study were to 1) develop a precision system model (PSM) that calculates daily NEmr_act for individual animals using GPS tracking collars and daily pasture weights, and 2) determine the impact of a virtually fenced rotational (VFR) grazing system versus a continuous system on NEmr_act expenditure. We hypothesized that 1) cattle within the VFR will have slightly elevated levels of daily NEmr_act than those that are in a continuous grazing system due to the increased walking behavior associated with the epoch of each new rotation.

MATERIALS AND METHODS

Institutional Animal Care and Use Approval

The animal care and handling procedures used in this study were approved by the South Dakota State University (SDSU) Animal Care and Use Committee (Approval Number: 2104-021E).

Study Area

This experiment was conducted at the SDSU Cottonwood Field Station (CFS), located in western South Dakota. The trial period was conducted over two summer grazing seasons from May to August in 2021 and 2022. The CFS is located within a mixed grass prairie ecosystem and is composed primarily of native C3 green needlegrass (*Nassella viridula* Trin.) and western wheatgrass (*Pascopyrum smithii* Rydb.) and C4 blue gramma *Bouteloua gracilis* Willd. Ex Kunth, buffalograss (*Bouteloua dactyloides*

Nutt.), and needle-and-thread (*Hesperostipa Comata* Trin. & Rupr) grasses with the inclusion of sedges (*Carex* spp.) There are also recent introductions of non-native grasses, such as Kentucky bluegrass (*Poa pratensis* Boivin & Love) and Japanese brome (*Bromus japonicus* Thunb.). Soil in the study area is predominately Kyle clay and Pierre clay (NRCS, 2022). The topography is gently sloping with rolling hills and relatively flat-topped ridges with a peak elevation of 784 m and a low of 710 m. The climate is semi-arid with hot summers and cold winters; annual precipitation for 2021 and 2022 was 278 mm and 267 mm, respectively (South Dakota Climate and Weather, 2023).

A long-term grazing study implemented in 1942 has been conducted at the CFS on six pastures ranging in size from 31 to 73 ha (Dunn et al., 2010). The long-term experimental design has been a randomized complete block with three levels of grazing intensity in two replicate blocks. When the study was initiated, pasture boundaries were situated to uniformly allocate topographic features (hills, draws, ecological sites) across all treatments. Pastures have been stocked with yearling steers to maintain pasture treatments with different stocking rates: light, moderate, and heavy. The long-term application of light, moderate, and heavy stocking rates has created three distinct plant communities found within NGP rangelands. Lightly grazed pastures consist of diverse plant communities predominantly western wheatgrass *Pascopyrum smithii* Rydb. and green needlegrass (*Nassella viridula* Trin.), while heavily grazed pastures are dominated by buffalograss (*Bouteloua dactyloides* Nutt.) and blue grama (*Bouteloua gracilis* Willd. Ex Kunth.). The moderately grazed pastures have an intermediate plant community, consisting largely of native species found in the NGP.

Grazing Management Treatments

Yearling steers in 2021 and 2022 were allocated into two treatment groups. The groups were a continuous grazing treatment (CG) and a VFR treatment. VFR steers were managed in a rotational grazing system using Vence^{TM} collars. Primarily cross-bred black angus yearling steers (n=127 and n = 135, in 2021 and 2022, respectively) were sorted into pastures based on initial body weight ranging from 256 to 444 kg. Each pasture was grazed separately by yearling steers at stocking rates comparable to the long-term grazing study (Dunn et al., 2010). Steers within CG had free access to the entire pasture for the duration of the grazing season. Steers within the VFR treatment were rotated among virtual 'paddocks' within the pastures for the duration of the grazing season. Across both grazing management scenarios, VF collars were used to track all animal locations at 5-minute intervals; only animals within the VFR were managed with virtual fence boundaries and auditory and shock enabled collars. The days spent in each paddock for the VFR treatment were determined based on bi-weekly clip plots for biomass estimation. The number of days in these paddocks were calculated using the SDSU Extension Grazing Calculator (Ehlert and Brennan, 2021). Three stocking rates were used and replicated for both treatment groups, CG and VFR; the light stocking rate was 0.32 AUM/ac, the moderate stocking rate was at 0.40 AUM/ac, and the heavy stocking rate at 0.72 AUM/ac (Dunn et al., 2010). Our experimental design was a randomized complete block design for the pastures, while the treatment design was a 2 x 3 factorial design.

Weight Data Collection and Processing

Average daily gains (ADG) were estimated using C-Lock Inc. (Rapid City, SD) SmartScales^{TM}. SmartScales^{TM} were placed in each of the pastures at the location of the stock tanks. Yearling steer weights were downloaded from C-Lock^{TM} through an application programming interface (API) that processed weights at the individual animal level and created a 3-day rolling average for daily weights to minimize variations in rumen fill and number of trips taken to the scale. ADG was calculated using a linear model to develop a regression equation for each individual animal with weight as the dependent variable and day of trial as the independent variable. The slope of the regression line was used for the ADG estimate.

Algorithm Development

The basis for this analysis was modified from an existing energetic calculation for determining NEmr_act (Tedeschi and Fox, 2020). The equation was developed from previously conducted research trials and empirically derived coefficients were assigned to the variables (Equation 1). The model was defined at the herd level as follows: NEmr_act expenditure was calculated by determining the average slope of the pasture, average daily distance traveled DDT, value varies based on management system i.e., confinement barn, conventional barn, dry lot, intensive grazing, continuous grazing), average weight, and average number of hours spent resting per day.

$$NEmr\_act = \frac{\begin{pmatrix} 0.1 * resting\ time + 0.062 * number\ of\ state\ changes + 0.621 \\ * km\ flat\ travel + 6.69 * km\ ascending\ travel \end{pmatrix} * FBW}{1000}$$

Equation 1. Equation that was developed to calculate Nemr_act costs of beef cattle on rangelands. Where NEmr_act is Mcals expended per day, resting time is reported in hours per day, number of state changes was held constant at 6 (based on the original equation), km flat travel was reported as DDT where elevation change between successive GPS points was less than 1 meter of elevation difference, km ascending travel was reported as DDT where elevation change between successive GPS points was greater than 1 meter of elevation difference (km ascending travel derived in equation 2).

The development of the algorithm used in the current study accounted for daily variations in individual animal behavior and weight that are not captured with the herd level model. Daily weights were estimated from SmartScales^{TM}, as described above. GPS enabled collars from Vence^{TM} were used to estimate DDT at the individual level. The coupling of these two precision technologies led to the development of a precision-informed model for calculating NEmr_act, hereafter referred to as the precision energetics model.

Step 1 of developing the precision model was classifying GPS data into three behaviors: grazing, resting, and walking based on rate of travel (Derner and Augustine, 2013). The total resting time for each day was calculated and used as the variable “resting time” in the equation. Step 2 was to partition DDT for an individual animal into flat or ascending travel. For each GPS point, a digital elevation map (DEM), sourced through the USDA (2023) and at a resolution of 10 m, was used to extract elevation data (m). Travel between successive fixes that were less than 1 m of elevation difference were defined as km traveled flat; elevation differences greater than 1 m were classified as km ascending travel. Movement data classified as km traveled flat was summed to estimate total daily km travel distance on flat terrain. For GPS points classified as km ascending travel, distance was calculated by Equation 2, based on the equation provided by Tedeschi and Fox (2020). This process resulted in both ascending and flat DDT for each steer over the grazing season.

$$km\ ascending\ travel = \frac{\left(ascending_{distance\_a} - ascending_{distance\_b}\right) * \cos\left(inclination * \frac{pi}{180}\right)}{\sin\left(inclination * \frac{pi}{180}\right)}$$

Equation 2. Km ascending travel was calculated as the elevation difference between point a and point b, Inclination was calculated as the inverse tangent of the slope fraction of the pasture multiplied by 57.32.

The model also accounted for the number of position changes per day; this value is the number of times an animal changed behaviors throughout the day (i.e., resting then walking). In our model we used 6 as the number of position changes per day, based on the value in Tedeschi and Fox (2020), which allowed us to hold one variable constant with the original equation. The last variable in the equation is full body weight (kg). Daily weights were collected using SmartScales^{TM}. These weights were recorded in pounds and converted to kilograms. Weights were calculated as three-day rolling averages and missing weight data points were linearly interpolated between two known values.

Statistical Analysis

The difference in NEm_act between grazing treatments and stocking rate was analyzed using a linear mixed effects model analysis of variance (ANOVA). The fixed effects were stocking rate, treatment, and year with individual animals as a random effect ($p < 0.05$).

RESULTS

There was a significant three-way interaction of stocking rate by treatment by year for NEmr_act (stocking rate x treatment x year, $P < 0.01$, Table 1). Steers in 2021 spent 1.92 Mcals per day while those in 2022 spent 1.53 Mcals per day, resulting in a 0.4 Mcal difference between years. There was a trend for Mcals expenditure to decrease as stocking rate increased. Steers in the heavy stocking rate spent 1.66 Mcals per day while animals in the light stocking rate spent the most, 1.89 Mcals. Steers in a moderate stocking rate had an intermediate NEmr_act at 1.75 Mcals per day (Figure 3.1). Within stocking rates and treatment groups we witnessed variations among individuals within the herds, indicated by individual dots in Figure 3.1. Animals within the VFR and light stocking rate had a range of 3.2 to 1.2 Mcals on average per day, with observed differences among animals on the same days.

DISCUSSION

The results calculated from the PSM for Nemr_act is within the bounds of livestock physiology. Previous findings suggest that EE cost of grazing is approximately 1.46e-6 Mcals/(kg of BW0.75 · m), and locomotion while grazing is 1.45e-6 Mcals/(kg of BW0.75 · m) (Brosh et al., 2006). A simple example calculation with an animal that weighs 300 kg and walks 6 km per day would equate to approximately 1.98 Mcals expended, which is near our values from the PSM. The EE in our model is realistic based on the amount of forage that an animal would need to consume to offset the increased NEmr_act. In addition, the daily EE for activity in animals in small grazing allotments has been found to be approximately 1.4 Mcals per day (Tedeschi and Fox, 2020).

Previous research has shown that grazing management strategy does not impact energetic differences in yearling steers (Jorns et al., 2022). However, our results indicate that stocking rate and treatment may influence EE. Pedometers have been used to calculate DDT and relate that to EE for rangeland cattle (Anderson and Urquhart 1986; Walker and Heitschmidt, 1989; Umemura, 2013). The use of GPS to calculate DDT may be underestimated due to “meandering” movement behavior not captured between points

(McGavin et al., 2018). Walker et al. (1989) used calibrated pedometers attached to the metacarpus of the foreleg and found that short duration grazing animals traveled significantly more than continuous grazing animals. One benefit to using pedometers is that they may more accurately represent distance traveled versus GPS fixes, which could potentially underestimate the daily distance traveled; however, pedometers fail to account for changes in elevation (Jorns et al., 2022). With GPS technology we can capture the exact location of an animal within a pasture and calculate the elevation changes associated with travel based on DEM, resulting in a more accurate calculation of NEmr_act. A possible reason for differing EE values of grazing cattle in our study could be the accounting for topography when estimating EE (Osuji et al., 1974; Brosh et al., 2006; Tedeschi and Fox, 2020; Jorns et al., 2022).

Pedometers also fail to accurately measure DDT due to several variables. Animal step length can vary based on frame size, genetics, and gait; unless each individual animal is measured for stride length there is an assumption that a subsample of animals is representative of the herd. This could result in an artificial inflation or decrease in DDT estimates. GPS sampling intervals are crucial to accurately capture DDT of grazing cattle. Large bouts between GPS intervals increase the likelihood of underestimating the true distance traveled. GPS and pedometers in tandem result in the most accurate classification of grazing, resting, and walking time (Ungar et al., 2010); the combination of technologies such as GPS, pedometers, and accelerometers may provide a more accurate classification of movement behaviors across elevation gradients and subsequently Nemr_act.

Individual animal body weight may be an important factor for calculating Nemr_act. Higher animal weight also results in higher Nemr_act. For example, an animal that weighs 317 kg with an ADG of 0.67 kg will expend 2.91 Mcals on average over the course of the summer; while an animal that weighs 408 kg (+91 kg) expends 3.73 Mcals per day in our model if resting and DDT are held constant at 13.2 hrs and 6.02 km, respectively. The only variable in this example that changed was the full body weight (FBW) of an animal; this result matches our understanding of how body size influences energetic costs. Future modeling work should emphasize which variables (e.g., FBW, DDT, elevation changes) most influence Nemr_act costs for grazing animals.

Other factors such as weather can also influence animal energetics. The addition of climate data may also help quantify EE of beef cattle in extensive systems. For example, extremely high temperatures result in heat stress, a factor known to increase energetic costs to regulate body temperature and maintain normal bodily functions (NRC 8th edition). Temperature and humidity index (THI) was used in previous research to determine what effect weather had on livestock energetics (Stegemiller et al., 2021). THI considers both temperature and humidity resulting in a numeric value that measures the discomfort experienced by individuals in warmer weather (NWS, 2023). Higher temperatures, and subsequent heat load on animals, may influence dry matter intake and DDT due to increased resting time or increased time loafing near water (Allen et al., 2013). This would likely result in days that are lower in NEmr_act costs, however this could still come at a cost of increased NEmr to regulate body temperature.

A second factor that can influence NEmr_act costs is genetics on both an individual and herd level. Some animal breeds may travel further from water and climb steeper gradients to forage (Bailey et al., 2015). EE could vary based on animal genetics and the location in which the cattle are grazing. Previous research has found that certain animals within a herd may utilize areas with greater elevation changes than others (Roath and Kreuger, 1982). Animals that travel more ascending/descending distance will likely increase grazing distribution within pastures, but potentially at a higher NEmr_act (Bailey et al., 2015).

The development of the original equation was designed with empirically derived values, including the number of position changes. This variable was not assessed in our model and was derived from cattle in confined systems. If the number of position changes were to increase from 6 to 24 (+ 400%) in Equation 1, NEmr_act increases by approximately 18% (+0.86 Mcals/day). Further, rangeland cattle frequently switch from grazing, walking, resting, and standing multiple times per day. Future analysis should seek to quantify what constitutes a state change in behavior for rangeland cattle.

In conclusion new technology such as VF and pasture-based weighing systems can be used to calculate NEmr_act. As VF scales across the United States the potential to assess big data with models like our PEM opens a new avenue for research and management. This would allow researchers to include other variables such as genetics for creating energetic models for extensive rangeland systems.

MANAGEMENT IMPLICATIONS

While the savings of 0.3 Mcals per day, observed difference in stocking rate, per animal may seem trivial, it has large implications for cattle production. In South Dakota, there are approximately 3,550,000 cattle raised each year (USDA, 2023) and nearly 23 million raised on rangelands within the NGP (Briske et al., 2017). A savings of 0.3 Mcals on 23 million head of cattle for a grazing period of approximately 5 months equates to approximately 1 billion Mcals. Ultimately the adoption of precision agricultural technology could provide the ability for producers to marginally improve beef cattle production efficiency.

One potential application for this algorithm is to determine which individuals within a herd are more energy efficient. Daily Nemr_act estimates coupled with genetic data may be used to identify cattle that are more efficient within a specific ecoregion. Genetics also creates variation in animals and their performance; this variation is not independent of location. The analysis conducted for this trial had an average slope below 6% with a max elevation difference of 74 m. Cattle grazing extensive rangelands within the intermountain west with greater variations in both topography and slope will likely impact energetics to a greater extent. As the rate of precision technology and virtual fencing is adopted, applications of the algorithm developed in this study may be used to quantify these differences at larger landscape scales across western rangelands.

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TABLES AND FIGURES

Table 3.1. Estimation of net energy for maintenance for activity (NEmr_act) in Megacals (Mcals) based on the PSM model created. Letters in Group indicate mean separations. SE is the standard error of the reported mean value.

Mcals Spent Per Day

Year	Treatment	Stocking Rate	Mcals/day	SE	Group
2021	VFR	Light	1.90	0.04	def
		Moderate	1.96	0.05	ef
		Heavy	1.83	0.05	cde
	CG	Light	2.05	0.04	f
		Moderate	2.00	0.04	ef
		Heavy	1.72	0.04	cd
2022	VFR	Light	1.79	0.05	cde
		Moderate	1.61	0.07	bc
		Heavy	1.46	0.05	ab
	CG	Light	1.64	0.06	bc
		Moderate	1.28	0.05	a
		Heavy	1.43	0.06	ab

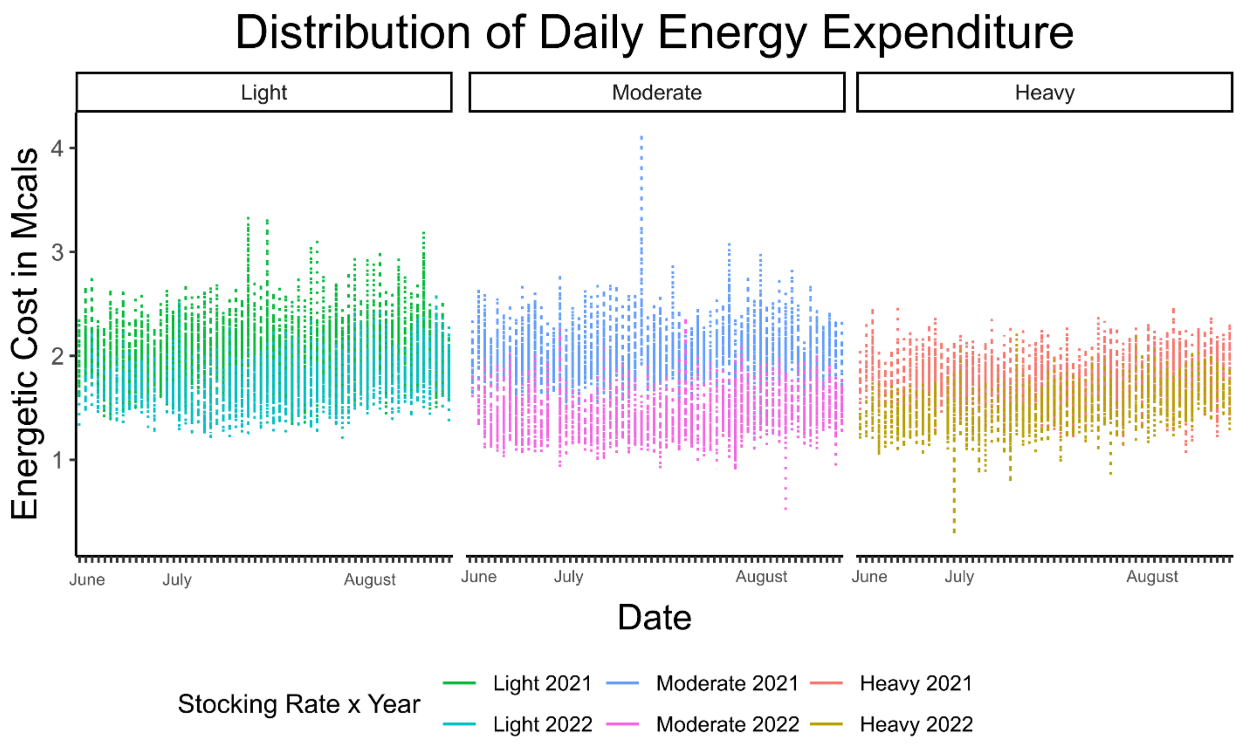

Figure 3.1. Daily net energy for activity (NEmr_act) in Mcals over a two-year period, with data presented for three different stocking rates (light, moderate, heavy).

CHAPTER 4. MANAGEMENT IMPLICATIONS OF VIRTUAL FENCING

Based on our results, we fail to accept three of our three hypotheses; we reject that 1) there are differences between DDT, grazing time, resting time, and walking time based on treatment group, 2) ADG was not significantly influenced by VF technology, 3) VF technology did not significantly impact NEmr_act expenditure. Our first hypothesis could partially be accepted since there was an increase in walking time per day depending on treatment group, with VFR yearlings having a slightly elevated level. While this finding is not statistically significant, it may be biologically significant. This is based on the lack of observed differences in treatment group from the precision system model of NEmr_act expenditure. Our findings would suggest that VF technology is a viable alternative to traditional fencing methods. While we reject our hypotheses that there would be differences between treatment groups, the lack of observed differences results in meaningful findings that provide promise of this technology for wide scale producer adoption.

Labor, cost, and infrastructure are the primary limitations to implementing management intensive grazing systems. The primary consideration to make when implementing precision technologies is does it maintain or improve beef cattle production? Our findings would indicate that there is minimal impact on animal behavior, with an elevated response in walking time per day. With marginal modifications in animal behavior, VF would be a viable option for producers to adopt given the right circumstances. The increasing pressure from consumers and land management agencies to manage rangelands to improve ecosystem services and land management objectives makes traditional fencing difficult to obtain these objectives. VF can serve as a cost effective and labor efficient option to achieve desired management goals.

VF technology could improve regulating, supporting, cultural, and provisioning ecosystem services. For example, removal of interior fences on public lands could improve wildlife habitat by reducing barriers to wildlife migration (regulating), while improving recreation experiences (cultural). This technology could also be used to achieve specific management objectives that were traditionally labor intensive with other tools i.e., creating blowouts in the Nebraska Sandhills with VF as opposed to salt/mineral blocks. Blowouts are depressions on the top of sand dunes that can offer various ecosystem functions. Other potential applications include the ability to easily direct livestock movement under wildfire conditions and controlling water access to livestock without the use of poly wire, e.g., protecting riparian areas.

Government agencies such as the United States Forest Service and Bureau of Land Management (BLM) are in the planning process of what VF could provide for producers that have leases on federal or state land. Proving the efficacy of this technology, evaluating the impact on the animal, communicating the benefits and challenges to producers, and increasing cattle production is of interest to both producers and government agencies.

Though the Vence™ system utilizes fixed base stations, mobile base stations could potentially increase applications of this technology by providing even greater flexibility. This would aid in livestock management in privately owned leased land where the investment of physical infrastructure isn't economically feasible or limited by the permittee. Portability of base stations could open opportunities for individuals to implement custom grazing operations. Individuals or eventually companies could offer targeted, adaptive multi-paddock, and crop-livestock grazing services with a low barrier to entry cost compared to owning and maintaining a livestock operation. VF isn't the only technology that could revolutionize rangeland beef cattle production.

SmartScales^{TM} and VF technology may serve as a cost-effective option for researchers to collect large amounts of data that is needed to develop and inform nutrition models for rangeland cattle. The benefit of creating models specifically for cattle on extensive rangelands would directly benefit producers in increasing the viability of their operations. This increase in information is only beneficial if there is a way for producers to manage and interpret large amounts of data being collected.

This leads us to a need of data management and model creation for rangeland nutrition models. Ultimately, the use of precision technologies can inform nutrition models to allow producers to select for more efficient animals out on rangelands. Our ability to increase the efficiency of beef cattle production on rangelands will come from marginal improvements as a result of precision technology.