An Examination of Virtual Fencing as a Tool to Manage Beef Heifers and Cow-calf Pairs in Western Canada

by

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Abstract

This study encompasses the evaluation of Nofence virtual fencing (VF) technology for managing grazing cattle in western Canada, addressing both technical performance and animal behavior. Two key investigations were conducted: one focusing on the technical efficacy of VF collars during summer and winter conditions in a northern temperate climate, and the other exploring cattle behavior and learning within VF rotational grazing systems. Key metrics of the technical performance study included network connectivity, collar failures, and battery and solar charging performance. The findings indicated robust network connectivity with mean connection intervals well within the expected limits and minimal connectivity issues. Collar failures were infrequent, primarily due to network connection problems and physical loss. Battery performance remained strong, maintaining high charge levels even during winter with limited daylight. These results highlight VF's potential to reduce fencing costs and enhance grazing management in western Canadian environments, provided reliable cellular network access. The second study examined the training and compliance of heifers and first-calf cows with VF technology during rotational grazing. Heifers learned to comply with VF boundaries within 5-7 days, with a mean ratio of electrical stimuli to audio cues (E:A) of 17.9% (±18.4) during training decreasing to 5.2% (±11.2) during rotational grazing. Cows with calves at side, previously experienced with VF, received an E:A ratio of less than 2.5% during re-training and rotational grazing. All animals were successfully contained by VF boundaries more than 99% of the time. No significant associations were present between the number of VF stimuli, and animal characteristics and performance. Grazing pressure and stocking rate influenced the number of VF stimuli received and the duration of audio cues. The study concludes that VF technology effectively manages rotational grazing, with cattle demonstrating learning and compliance to VF boundaries. Further research is needed to explore the effects of higher stocking rates, grazing pressure, and intrinsic animal characteristics. Combined, these studies demonstrate the technical viability of VF technology during summer and winter in western Canada and its effectiveness in

managing cattle behavior and grazing patterns. VF technology offers significant benefits for cost reduction, management flexibility, and sustainable use of rangelands in the Canadian beef industry, contingent on adequate network connectivity and thoughtful implementation.

Preface

This thesis is an original work by Alexandra Harland. The research project, of which this thesis is a part, received research ethics approval from the Animal Care Committee at the University of Alberta (Animal Use Protocols #3850 and #4004) and the College Animal Care Committee at Lakeland College (SwatheGrazingRES – 09 – 21).

Dedication

I would like to dedicate this thesis to the educators, mentors, and program administrators in the Department of Agriculture, Food, and Nutritional Science at the University of Alberta, who selflessly give their time, attention, guidance, and support to all the students who walk through their halls. You make such an impact on so many lives – thank you.

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List of Abbreviations

Abbreviation	Definition
AC	audio cue
ACIS	Alberta Climate Information Service
ADG	average daily gain
AMP	adaptive, multi-paddock grazing
ANPP	annual net primary production
AUM	animal unit month
AUP	animal use protocol
BC_{angus}	breed composition (angus)
CCAC	Canadian Council on Animal Care
CRTC	Canadian Radio-television and Telecommunications Commission
cV	centivolt(s)
dB	decibel(s)
DMI	dry matter intake
E:A	electrical shock to audio cue (ratio)
ECCC	Environment and Climate Change Canada
ES	electrical shock
EWT	estimated bodyweight
g	gram(s)
GLMM	generalized linear mixed model
GLONASS	Global Navigation Satellite System, a Russian satellite navigation system
GNSS	global navigation satellite system, a satellite navigation system with global coverage
GPS	Global Positioning System, an American satellite-based radio navigation system
ha	hectare(s)
HILF	high intensity, low-frequency grazing
hr	hour(s)
HS	high stimuli
IRR	incident rate ratio
IZF	inclusion zone frequency

J	joule(s)
KC	Kinsella Composite
kg	kilogram(s)
km	kilometre(s)
KRR	Kinsella Research Ranch
kV	kilovolt(s)
LS	low stimuli
Ltd	Limited
m	metre(s)
mA	Milliamp(s)
min	minute(s)
MS	moderate stimuli
n.d.	no date
NCI	network connection interval
no	number
NRCC	National Research Council Canada
◦C	degrees Celcius
p	probability value
R^2	coefficient of determination
RD	rib fat depth
RFI_{fat}	residual feet intake, adjusted for backfat thickness
SD	standard deviation
SDG	short duration grazing
SE	standard error
sec	second(s)
SEM	standard error of the mean
VF	virtual fencing
X^2	chi squared statistic

Chapter 1: Introduction and Literature Review

1.1. Beef Cattle Production in Western Canada

Grazing cattle play an integral role in the western Canadian economy. Beef cattle production contributed $13.5 billion in farm cash receipts in 2023, of which the province of Alberta in western Canada accounted for $8.2 billion (Statistics Canada 2024b). As of January 1, 2024, Alberta alone has 4.6 million beef cattle, 58% of which are on cow-calf operations (Statistics Canada 2024a). Eighty percent of Canadian beef cattle producers practice some form of grazing, and of those operations a further 80% have cow-calf pairs (Sheppard et al. 2015).

Grazing practices are diverse in terms of timing and frequency of livestock exposure to pasture, stocking rates, and management goals, which affect livestock performance and profit. Rotational grazing, defined as a grazing method that utilizes recurring periods of grazing and rest among three or more paddocks throughout a grazing season (Allen et al. 2011), is practiced by up to 57% of beef cattle operations in Alberta (Pyle et al. 2018) and 78% of cow-calf producers across the Canadian prairies (Chorney and Josephson 2000). Livestock exposure to pasture during rotational grazing can vary from grazing period durations as short as one day to as long as several months, with a few weeks being the most common duration (Teague et al. 2013).

Stocking rate, defined as the number of animals in a grazing area over a period of time (Allen et al. 2011), is used to describe the intensity of pasture use by livestock. Stocking rate is often discussed as being high, moderate, or light in intensity, and the definitions of these characterizations vary across range types with differences in precipitation, native vegetation, and herbage productivity (Holechek 1988). As such, stocking rates are generally defined by the impact the cattle have on the existing vegetation. A high stocking rate, i.e., heavy grazing, results in a degree of herbage utilization that causes a reduction in desirable forage species, a moderate stocking rate results in a degree of utilization that neither reduces nor allows for the increase of desirable species, and light stocking results in utilization that allows desirable species to maximize their herbage production (Holechek et al. 1999). Stocking rate directly impacts pasture productivity, such that a decrease from heavy to moderate stocking rates has been reported to result in a 35% increase in herbage production (Van Poollen and Lacey 1979). Implementation of stocking rates varies across beef cattle operations, for example, Alberta beef producers reported stocking rates from 1.5 to as high as 4.2 AUM ha^{-1} (Bao et al. 2019). Bao et al. (2019) and Pyle et al. (2018) report that stocking rates are more likely to be higher in areas with cooler temperatures and higher precipitation, on producer-owned pastures rather than on grazing leases, on tame or previously cultivated pastures compared to native range, and on operations where supplemental feed was supplied at pasture

Livestock are often grazed in areas that are challenging to work in due to remoteness or rugged terrain, or are otherwise unsuitable for more profitable annual crop production due to difficult slope, limited precipitation, or soil that is not suitable for annual crops (Bailey et al. 2021). Herbage production in these areas may be limited, meaning that cattle are often widely distributed over the vast areas of land that are needed to support grazing ruminants. Mustering, herding, and the transportation of cattle at the beginning or end of a grazing season are necessary parts of the cow-calf production cycle but are difficult and expensive to carry out due to the remoteness, challenging terrain, and distribution of animals across large areas of land. In particular, mustering and herding is physically demanding work that is carried out, often on horseback, in difficult weather for days or weeks at a time (Butler et al. 2006; Bailey et al. 2021). Additionally, extensively raised livestock may also be exposed to threats such as variable access to food and water, extreme weather, predators, and disease, and remote or rugged conditions make it difficult or impossible to monitor livestock health and intervene (Temple and Manteca 2020; Bailey et al. 2021). Livestock distribution, movement, and monitoring challenges are currently labour intensive and expensive for beef producers to overcome; for example, some of the most remote areas will use helicopters for locating, herding, and performing health checks on livestock (Butler et al. 2006; Bailey et al. 2021).

1.2. Rangeland Sustainability and Grazing Management

Rangeland sustainability, a critical topic in environmental conservation and food production and security, is complicated by numerous and conflicting definitions of what rangelands are. In general, rangelands have been defined as land that is not used for growing crops, and on which the vegetation is primarily graminoids, forbs, or shrubs (Lund 2007), with some definitions further stipulating that the land is used as a natural ecosystem for the production of grazing livestock and wildlife (Allen et al. 2011). Rangelands provide vital goods and services including recreation and enjoyment, a way of life for rangeland-dependent communities, forage for domestic animals, wildlife habitat, water storage and filtration, and carbon sequestration (Maczko et al. 2004). These services are unique to grasslands and are not provided by annual croplands, due to the replacement of native species with cultivated forages and crops and the impacts of cultivation on soil and hydrological function (Pyle et al. 2021). The maintenance of rangeland soil and hydrologic function, plant resources, and productive capacity is crucial to sustain rangelands through challenges like drought and fire, build resilience to climate change, and protect other ecosystem services such as culture and recreation (Maczko et al. 2004; Döbert et al. 2021). In the face of our growing global population and the increasing concern about the appropriate use of rangelands, sustainable grazing practices are essential for ensuring industry and food security, safeguarding ecosystem functions, protecting biodiversity, and building resilience to a warming climate (Döbert et al. 2021).

Improper grazing strategies can negatively impact rangeland function by allowing for uneven utilization of pasture by cattle. In particular, over-utilization is one of the primary causes behind grassland degradation and desertification (Holechek et al. 1999; Geist and Lambin 2004; Mysterud 2006;

Pyle et al. 2021). High utilization of vegetation by grazing cattle can overwhelm the ability of plants to regrow and lead to a shift in or collapse of vegetation communities (van de Koppel et al. 1997). Over-grazing can result in reduced vegetation and litter cover, which degrades soil stability and function, decreases water infiltration and water holding capacity, and potentially causes a negative feedback loop where vegetation biomass and soil condition are both steadily decreasing (van de Koppel et al. 1997). Over-grazing can be present even when an appropriate number of herbivores are populating an area, through the repeated over-selection of palatable forage species, which can result in their overall decrease or disappearance (Teague and Dowhower 2003; Mysterud 2006). Additionally, concentrated livestock use of riparian areas and lowlands can lead to stream bank, fish habitat, and water quality degradation (Bailey et al. 2021). Finally, under-utilization and under-stocking may also have negative impacts on rangeland condition and function, allowing the ingress of woody weed species leading to shifts in biodiversity and ecosystem type, and contributing to an increased fire risk due to the accumulation of fine fuels (Stevens et al. 2021).

While the grazing of domestic cattle can have a negative impact on rangelands, historically grasslands have co-evolved with native herbivores experiencing periods of concentrated defoliation followed by periods of herbivore absence (Teague and Kreuter 2020). It follows that the appropriate application of domestic ruminants to rangeland can mitigate the negative effects of grazing livestock and maintain, or even improve, rangeland productivity and function (Asamoah et al. 2003). Appropriate management of grazing cattle can create a beneficial equilibrium between defoliation and plant growth, such that there is maintenance or improvement of plant diversity, the production of herbaceous biomass, wildlife habitat, litter cover, and hydrologic function of soil (Van Poollen and Lacey 1979; Pyle et al. 2021; Döbert et al. 2021). Additionally, it is possible to see an improvement of carbon sequestration in grasslands, particularly those that are degraded or have a history of cultivation (Teague and Kreuter 2020).

Stocking rate is one of the primary determinants of pasture utilization by cattle, and is therefore a crucial aspect of grazing management, productivity, and rangeland sustainability. Lighter stocking rates are better for rangeland condition and sustainability (Holechek et al. 1999; Teague and Dowhower 2003; Pyle et al. 2021), but under continuous grazing incur an opportunity cost and decrease income generation. Rotational grazing has shown the potential to maximize stocking rates and profit while minimizing negative environmental impacts (Teague and Kreuter 2020). Rotational grazing systems are often characterized by a higher stocking rate applied for short grazing durations, generally from one to ten days; specific systems are numerous, including AMP, high intensity low frequency (HILF), holistic, short duration (SDG), time-controlled, and cell grazing (di Virgilio et al. 2019). For example, AMP grazing uses multiple paddocks to graze herds of cattle, utilizes high stocking rates for short amounts of time, ensures there is sufficient post-defoliation plant left to recover, and that long periods of rest allow for sufficient vegetation recovery (Teague and Kreuter 2020; Bork et al. 2021). Rotational grazing affords producers a high degree of control over where, when, and for how long their livestock graze, however, it requires more infrastructure, time, and labour than less intensive grazing strategies.

Perspectives on the usefulness of rotational grazing as a strategy to improve rangeland sustainability vary – some research has reported little or no differences between rotational and continuous grazing (Holechek et al. 1999; Briske et al. 2008, 2013), but others have provided evidence of the benefits associated with rotational grazing (Teague et al. 2011; McDonald et al. 2019; Hillenbrand et al. 2019; Döbert et al. 2021). Criticisms of research denying any benefit of rotational grazing point out that grazing systems were often confounded by stocking rate in the experimental design, and that the chosen rotational grazing methods were not adaptive processes, and therefore are not representative of the application of rotational grazing (Teague et al. 2013; Bork et al. 2021). Reported benefits of rotational grazing include a more uniform relative use of plant communities, enhancement of ground cover, increased animal production, an improvement in water infiltration in grassland soils, and an improvement in the presence of desirable forage species (Asamoah et al. 2003; Teague et al. 2011; Hillenbrand et al. 2019; Bork et al. 2021).

Management decisions such as pasture utilization, stocking rate, and grazing system have a direct impact on the function and productivity of rangelands. While domestic grazing ruminants can pose a threat to pasture health, producers can maintain or improve the condition of land through the judicious application of grazing cattle. However, grazing systems that give producers more control over when and how cattle graze are also more expensive and labour intensive. Ultimately, the use of grazing strategies that appropriately match cattle intake to rangeland production support the ecological function of rangelands, protecting ranch profitability and longevity, and ensuring that rangelands will continue to exist and provide numerous goods and services in the future to come.

1.3. Virtual Fencing for Cattle Management

1.3.1. Introduction to Virtual Fencing

No single grazing management strategy will benefit all ranchers or rangeland, due to variation in climate, landscape, remoteness of location, soil, and vegetation (Asamoah et al. 2003; Bailey et al. 2021). Additionally, flexibility of grazing management is crucial due to the physical scale, remoteness, and variation in environmental conditions experienced by beef cattle operations (Aquilani et al. 2022). Management flexibility is critical in the effort to balance economic profit with rangeland conservation, which relies on good grazing management to place the right animal in the right area for the appropriate amount of time (French et al. 2015; Stevens et al. 2021). Physical fencing is the primary technology used to control cattle distribution in North America. It is costly and labour intensive to install, maintain, or change, and is one of the main barriers to the implementation of flexible, adaptive grazing management strategies (Butler et al. 2006; Wang et al. 2020). In contrast, the emerging technology of virtual fencing offers dynamic, flexible, virtual boundaries that can be managed remotely, increasing grazing management control and flexibility beyond what is possible with physical fencing, without a significant increase in labour and infrastructure (French et al. 2015; Stevens et al. 2021; Goliński et al. 2023).

Virtual fencing (VF) utilizes an animal-mounted device, often a collar, to track livestock locations, and a management software to specify virtual pasture boundaries, generally a mobile phone application. A combination of a neutral stimulus (audio cue) followed if necessary by an aversive stimulus (electric shock) prevent trained animals from crossing virtual pasture boundaries, and thus contain livestock in the desired area (Goliński et al. 2023; Hamidi et al. 2024). Currently, there are several companies offering VF technology in various stages of commercial development. Nofence (Batnfjordsøra, Norway), Vence (San Francisco, CA, USA), eShepherd (Melbourne, Australia), and Halter (Auckland, New Zealand) have made advanced progress in VF technology, with all four companies providing collars to researchers and/or producers for use on grazing animals.

1.3.2. Nofence Virtual Fencing System and Operation

The research contained within this thesis was conducted using the Nofence VF system, which utilizes a mobile phone application to control a collar-mounted device. The collar operating unit includes a Bluetooth receiver, mobile network receiver for 2G and 4G LTE networks, an accelerometer, a re-chargeable lithium-ion battery, two side-mounted solar panels, and a global navigation satellite system (GNSS) receiver that connects to both Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) satellites (Nofence AS (Ltd.) 2023). The GNSS receiver monitors the location of the animals and triggers audio and electrical stimuli independent of mobile network connection. Mobile network connection is necessary to send and receive messages from the phone app to the collars.

Collars are programmed to report GPS locations more frequently when near a virtual boundary or when the accelerometer detects greater movement. To conserve battery charge, locations are reported less frequently when there is little animal movement or when the animal is greater than 12 metres from the virtual boundary (Nofence Ltd. 2023). Collars record regular data observations (including GPS locations) every 15 minutes and record all spontaneous events (such as stimuli or escapes). Mobile network connection is required to send data observations to the Nofence servers for storage. When insufficient network connection causes a disruption in sending or receiving data to the Nofence servers, the collar will try to connect once more after a 15-minute interval. If this attempt is unsuccessful the phone application will indicate the collar has insufficient network coverage. In the event of insufficient network connection, messages are locally buffered (stored) for approximately 14 days.

Details about the VF operation can be accessed from the Nofence Ltd. manual (2023) and Hamidi, et al. (2024). Briefly, when an animal approaches the virtual boundary between the inclusion (where animals should be) and exclusion (where animals should not be) zones, the collar plays a warning audio cue. The warning is a maximum of 82 dB and varies from a specific low-pitched tone to a specific higher-pitched tone. The velocity at which the animal is moving determines the rate at which audio cues change in tone, with a total warning duration of 5 – 20 sec depending on animal velocity and how quickly they respond to the audio cue. The audio cue ends when either 1) the animal turns around and the collar records a position that is one metre away from where the warning was triggered, or 2) when the entire audio tone scale has been played. Once the audio warning is complete, if the animal has not turned away from the virtual boundary an electrical shock is administered. The delivered shock is between 1.5 and 3 kV, depending on environmental conditions, and the collar unit has a maximum stored power capacity of 0.2 J. If the animal continues into the exclusion zone despite the audio and electrical cues the collar will emit another warning tone followed by another shock. Animals receive a maximum of three warnings, each of which is followed by a shock, after which they are considered escaped. Collars of escaped animals do not discharge any further stimuli but continue to track their location. Once an escaped animal returns to the inclusion zone their collar resumes normal operation.

1.3.4. Learning and Welfare

Previous research into VF has consistently reported that cattle successfully learn to associate audio cues with a subsequent electric shock, and therefore avoid behaviours that would lead to shocks, i.e. crossing VF boundaries (Bishop-Hurley et al. 2007; Lee et al. 2009; Verdon et al. 2020; Colusso et al. 2020; Aaser et al. 2022; Hamidi et al. 2024). One of the earlier VF studies concluded that animals learned a negative association between a shock and the location where it was received, which changed their future behaviour even after the VF system was disabled (Markus et al. 2014). This location-specific avoidance is not reported by the majority of VF research, indeed multiple studies have shown that animals rapidly cross a deactivated VF boundary to access areas from which they were previously excluded (Campbell et al. 2017; Marini et al. 2018; Colusso et al. 2021b). The ability of cattle to respond appropriately to VF boundaries, i.e. to hear a warning and then turn around to avoid the shock, after an extended break without reinforcement is largely untested, although Verdon and Rawnsley (2020) did not see a benefit from previous VF experience on the response of 22-month old heifers upon re-exposure to VF after a 12+ months long break.

Most of the studies conducted on the welfare of animals within a VF system have concluded that VF has no effect on animal welfare. The use of an audio cue as a conditioned stimulus is supported by Kearton et al. (2022), who concluded that the predictability and controllability of the audio cues and electrical stimuli induces a minimal stress response that does not compromise animal welfare. Although it has been noted that individual variation in behaviour under VF may cause successful containment of the herd to come at a welfare cost for some animals (Lomax et al. 2019), research that investigated the possible effects of VF stimuli on milk and fecal cortisol levels, feed intake and milk yield, and activity and grazing behaviour, found no evidence of negative impacts of VF stimuli on cattle welfare (Aaser et al.

2022; Sonne et al. 2022; Hamidi et al. 2022; Fuchs et al. 2024). While the electric shocks that are experienced by cattle within a VF system do cause temporary pain or distress, evidence currently supports that the potential benefits of VF justify the controlled and minimal application of shocks.

1.3.3. Utility and Applications of Virtual Fencing

The main benefit of VF technology to the cattle industry is the potential for greater management flexibility, and therefore more efficient resource utilization, without the associated increase in cost and labour that is unavoidable with traditional fencing and management systems. Applications of the technology include rotational and other intensively managed grazing (Campbell et al. 2017, 2021; Verdon et al. 2021, 2024; Staahltoft et al. 2023), the management of plant encroachment (Log et al. 2022), the management of fire risk and fuel breaks (Log et al. 2022; Boyd et al. 2023), and the protection of sensitive ecological areas (Campbell et al. 2019a, 2020; Boyd et al. 2022).

To date, literature agrees that cattle can be effectively contained within an inclusion zone by VF (Umstatter et al. 2015; Marini et al. 2018; Campbell et al. 2019a; Lomax et al. 2019; Ranches et al. 2021), even with attractants such as greater forage availability or extra hay present in the exclusion zone (Campbell et al. 2018, 2020; Langworthy et al. 2021). In addition to this, Campbell et al. (2019a, 2020) concluded that VF was able to exclude cattle from grazing sensitive areas and riparian zones, and several studies indicate that cattle can be herded or moved passively using a VF system (Campbell et al. 2017, 2021; Staahltoft et al. 2023; Verdon et al. 2024). Variation in individual learning rates and behaviour within VF systems have been widely reported (Campbell et al. 2018; Lomax et al. 2019; Colusso et al. 2021b; Aaser et al. 2022), although the reason for this variation remains unclear.

Research on the utilization of VF has mainly focused on steers, heifers, or dry cows, which does not reflect the high proportion of grazing beef cattle that are cows with calves at side. Furthermore, many studies have utilized small, i.e. fewer than 20, groups of cattle or a short duration of grazing and

VF deployment that do not represent the herd size and extended periods of grazing often utilized by beef cattle producers (Sheppard et al. 2015). While it has been reported that cattle can be contained by VF across light, moderate, and heavy stocking rates (Vandermark 2023), the use of more intensive stocking rates and densities has yet to be fully investigated. Finally, the performance of VF remains untested in some regions, particularly in cool, temperate climates and rural or remote locations that are characteristic of western Canadian rangelands. Challenges specific to these regions include extreme high and low temperatures, low winter sunlight affecting battery solar charging, and unreliable cellular networks. For successful adoption, VF technology requires extensive testing under field conditions that reflect industry and region-specific context.

1.4. Study Overview and Research Objectives

It has been estimated that 80% of Canadian cattle producers practice some form of grazing (Sheppard et al. 2015), with farms reporting a total of over 5 million ha of land in tame or seeded pasture, and 14 million ha of natural pasture in 2016 (Statistics Canada 2017). The widespread distribution of cattle across rangelands means that grazing management plays an important role in the sustainable use of land. Inappropriate management leading to over- or under-utilization of pasture by cattle can lead to grassland degradation, shifts in biodiversity and ecosystem type, desertification, the ingress of woody weed species, and an increase in wildfire risk (Teague and Dowhower 2003; Geist and Lambin 2004; Pyle et al. 2018; Stevens et al. 2021). In contrast, evidence also shows that appropriate utilization of rangelands, achieved by controlling when, where, and how often cattle graze, can improve vegetation productivity, biodiversity, hydrologic function, soil aggregate stability, and carbon sequestration in pastures (Van Poollen and Lacey 1979; Pyle et al. 2021; Döbert et al. 2021).

Controlling cattle on pasture necessitates the use of physical fencing, which is resource intensive to install and maintain, and difficult to reconfigure (Butler et al. 2006). It is often expensive and labour intensive to manage grazing cattle to optimize livestock production and have a positive impact on rangeland condition, which can prevent livestock producers from adopting alternative, beneficial grazing strategies (Wang et al. 2020). Virtual fencing is a new technology that proposes to increase the control and flexibility of grazing management for a fraction of the labour and infrastructure necessary within conventional, physical fencing systems, and has already been the subject of an impressive amount of research (Goliński et al. 2023). However, cattle production operations are diverse, with challenges and opportunities unique to their specific locations, cultures, and management goals. It is therefore important to continue investigating VF in a multitude of locations, applications, and with producer consultation and input.

In order to use VF technology successfully and optimize animal welfare outcomes it is essential that livestock are trained to respond appropriately to VF boundaries, such that the animal stops and turns around upon receiving an audio cue, rather than continuing forward across the VF boundary (Umstatter 2011; Hamidi et al. 2024). Several studies have shown that cattle learn to associate audio cues with subsequent electrical shocks and are able to avoid the incidence of shocks (Lee et al. 2009; Verdon and Rawnsley 2020; Hamidi et al. 2024), but few have addressed the conditions under which cattle are best trained or the length of time that is necessary to achieve optimal training (Hamidi et al. 2024). Additionally, there is little research addressing the ability of cattle with VF experience to respond appropriately to VF boundaries after extended periods without active use, which is often necessary when producers begin spring and summer grazing after a winter break.

The main benefit of VF technology, i.e. greater management flexibility, relies on the concept that cattle can be contained by static and dynamic VF boundaries in order to be useful in herding, mustering, and adaptive grazing strategies. Research has already shown that cattle can be contained by static and dynamic VF boundaries, and preliminary trials on the use of dynamic VF boundaries are promising (Campbell et al. 2019a, 2021; Confessore et al. 2022; Staahltoft et al. 2023). However, a few studies encountered problems when using VF boundaries to control animal distribution (Campbell et al. 2018; Verdon et al. 2021). This highlights the importance of understanding not only whether cattle can be contained by VF, but also the factors that contribute to the success or failure of VF boundaries.

Additionally, while the cow-calf industry accounts for over two-thirds of the Canadian beef herd (Statistics Canada 2024a), many of the current VF studies utilized steers, heifers, or dry cows. Therefore, it is necessary for future VF research to utilize cattle that are accompanied by calves at side and represent a variety of ages groups to reflect the realities of Canadian beef producers. Finally, the performance of VF should be assessed under field conditions that are characteristic of western Canadian beef producers during summer and winter grazing.

While VF is a potential asset to livestock producers who aim to balance economic profit with rangeland conservation, these capabilities are not fully tested. The goal of this research was to investigate the efficacy of VF to manage beef cows and heifers under conditions that are representative of the cow-calf industry in western Canada. Two rotational grazing trials were conducted using the Nofence VF system during the summers of 2022 and 2023, first with heifers that were naïve to VF technology, and later with cows having uncollared calves at side, that were experienced with VF. An additional technical trial was performed over the winter of 2022 to 2023 to provide insight into Nofence collar performance during harsh winter conditions characterized by low daily temperatures and reduced hours of daylight.

Specifically, the objectives of this research were to 1) evaluate the cellular network connectivity performance of Nofence VF collars in a rural Canadian area; 2) describe any failure occurrences of Nofence collars while deployed in the field; 3) describe trends in battery discharge and solar re-charging during summer and winter deployment; 4) investigate whether heifers naïve to VF, and first-calf cows with previous VF exposure, learn or re-learn to comply with virtual boundaries; 5) assess whether VF is able to contain heifers and cow-calf pairs in virtual sub-pastures during rotational grazing; and 6) describe factors that may affect the successful utilization of VF technology. The results of this thesis provide novel insight into the utility of VF technology in a cool, temperate climate during summer and winter conditions, it's ability to manage heifers and cow-calf pairs during rotational grazing, and discusses multiple factors of success.

1.5. Literature Cited

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Chapter 2: Evaluation of the technical performance of the Nofence virtual fencing system in Alberta, Canada

2.1. Abstract

This study evaluates the technical performance of Nofence virtual fencing (VF) collars for managing grazing cattle in the northern temperate climate of central Alberta, Canada. VF technology, which uses GPS-enabled collars to control cattle movement through audio cues and electrical shocks, offers a potential alternative to traditional fencing. The study assessed VF performance during both summer and winter seasons throughout four grazing trials in 2022 and 2023, focusing on network connectivity, collar failures, battery performance, and solar charging capabilities. The mean network connection intervals (NCI) ranged from 8.1 (± 6.2) to 9.4 (± 5.4) mins throughout the trials, well within the ideal 15 min interval, and poor network connection occurred less than 1% of the time. Fourteen collars experienced a network connection failure that did not persist after a manual reset. Four cattle removed their collars, which were then recovered and redeployed. While the mean solar charging rate was lower for the winter trial (3.1 ±10.8 mA h^{-1}) than the summer trials (7.9 ±18.0 to 12.4 ±22.1 mA h^{-1}), mean battery charge was greater than 96% for all trials, even during winter with limited daylight. While reliable cellular network access is crucial, these results indicate that Nofence VF collars can effectively function in diverse environmental conditions and may be suitable for broader adoption in western Canadian grazing practices.

2.2. Introduction

In Canada, some form of grazing is practiced by 80% of cattle producers (Sheppard et al. 2015). Grazing by commercial beef cattle most commonly occurs from June through October, when forage is abundant and relatively accessible (Sheppard et al. 2015). In addition to summer and fall grazing, over half of producers also incorporate winter grazing as an important strategy to reduce winter feed costs, where the main sources of feed are bales, processed forage, and stockpiled forage (Sheppard et al. 2015). Cattle may be grazed nine or more months of the year, and fencing plays a crucial role in controlling access to feed while on pasture. It follows that the construction and maintenance of fences represents a significant cost in the management of beef cattle while grazing on pasture (Tanaka et al. 2007).

A particular practice that exacerbates the significant cost of fencing is the utilization of rotational grazing. Rotational grazing systems require a series of smaller sub-pastures be constructed using either permanent or temporary (electric) fencing to control where, when, and how often cattle graze. In western Canada, surveys indicate that rotational grazing is practiced by 57 - 78% of cattle producers, where rotational grazing is defined as a system in which livestock are moved between pastures (Chorney and Josephson 2000; Pyle et al. 2018). Frequency of rotations may vary from once a season to once a day, with increasing complexity leading to significant increases in infrastructure cost and labour (di Virgilio et al. 2019).

Virtual fencing (VF) is an alternative strategy to physical fencing that is gaining attention worldwide and offers significant potential to control the spatial distribution of grazing animals (Goliński et al. 2023). Virtual fencing utilizes a programmable, collar mounted technology platform with an on-board global positioning system program that tracks animal location while providing a combination of audio cues and associated electrical stimuli to train cattle to respect virtual boundaries, thereby confining animals to a targeted grazing area (Goliński et al. 2023). Boundaries are programmed to the collar via a cellular application, which can then be changed in real-time and used to monitor the location of the animal, as well as ongoing collar performance (Goliński et al. 2023). Several collars have been developed and are in various levels of commercialization globally, including Nofence (Batnfjordsøra, Norway), Vence (San Francisco, USA), eShepherd (Melbourne, Australia), Halter (Auckland, New Zealand), and Corral Technologies (Lincoln, USA).

Virtual fencing technologies are relatively new, and their technical performance remains largely untested within cool temperate regions such as those in western Canada. The utility of VF may be limited in this region due to technical reasons, for example a lack of cellular network coverage, or environmental conditions such as cold weather and short daylengths that limit solar charging, particularly during winter. Widespread adoption of advanced technologies such as VF requires their evaluation under field conditions, including the specific environments within which grazing by cattle is likely to occur. The goal of this study was to evaluate the performance of the Nofence VF system for its technical soundness while deployed on commercial beef cattle grazing within the northern temperate climatic conditions of central Alberta, Canada. Specific objectives were to: 1) evaluate the connectivity of Nofence VF collars to available cellular networks, 2) describe the failure occurrences of Nofence collars while deployed in the field, and 3) describe the trends in battery discharge and solar panel recharging capacity, including how this varies across summer and winter grazing.

2.3. Materials and Methods

2.3.1. Study Areas

In this study we evaluated the performance of Nofence VF collars at two different locations in central Alberta, Canada, that encompassed contrasting phases of the seasonal cattle production cycle. Collars were evaluated during the summer on heifers in 2022, and subsequently on the same cows in 2023, while cattle grazed perennial tame pasture from June through August at the University of Alberta

Roy Berg Kinsella Research Ranch (KRR), situated 150 km SE of Edmonton, Alberta, Canada (53˚0’29.919”, -111˚30’57.8334”). The landscape of this area is a gently to strongly rolling hummocky moraine. The nearest cell towers relative to the test pastures were 11.19 km to the SE for 2G service and 11.7 km SE for 4G LTE service. The KRR has normal mean daily temperatures of 16 ^{o}C and 15 ^{o}C during July and August, respectively (Environment and Climate Change Canada [ECCC] 2024a), with typical daily illumination hours (dawn to dusk) exceeding 15 hr throughout summer (National Research Council Canada [NRCC] 2012).

Collar performance during the winter of 2022 was tested on steers while they grazed swathed annual forages from December through January at the Lakeland College G.N. Sweet Livestock Research Facility (LLRF), located at Vermilion, Alberta, Canada (53˚20’39.0264”, -110 ˚52’41.8002”). The nearest cell tower for 2G service was 2.26 km NE of the study area, and the nearest tower for 4G LTE service was 1.75 km NE. The grazing area included 13.6 ha of snow-covered sub-pastures previously planted to annual forages in June 2022, and swathed in October 2022 to stockpile forage biomass in preparation for winter grazing. This location typically experiences normal mean daily temperatures of -11^{o}C and -12^{o}C for December and January, respectively (ECCC 2024), and received less than 8 hours of illumination per day for the same period (NRCC 2012).

2.3.2. Nofence Virtual Fencing System

The Nofence VF system is composed of an animal collar and a mobile phone application. The collar operating unit includes a Bluetooth receiver, mobile network receiver for 2G and 4G LTE networks, an accelerometer, a re-chargeable lithium-ion battery, two side-mounted solar panels, and a global navigation satellite system (GNSS) receiver that connects to both Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) satellites (Nofence Ltd. 2023). The GNSS receiver monitors the location of the animals and triggers audio and electrical stimuli independent of mobile network connection. Mobile network connection is necessary to send and receive messages from the phone app to the collars.

Collars are programmed to report GPS locations more frequently when near a virtual boundary or when the accelerometer detects greater movement. To conserve battery charge, locations are reported less frequently when there is little animal movement or when the animal is greater than 12 metres from the virtual boundary (Nofence Ltd. 2023). Collars record regular data observations (including GPS locations) every 15 minutes and record all spontaneous events (such as stimuli or escapes). Mobile network connection is required to send data observations to the Nofence servers for storage. When insufficient network connection causes a disruption in sending or receiving data to the Nofence servers, the collar will try to connect once more after a 15-minute interval. If this attempt is unsuccessful the phone application will indicate the collar has insufficient network coverage. In the event of insufficient network connection, messages are locally buffered (stored) for approximately 14 days.

The operating and storage temperature range for the collar is reported to be -25 to +65^{o}C (Nofence Ltd. 2023). The collar uses a two-part adjustable neck strap to remain on the animal, comprised of metal side chains and a rubber connector for comfort on the top of the neck. For the Nofence cattle collar model, the entire weight is 1446 g. The mobile phone application can be downloaded for free on any iPhone or Android device, and is used to manage the VF system.

Details about the VF operation can be accessed from the Nofence Ltd. manual (2023) and Hamidi, et al. (2024). Briefly, when an animal approaches the virtual boundary between the inclusion (where animals should be) and exclusion (where animals should not be) zones the VF collar plays an audio cue. Upon completion of the audio cue, if the animal has not turned away from the virtual boundary and exclusion zone an electrical stimulus is administered. If the animal continues into the exclusion zone the collar will emit a maximum of three audio cues followed by electrical stimuli, after which the animal is considered escaped. Collars of escaped animals do not discharge any further stimuli but continue to track their location. Once an escaped animal successfully returns to the inclusion zone their collar resumes normal operation.

2.3.3. Description of Grazing Trials

The animals in this study were handled according to the guidelines established by the Canadian Council on Animal Care (Canadian Council on Animal Care [CCAC] 2009) and with the approval of the Animal Care Committee at the University of Alberta (Animal Use Protocol 3850) and the College Animal Care Committee at Lakeland College (SwatheGrazingRES – 09 – 21).

Technical performance data of the VF collars were collected over the course of four separate grazing trials using the same Nofence VF collars and system. Water was available ad-libitum in all trials. The following is a description of cattle number, type, time of grazing (dates), and grazing system, including average sub-pasture size and grazing schedule, employed in each trial:

1) Fifty-one commercial British-Continental crossbred cattle (49 yearling heifers and two breeding bulls) were rotationally grazed at KRR from June 24 to August 30, 2022. All cattle were naïve to VF. Cattle were fitted with v2.1 Nofence VF collars, and after an 11-day training period the capabilities of the Nofence VF collars were evaluated during an eight-week rotational grazing trial. The VF system was used to rotate cattle approximately every 7 days through 6 sub-pastures, averaging 4.77 (± 0.76) ha in size. Pastures mainly featured rolling, open grassland with minimal shrubland and no forested areas.

2) Sixty yearling Simmental cross steers were strip grazed in a winter swath grazing trial managed by temporary physical electrical fencing at the Lakeland College Vermillion campus from November 30, 2022 to January 20, 2023. A subset of 30 steers received v2.1 Nofence VF collars

and the VF boundary was programmed to always coincide with the physical electric fence. While the steers interacted with the VF boundary and received stimuli, the use of VF was not intended to control cattle movement or test their compliance to the system. All cattle were naïve to VF, and after a 12-day acclimation period the technical performance of the collars was tested while steers grazed six experimental sub-pastures (average sub-pasture size of 2.27 (± 0.08) ha), rotating approximately every three days). Cattle grazed a variety of swathed annual forages on open, flat grassland with access to wind shelters.

3) Thirty purebred Angus cattle (28 cows with calves at foot and two breeding bulls) were grazed continuously in one pasture (24.1 ha) at KRR from June 23 to August 9, 2023. Our purpose was to test the capability of Nofence VF collars to restrict cattle from grazing in riparian areas embedded within the pasture, following a 5-day training period. Cows received 23 v2.2 and 5 v2.1 Nofence VF collars, and bulls received two v2.1 VF collars (calves remained uncollared). All cattle were naïve to VF. The pasture was a combination of rolling grassland, shrub, and dense Aspen forest habitats. The VF system was used to exclude cattle from seven riparian areas.

4) A subset of 39 cattle from #1 above (now first-calf cows with calves at side) and three British-Continental bulls were rotationally grazed at KRR from June 27 to August 16, 2023. The cows had experienced VF during the 2022 trial (see #1 above) and the bulls were naïve. Cows and bulls received v2.1 Nofence VF collars, and calves remained uncollared. After a 3-day retraining period the VF system was used to rotate cattle approximately every 5 days through 9 sub-pastures, on average 3.9 (± 1.45) ha in size. The physical pastures were the same as described in #1.

2.3.4. Technical Data Compilation

Fifty-one collars (version 2.1) were used during 2022 trials and 25 new collars (version 2.2) were added in 2023 for a total of 76 collars. Quality of VF collar network connectivity, collar failures, battery charge, and solar charging rate were compiled from the four trials described above. The quality of network connection was described through network connection intervals, network connection outages, and the frequency of unsuccessful connections. The Nofence VF system uses the cellular network to send records of data from the collars to the Nofence servers. The network connection interval (NCI) was therefore defined as the amount of time lapsed between a data observation and the most recent, prior observation. The interval between successive data observations should be no more than fifteen minutes (Nofence Ltd. 2023), and any interval of less than 30 minutes was considered to be good network connection. NCIs that were 30 minutes or greater in length, but less than 48 hours, were defined as network connection outages and represented poor connection. NCIs 48 hours or longer were considered collar failures.

Collar failures occurred when collars were unable to operate properly as a VF management system for at least two days (48 hours), and/or required researcher intervention to regain operational status. Four categories of collar failures were experienced in this trial: 1) user error; 2) hardware or software failure; 3) situations where the collar was lost by the animal; and 4) network connection failure, where either the collar continuously failed to connect to Nofence servers for at least 48 hours, or the collar was manually reset before the two-day threshold, due to scheduled handling. A manual reset involves removing the battery from the collar for 10 seconds and then reinserting (Nofence Ltd. 2023). The number of failures in each category was recorded for each trial. The number of failures was minimal and could not be analyzed statistically.

Instantaneous battery charge is the battery voltage as measured and recorded by the VF collars for each data observation, and was expressed as a percentage of the maximum battery capacity (420 cV) for clarity (Nofence Ltd. 2023). It represents the difference between the energy required for the collar to function, and the charging capabilities of the solar panels on the VF collars. Milliamperes of current as accumulated by the solar panels in 30-minute intervals were recorded by the VF collars and expressed as a solar charge rate in mA/hour.

Hourly temperature data for all trial periods were accessed from the Government of Canada weather stations located in Kinsella and Vermillion, AB (ECCC 2024b, 2024c). Illumination hours per day were defined as the number of hours between sunrise and sunset each day, and retrieved from the National Research Council of Canada sunrise/sunset calculator (NRCC 2012).

2.3.5. Statistical Analysis

All data were compiled and analyzed separately for summer and winter due to key differences between locations and animals. One collar in winter 2022 and 5 collars in summer 2023 did not record battery or solar charge data. NCIs of 48 hours or longer were separated from the network connection quality analysis and treated as collar failures. Recorded battery voltages of more than 420 cV were removed as errors. Finally, outliers for NCIs, network connection outages, and solar charge rates were identified as values more than 4 standard deviations away from the mean and removed.

The following summary statistics were compiled by year, season, animal class, and collar version: 1) mean and standard deviation (SD) of NCI, network connection outage duration, instantaneous battery percent, and solar charge rate; 2) mean (with range) of daily temperature, daily illumination, and minimum instantaneous battery percent; 3) frequency of poor network connection; and 4) numbers and nature of collar failures. Additionally, maximum duration of a network connection outage, mean (and SD) NCI and daily instantaneous battery percent, and mean (and range) hourly temperature were calculated across year and season.

To investigate the relationships between solar charging and environmental factors a generalized linear mixed model (GLMM) for each trial was fitted in the software *R* version 3.3.3 (R Core Team 2024) using the package *glmmTMB* (Brooks et al. 2017). Solar charging rate was summed as the amount of charge accumulated in a day (mA day^{-1}) and identified as the dependent variable. Air temperature (◦C), averaged over each day, and daily illumination (hr) were set as the fixed effects. The model accounted for repeated measures using random effects; more specifically, by setting serial number and date as random effects the model estimated the variability between subjects and dates while also considering the correlation between multiple measurements within the same subject (Laird and Ware 1982; Bolker 2015; Fox and Weisberg 2019a). Additionally, a zero-inflation component was included to account for a disproportionate number of zeros in the data, modeled as a function of air temperature. Due to the nature of the response variable as a rate measurement, the poisson family was chosen for the model.

The *DHARMa* package (Hartig 2022) was used to check model fit through the dispersion of fitted versus simulated residuals and the incidence of outliers in the residuals. The *car* package (Fox and Weisberg 2019b) was used to assess the significance of fixed effects and interactions, and the *performance* package (Lüdecke et al. 2021) was used to obtain the conditional R^2 value of each model. Models with significant effects (chi-squared test, $p < 0.05$) were plotted using *ggeffects* (Lüdecke 2018) and *ggplot2* (Wickham 2016).

2.4. Results

Northern temperate climates, such as in western Canada, experience seasonal changes that may affect the performance of technology such as VF. Marked differences in temperature and sunlight occurred between the contrasting seasons of collar use (Table 2.1). Summer deployment (June - August) coincided with warm ambient temperatures and long daylight hours. In contrast, winter deployment (December – January) was associated with extended periods of cold (sub-freezing) temperatures, with absolute temperatures as low as -40.8ºC (ECCC 2024c), and significant daily illumination restrictions given the co-occurrence with the winter solstice (Table 2.1). Therefore, the performance of Nofence VF collars was assessed during summer and winter, which represent two seasonal extremes.

2.4.1. Collar Network Connectivity

During 2022 the mean NCI for v2.1 collars was 8.9 (± 6.1) minutes in summer and 9.1 (± 5.4) minutes in winter. During 2023 the mean NCI during summer grazing was 8.1 (± 6.2) and 9.4 (± 5.4) min for collar versions 2.1 and 2.2, respectively. The average length of a network connection outage did not appear different between years, seasons, collar versions, or animal classes (Table 2.1). The frequency of poor network connectivity was low, with poor connections reported 0.01% to 0.33% of the time in 2022, and 0.08% to 0.32% of the time in 2023 (Table 2.1). The maximum length of a network connection outage that resolved itself within two days was 34.1 minutes for v2.1 collars in winter, 90.1 minutes for v2.1 collars in summer 2022, and 90.5 and 45.3 minutes for v2.1 and v2.2 collars in summer 2023, respectively. Although it was considered a collar failure, it is notable that one of the v2.1 collars in 2023 self-resolved a network connection outage after 11.8 days.

2.4.2. Collar Failure

Two collar failures occurred in 2022 and 18 in 2023, for a total of 20. In all cases the collars were retrieved or manually reset, and most were returned to the trial. Of the 20 failures, 18 were unique collars which did not experience additional failures. One of the repeat failures was caused by user error, while the other repeat failure occurred when a steer lost a collar in winter 2022 and this collar later experienced hardware or software issues and was not deployed. Collars were physically lost by animals four times in total (each time the collar was tracked using the mobile application and retrieved); once in the winter of 2022 as noted above and three times during summer 2023 (one cow and two bulls).

Of the 20 total failures 14 were caused by persistent network connection problems. The v2.1 collars experienced one connection failure in 2022 and nine during 2023. Of those nine, four were manually reset before the two-day failure threshold because of regularly scheduled animal handling and five were manually reset after the two-day failure threshold. Version 2.2 collars experienced four connection failures in 2023, none of which resolved on their own. These collars were not manually reset due to restricted access to the cattle.

2.4.3. Battery and Solar Charging Performance

Mean battery charge levels were high for all seasons, remaining above 96% of battery capacity during each grazing trial (Table 2.1). The mean minimum battery percent levels remained above 94% for each trial (Table 2.1). The average rate of solar charging for collars varied widely from a high of 12.4 (± 22.1) mA/hr in summer 2023, to a low of 3.1 (± 10.8) mA/hr in winter (Table 2.1). The maximum solar charge rate for all groups was 104 mA/hr. During both summer trials the mean daily battery voltage declined for a short period of time before maintaining a voltage of approximately 400 cV, whereas the mean daily battery voltage during winter experienced two periods of decline, interrupted by a period of recovery (Figure 2.1). Solar charging appeared to occur after a battery voltage threshold of 410 cV or less, with the highest solar charge rates occurring at battery voltages of 395 – 410 cV (Figure 2.2).

The effects of temperature and illumination on solar charging rate are summarized in Table 2.2 and Figure 2.3. Briefly, there were no significant effects of temperature, daily illumination, or an interaction thereof, on solar charging rate during winter of 2022 (chi squared test, $p < 0.05$), and a positive effect of temperature on solar charging in 2022, and a negative effect in 2023. However, the effects on solar charging rate in both years were affected by significant interactions between temperature and illumination (chi squared test, $p < 0.05$).

2.5. Discussion

2.5.1. Network Connection

One of the challenges facing VF in Canada is the limited cellular network available in rural areas. Cellular infrastructure is often focused near towns and cities, and along highways or other travel routes (Canadian Radio-television and Telecommunications Commission [CRTC] 2021), leaving many cattle producers in areas of limited or absent cellular networks. Stable network connection is needed to fully utilize the features of VF (such as livestock monitoring and changing VF boundaries), and Campbell et al. (2019a) noted that issues with connection and downloading virtual pasture information may impact animal welfare by increasing the incidence of audio and electric cues. This study took place in areas of western Canada with network connection that is considered "good" by local, rural standards, but is limited compared to the network access experienced by urban areas.

Connectivity of both versions of Nofence collars during all seasons was generally good, with mean NCIs well within the suggested maximum length of 15 minutes (Nofence Ltd. 2023). Mean bouts of network connection outages were barely over the 30-minute threshold, and the frequency of poor connectivity was very low (Table 2.1). The overall connectivity of collars in all seasons exceeded expectations, but it should be noted that the frequency of poor connection ranged from 0.07% to 0.32% across years during the summer trials, and was only 0.01% during the winter trial (Table 2.1). Possible sources of the variation in connection quality during summer trials include signal interference from surrounding infrastructure and environment, and variations in network provider capacity and performance. There was no clear effect of collar age or version on network connection success and quality, although these factors should be monitored over the lifespan of the technology. The variation in network connection between summer and winter trials can be explained by the role of geolocation and proximity to the nearest cell tower, in addition to the above-mentioned factors.

While many other studies have been published on the use and efficacy of VF technology to manage grazing livestock, few address the detailed technical performance of VF collars. Prior research has documented connection issues or unspecified technical problems that interfere with collar function, or data storage and retrieval (Colusso et al. 2020; Campbell et al. 2021; Eftang et al. 2022). Furthermore, several studies utilizing collars that store data internally, rather than transmitting it over the cellular network, also reported problems with internal data storage and retrieval (Umstatter et al. 2015; Campbell et al. 2019a, 2020; Verdon et al. 2021). The results of this current study suggest that environmental factors did not limit Nofence technical performance, and cellular network connection remained favorable when sufficient network was available.

2.5.2. Collar Failure

While limited information is available about VF collar failures, other studies have noted that collars fail due to poor network connection (Eftang et al. 2022) or other unspecified technical problems (Brunberg et al. 2017; Campbell et al. 2019a; Langworthy et al. 2021). In the current study most failures were due to network connectivity, followed by collars lost by animals while grazing; in contrast, hardware and software failures were rare. It is important to note that the use of v2.1 collars led to only one connection issue during summer 2022, but one year later the same collars experienced 9 network connection related failures (Table. 1). This abrupt increase in connection failures could be due to collar longevity issues, animal behaviour, or environmental disruptions such as weather and cloud cover. Importantly, each collar that experienced a connection failure was subsequently reset manually, and thereafter continued to operate normally with no further failures; no collars experienced a connection failure twice. This suggests that while any collar may have trouble connecting to the cellular network, certain collars did not consistently experience problems.

The next most significant source of collar failure was physical collar loss from the animal. One of the four losses was likely caused by user error resulting in the collar fitting too loosely. The second collar was recovered in a densely wooded area with one of the support chains unfastened from the neckband, indicating that it was likely dislodged by the travel of the cow through the bush. The final two collars fell off breeding bulls; it was difficult to fit collars to bulls as their neck circumference was often larger than their head, which enabled the collar to slip off more easily. Researchers were notified of all four collar losses through the mobile application, and GPS location and Bluetooth connectivity facilitated their recovery. These experiences of collar loss are consistent with other studies; Campbell et al. (2019) noted five occasions over 27 days where VF collars came off cattle, and Log et al. (2022) experienced four collars falling off goats over 8 weeks of grazing.

These common experiences of collar failure highlight the importance of collar fit and plans to manage a lost or disconnected collar, especially when there is limited access to animal handling for collar redeployment. Three of the four trials included scheduled animal handling events every two weeks, where collars could be checked and manually reset if necessary. In the remaining trial (summer grazing 2023 by the small cow/calf herd) there was no immediate access to handling facilities for the duration of the collar deployment, and five collar failures were unable to be resolved. This mirrors the experience of many cattle producers, who extensively manage their cattle and may face infrastructure and labour restrictions on animal handling (Alemu et al. 2016). In the absence of regularly scheduled cattle handling, it may be months before a producer is able to address a failed VF collar.

These collar failure experiences that are common among multiple studies highlight the importance of proper collar fit and plans to manage a lost or disconnected collar, especially when there is limited access to animal handling for collar redeployment. For example, it was anecdotally noted that when two bulls lost their collars during summer grazing in 2023 they stayed with the cows in the inclusion area rather than wandering off. The behaviour of animals with failed collars requires further research to shed light on the impacts on herd behaviour, animal welfare, and VF success.

2.5.3. Battery Performance and Solar Charging Rate

Investigation into the battery and solar charge performance of the Nofence collars yielded surprising results. It was expected that the solar panels would perform well during summer grazing with ample daily illumination; however, it was unexpected that the mean daily battery voltage would remain well above 90% in winter (Figure 2.1), despite a reduction of illumination hours of almost 50% compared to summer grazing (Table 2.1). Additionally, it is evident from Figure 2.1 that while the batteries in winter experienced a larger voltage decline than in summer, the solar panels could recover some of the lost voltage despite the limited illumination. Winter grazing is already practiced by 68% of beef cattle producers in the western prairie provinces (Sheppard et al. 2015), and these results show that Nofence VF may be a suitable tool to manage winter grazing as the solar charging panels and basic operations continue to work throughout a Canadian winter.

The mean solar charging rate during winter was less than a third of the solar charging rate in summer, and the version 2.2 collars in the partially forested pasture experienced a mean solar charging rate approximately two-thirds of the collars in pastures dominated by open grassland (Table 2.1). As noted in the results, the maximum solar charging rate was the same for all groups. This first suggests that environmental conditions, such as winter conditions characterized by short daylight hours and low temperatures, reduced the overall capacity of collars to accumulate solar charge, but that high rates of solar charging could be achieved when conditions allowed.

Secondly, these results indicate that there may be an effect of habitat and animal behaviour on overall solar charge accumulation. Eftang et al. (2022) implicated battery problems as a possible source of insufficient data records, and Log et al. (2022) noted that environmental conditions affected Nofence VF solar charging performance, with batteries running out of charge after 8 – 15 days of continuous use on goats. The lack of adequate battery charge was attributed to the densely forested nature of the study environment, and the goats’ behaviour of resting in shady areas. This is consistent with our results, where animals with greater access to shady, forested habitat experienced a lower mean solar charging rate than animals that remained in open grasslands.

While a difference in solar charging rate was noted between cattle grazing in different environments during this study, the batteries themselves remained nearly fully charged. This contrasts with the results of Log et al. (2022), where the goat collar batteries ran out of charge entirely. The likely explanation for this is battery size and capacity; Nofence goat collars use three cell lithium ion batteries rather than the higher capacity six cell lithium ion batteries found in cattle collars (Nofence Ltd. 2023). While there were no significant differences in battery and solar charging performance across years (Table 2.1), two years is not a sufficient amount of time to evaluate collar longevity. Further studies are needed to determine the lifespan of battery and solar panel function, particularly when operating in sub-optimal conditions such as harsh winter conditions.

This study did reveal that solar charging rate could be affected by air temperature and the hours of illumination per day. There was a significant interaction between the two effects during the summer 2022 trial where lower hours of illumination tended to correspond with a slower increase in solar charging rate across increasing temperatures. There was also a significant interaction between the two effects during summer grazing in 2023, but conversely, lower hours of illumination tended to correspond to an increase in solar charging rate, whereas higher hours of illumination corresponded to a decrease in solar charging rate. The trends from 2022 support the logical conclusion that hours of illumination are the main limiting factor, and as hours of illumination increase so does the capacity of solar panels to respond to an increase in temperature. However, the trends from 2023 do not support this idea; additionally, the lower conditional R^2 value of the 2023 regression indicates that the model does not explain as much of the variance as the 2022 model. Therefore, it is logical to conclude that there are other factors, such as cloud cover and precipitation, the behaviour of the animals, or the presence of offspring, that contributed more to the effects on solar charging in 2023 than in 2022.

Ultimately, the effect of either variable had a negligible effect on collar function and battery performance throughout all three trials.

2.6. Conclusion

The findings of this study provide evidence that Nofence VF collars can operate under a wide range of environmental conditions in western Canada and have the potential to be a useful tool for the management of grazing cattle, provided network connectivity is available. Collar failures were uncommon, mostly caused by network connection failure and the occasional loss of a collar from the animal. Battery capacity and solar charging performance were able to maintain VF collar function during optimal (summer) and sub-optimal (winter) conditions. Connectivity issues were limited to a small amount of the time collars were use, with manual resetting required in rare situations. However, there are large areas in western Canada that do not have access to cellular networks. Recent advancements in satellite-to-cellular networks may resolve network access problems, even for rural Canadian producers. For example, in April of 2023 Rogers Communications Inc. announced a partnership with the America aerospace company SpaceX to bring satellite-to-cellular network access to areas traditionally beyond existing network limits (Thiel 2023). Advancements such as these increase the availability of the cellular network to rural producers and are important for the continuing development and adoption of geospatial agriculture technology. This research provides novel insight regarding the technical performance of Nofence VF collars, as a first step to evaluating their potential for utilization in western Canadian grazing lands.

2.7. List of Tables

Table 2.1. Summary statistics of the technical performance of Nofence virtual fencing collars during winter and summer grazing trials in 2022 and 2023.

Attribute	2022			2023		
Environmental Conditions						
Season of use	Summer		Winter	Summer		
Deployment date	June 24 – Aug. 30		Nov. 30 – Jan. 19	June 23 – Aug. 15		
Mean (range) daily temperature (∘C)	+17.5 (+5.7 to +32.0)		-15.9 (-37.6 to -3.0)	+17.2 (+3.6 to +29.1)		
Mean (range) daily illumination (hr)	15.7 (13.8 - 16.9)		7.8 (7.6 - 8.3)	16.1 (14.8 - 16.9)		
Collar version number	2.1		2.1	2.1		2.2
Animal class & number	Heifers (49)	Bulls (2)	Steers (30)	Cow-calf (45)	Bulls (5)	Cow-calf (23)
Collar Performance						
Poor network connection (% of time)	0.23	0.07	0.01	0.16	0.32	0.08
Mean (± SD) duration of network connection outage (min)	30.6 (± 3.7)	30.0 (± 0.01)	30.3 (± 0.9)	31.1 (± 4.5)	30.5 (± 2.2)	30.3 (± 2)
Mean (± SD) battery charge (%)	96.4 (± 0.8)	96.4 (± 0.6)	96.1 (± 1.2)	96.2 (± 0.9)	96.3 (± 0.5)	96.6 (± 0.7)
Mean (± SD) battery charge (%)	96.4 (± 0.8)	96.4 (± 0.6)	96.1 (± 1.2)	96.2 (± 0.9)	96.3 (± 0.5)	96.6 (± 0.7)
Minimum battery charge (%) (range)	94.5 (85.5 - 95.0)	95.0 (95.0 - 95.0)	94.0 (92.1 – 96.0)	94.5 (87.1 – 97.4)	94.5 (93.8 – 95.0)	95.1 (92.6 – 96.9)
Mean (± SD) solar charge rate (mA/hr)	11.4 (± 23.1)	10.7 (± 22.0)	3.1 (± 10.8)	12.4 (± 22.1)	10.4 (± 19.6)	7.9 (± 18.0)
Collar Failure						
Physical collar lost from animal (no.)	0	0	1	1	2	0
Failed network connection (no.)	1	0	0	9	0	4
User error (no.)	0	0	0	1	0	0
Hardware failure (no.)	0	0	0	1	0	0

Table 2.2. Summary of results from a poisson generalized linear mixed model investigating the effects of temperature (Celcius) and illumination (hrs) on daily solar charging rate (mA day^{-1}). The Chi Squared Test of Independence was used to assess whether variables and their interaction were significant, and effect sizes are represented using the incident rate ratio.

Variable	Temperature	Illumination	Temperature x Illumination
Summer 2022			
X^2 (p-value)[1]	155.0 (< 0.001)	23.7 (< 0.001)	170.1 (< 0.001)
IRR (SE)[2]	0.45 (0.03)	0.25 (0.03)	1.1 (0.004)
Summer 2023			
X^2 (p-value)	0.8 (0.4)	17.9 (< 0.001)	60.0 (< 0.001)
IRR (SE)	2.74 (0.36)	1.85 (0.33)	0.94 (0.008)

[1] *Chi squared statistic.*

[2] *Incident rate ratio, used to estimate the relative change in the rate of occurrence of events.*

2.8. List of Figures

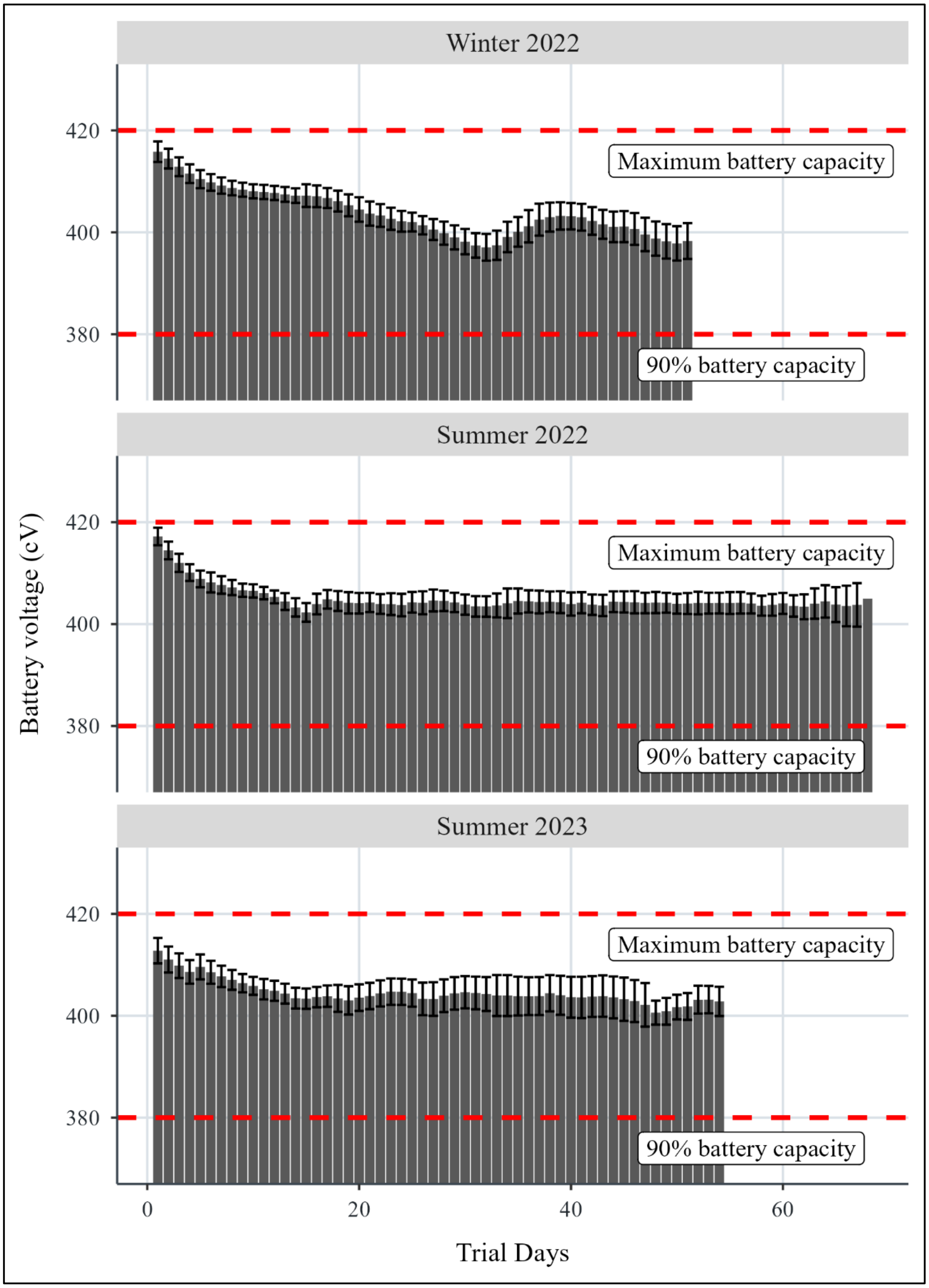

Figure 2.1. Mean (± SD) daily battery voltage across trial days during winter grazing in 2022 and summer grazing in 2022 and 2023.

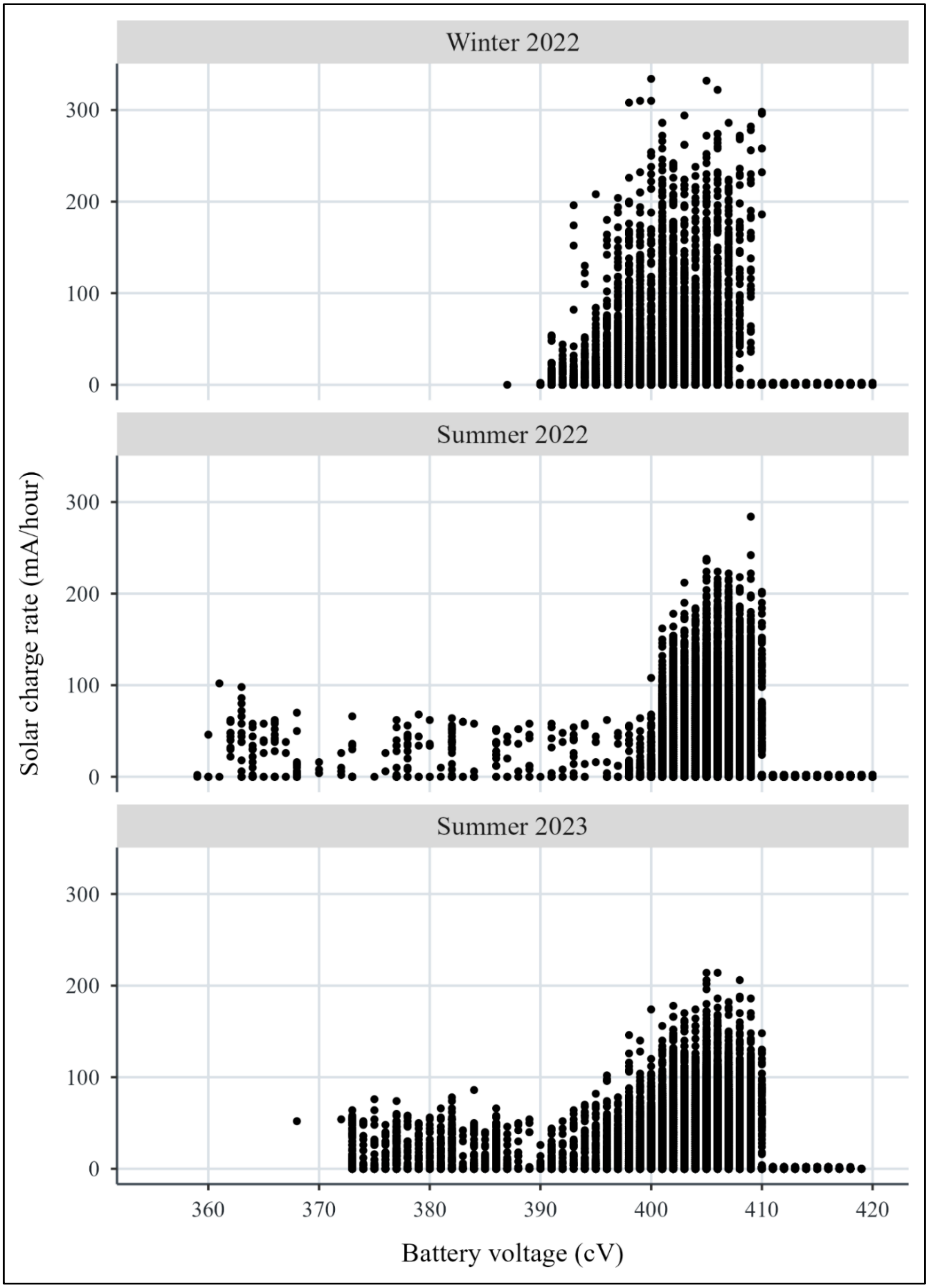

Figure 2.2. A comparison of the reported solar charging rates and their respective battery levels, showing the drop in charging at 410 cV, with maximum battery capacity being 420 cV.

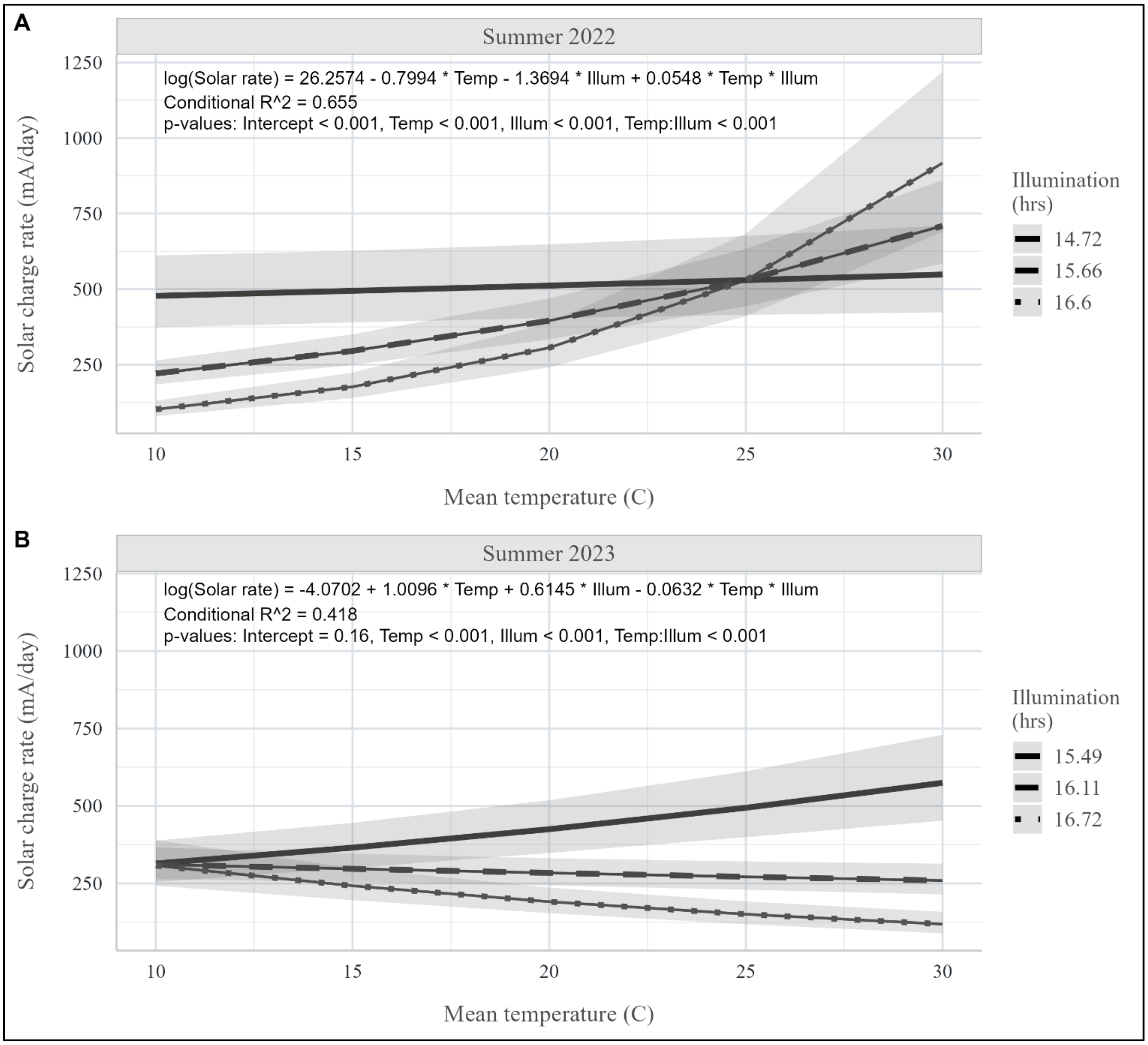

Figure 2.3. Poisson generalized linear mixed models comparing the effects of temperature (Celsius) and daily illumination (hr), and the interaction thereof, on daily solar charging rate (mA day^{-1})

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Chapter 3: The efficacy of virtual fencing to manage beef heifers and cow-calf pairs: discovering factors of success

3.1. Abstract

This study investigated the use of Nofence virtual fencing (VF) technology to manage rotational grazing for heifers and first-calf cows in central Alberta, Canada. The research focused on the training and behavioral responses of heifers and cows with uncollared calves at side trained to VF, examining individual learning, containment effectiveness, and factors influencing VF success. Two seasons of rotational grazing using VF collars equipped with GPS, cellular connectivity, and solar-powered batteries were conducted; first with heifers that were naïve to VF, and then with the same animals as cow-calf pairs and prior VF experience. Heifers learned to comply with VF boundaries within 5-7 days, with a mean ratio of electrical shock to audio cues (E:A) of 17.9% (±18.4) during training, decreasing to 5.2% (±11.2) during rotational grazing. Cows with calves at side and previous experience with VF received an E:A ratio of less than 2.5% during re-training and rotational grazing. All animals were successfully contained by VF boundaries more than 99% of the time. No correlations were present between the number of VF stimuli and animal characteristics or their performance. Grazing pressure and stocking rate influenced the number of VF stimuli received and the duration of audio cues. The study concludes that VF technology effectively manages rotational grazing, with cattle demonstrating learning and compliance to VF boundaries. Further research is needed to explore the effects of higher stocking rates, animal characteristics such as feed efficiency and breed composition, animal behaviour, and potential for herd control using VF collars on a subset of animals. The findings support VF's potential to enhance cattle management flexibility and resource utilization in the Canadian beef industry.

3.2. Introduction

There are 11.8 million beef cattle being raised in Canada, 80% of which graze on 18.5 million hectares of tame or native pastureland, accounting for 30% of the total farm area in Canada (Sheppard et al. 2015; Statistics Canada 2022, 2024a). The management of grazing cattle therefore plays an important role in the sustainable use of land, and often relies on physical fences, such as barbed wire, permanent electric, or temporary electric fencing, to control the distribution of cattle in space and time. The type and amount of fencing installed by a producer can vary depending on land management goals, the resources at hand, and the preferred grazing system to be used, including either continuous or rotational grazing of varying complexities (Sheppard et al. 2015; Holley et al. 2020). The construction and maintenance of fences represent a significant cost in the management of grazing beef cattle, especially when additional control or system complexity is desired by the producer (Bishop-Hurley et al. 2007). Moreover, the inflexibility of physical fences limits the ability of producers to respond to naturally changing circumstances (Aaser et al. 2022), and negatively impacts wildlife movement and broader ecosystem structure (Jachowski et al. 2014). This highlights the necessity for alternative management solutions.

Virtual fencing (VF), an innovative technology proposed as an alternative to physical fencing, has the potential to reduce the infrastructure cost of cattle management, enhance the efficiency of beef operations, and address select environmental impacts of the industry (Goliński et al. 2023; Hamidi et al. 2023). Several VF systems are in various stages of commercialization globally, including Nofence (Batnfjordsøra, Norway), Vence (San Francisco, CA, USA), eShepherd (Melbourne, Australia), Halter (Auckland, New Zealand), and Corral Technologies (Lincoln, NE, USA). This study focused on the Nofence VF system, which uses a mobile phone application (app) to control a collar-mounted device equipped with global positioning system (GPS), Bluetooth, and cellular network capabilities, an accelerometer, and a lithium-ion battery supported by solar panel recharging (Nofence AS (Ltd.) 2023). Virtual pasture boundaries are set in the app and downloaded to the collars, which continuously track animal locations and use a combination of audio cues followed by electrical cues to confine animals to targeted grazing areas, which can be changed in real-time (Hamidi et al. 2024). Recent studies have shown that Nofence VF collars are able to perform well in the temperate northern grasslands of western Canada, even during winter (see *Chapter 2*).

Training of animals is an essential first step to start using a VF system (Umstatter et al. 2015; Hamidi et al. 2024). During training cattle must associate an audio cue with a subsequent electric shock, and learn to avoid the shock by retreating from a virtual boundary. Several studies have shown that cattle naïve to VF learn to predict and control the incidence of electric shocks (Lee et al. 2009; Verdon et al. 2020; Hamidi et al. 2024), but further understanding of how cattle learn to comply with virtual fences is needed in order to optimize training and experience benefits from VF. Additionally, it is necessary to investigate how cattle with prior VF experience react to the technology after an extended break between exposures. Approximately 76% of beef cattle producers utilize seasonal feeding areas as an alternative to grazing during the winter months from November to April, and this results in periods of time varying from weeks to months in duration where cattle would not experience VF boundaries (Sheppard et al. 2015).

Current applications of VF include rotational grazing, management of encroaching plants, the creation of fuel breaks, and the protection of sensitive ecological areas (Campbell et al. 2020; Log et al. 2022; Staahltoft et al. 2023; Boyd et al. 2023). Rotational grazing, a system which utilizes at least three paddocks that are alternatively rested and grazed (Allen et al. 2011), is capable of providing ecological and livestock production benefits (Teague et al. 2011; Roche et al. 2015), but factors such as increased infrastructure and ongoing labour commitments are barriers to its adoption (Wang et al. 2020). Virtual fencing can facilitate the adoption of rotational grazing and other adaptive management strategies by offering greater control and flexibility in grazing management, without the associated increase in infrastructure and labour that is unavoidable with traditional fencing and management systems (Butler et al. 2006). Current research shows that VF can contain cattle in static grazing areas and preliminary work shows that cattle react favorably to changing VF boundaries, though success of static or dynamic VF boundaries may vary based on cattle and pasture management factors (Campbell et al. 2017, 2019a; Verdon et al. 2021; Campbell et al. 2021; Confessore et al. 2022). This highlights the importance of identifying factors that affect cattle behaviour and therefore the success of VF systems.

Virtual fencing is a new technology, and while it has already garnered much interest, gaps in the current body of research remain. This study explored the use of VF to manage rotational grazing for heifers and first-calf cows in the context of a commercial beef cattle operation. More specifically, we: 1) investigated whether heifers naïve to VF learn to comply with Nofence VF, and how first-calf cows with previous VF experience respond to VF stimuli after an extended break; 2) assessed whether Nofence VF successfully contains heifers and cows with calves at side in virtual sub pastures during rotational grazing; and 3) described factors that may affect the success of VF technology.

3.3. Materials and Methods

3.3.1. Study Area

The study was conducted at the Roy Berg Kinsella Research Ranch (KRR), a University of Alberta cattle research facility and cow-calf operation located in western Canada approximately 150 km SE of Edmonton, Alberta (53˚0’29.919”, -111˚30’57.8334”). The ranch falls within the Aspen Parkland natural subregion, has a cool continental climate, with a historical mean temperature of 17 ^{o}C during July and 391 mm annual precipitation (Alberta Climate Information Service [ACIS] n.d.), of which 70% falls during the summer growing season (May through September). The landscape of this area is gently to strongly rolling hummocky moraine, and beef cattle in this study grazed on tame pastures that were once subject to cultivation but have since been seeded to forages such as smooth brome (*Bromus inermis* L.), timothy (*Phleum pratense* L.), and alfalfa (*Medicago sativa* L.).

3.3.2. Study Animals

Animals used in this study include Kinsella Composite (KC) heifers (n = 49) and two KC bulls in 2022, and a subset of these same animals returning in 2023 as first-calf cows (n=39) with calves at foot aged 2-3 months as of June 1, 2023, and joined by three new KC bulls. The KC cattle have been uniquely developed at the KRR and are descendants of three synthetic lines composed mainly of Angus, Charolais, Galloway, Hereford, Brown Swiss, Holstein, and Simmental, which were fully combined into one herd by 1999 (Berg et al. 2014).

All cattle handling and VF collar evaluations were conducted under animal ethics protocols approved by the University of Alberta Committee on Animal Care and Use (AUP #3850 and #4004), following guidelines of the Canadian Council on Animal Care (Canadian Council on Animal Care [CCAC] 2009). As part of another ongoing study, animals were weighed and an ultrasound was used to assess rib and rump fat depths at the beginning and end of each trial, with weighing events repeated approximately every two weeks throughout each trial.

3.3.3. Forage Sampling

Standing forage biomass was measured in each VF sub-pasture before and after grazing to track changes in grazing pressure, a measure that quantifies the relationship between animal forage intake and the forage mass available within a grazing area at a specific point in time (Allen et al. 2011). In 2022 and 2023, six and four samples, respectively, consisting of the annual net primary production (ANPP), were harvested from within a 0.25m^2 quadrat; sampling locations were randomly chosen, but stratified by topographic position to be representative of the pasture. Litter was discarded and broad-leafed plants (forbs), the current annual growth of shrubs, and graminoids were harvested. Vegetation was dried to a stable weight and then weighed. Forage mass values were converted to kg ha^{-1} for analysis.

3.3.4. Nofence Virtual Fencing System

The Nofence VF system has been previously described (see section *2.2.2. Nofence virtual fencing system*, Hamidi et al. 2024). Briefly, it is comprised of 1) an animal collar featuring Bluetooth and mobile network receivers, an accelerometer, a re-chargeable lithium ion battery, two (side-mounted) solar panels to facilitate recharging, and a global navigation satellite system (GNSS) receiver (Nofence Ltd. 2023); and 2) a mobile phone application that is used to set parameters for virtual pastures, manage animal locations, and monitor collar performance. Network connection is necessary to download virtual pasture information to collars and exchange messages and notifications between the mobile application and collars. The GNSS receiver tracks the location of animals and triggers audio cues and electrical shocks independent of mobile network connection. The collar uses a two-part adjustable neck strap to remain on the animal, comprised of metal side chains and a rubber connector for comfort on the top of the neck. The total weight of the collar is 1446 g. The mobile phone application can be downloaded for free on any iPhone or Android device and is used to manage the VF system.

Details about the VF operation can be accessed from the Nofence Ltd. manual (2023) and Hamidi et al. (2024). Briefly, when an animal approaches the virtual boundary between the inclusion (where animals should be) and exclusion (where animals should not be) zones, the collar plays a warning audio cue. The warning is a maximum of 82 dB and varies from a specific low-pitched tone to a specific higher-pitched ton. The velocity at which the animal is moving determines the rate at which audio cues change in tone, with a total warning duration of 5 – 20 sec depending on animal velocity and how quickly they respond to the audio cue. The audio cue ends when either 1) the animal turns around and the collar records a position that is one metre away from where the warning was triggered, or 2) when the entire audio tone scale has been played. Once the audio warning is complete, if the animal has not turned away from the virtual boundary an electrical shock is administered. The delivered shock is between 1.5 and 3 kV, depending on environmental conditions, and the collar unit has a maximum stored power capacity of 0.2 J. If the animal continues into the exclusion zone despite the audio cue and shock, the collar will continue to deliver audio cues and shocks; animals can receive a maximum of three warnings followed by shocks, after which they are considered escaped. Collars of escaped animals do not discharge any further audio cues or shocks but continue to track their location. Once an escaped animal successfully returns to the inclusion zone their collar resumes normal operation.

Nofence VF collars have two modes: operating and teaching. In operating mode animals must return to a location that is one metre behind where the audio warning was triggered to end the audio warning. In teaching mode the warning is more easily switched off to support animal learning to control the shocks; for example, the audio warning will shut off if the animal moves their head or takes a few steps away from the boundary. While the most recent Nofence Ltd. operating manual (2023) does not describe specific criteria to switch from teaching to operating mode, the 2020 version states that the collar mode will automatically switch from teaching to operating once the animal has correctly responded to 20 audio warnings by avoiding the subsequent ES, which is corroborated by Hamidi et al. (2024). When animals wearing collars are moved to a new pasture, the collars automatically reset to teaching mode.

3.3.5. Rotational Grazing Trials

Cattle were confined within, and rotated between, sub-pastures, using Nofence VF technology in 2022 and 2023. Each trial was composed of two phases: training and rotational grazing. Rotational grazing was further divided into grazing periods; discrete periods of time during which animals were contained within sub-pastures delineated by VF within larger, physically fenced pastures (Figure 3.1). Grazing phases refer to the start, i.e., first two days, or end, i.e., last two days, of each grazing period. Virtual fences were deactivated and cattle were mustered and herded by ranch staff approximately every two weeks for weighing. Water was available *ad-libitum* in all trials, which were conducted as follows:

5) The first rotational grazing trial took place from June 24, 2022 to August 30, 2022, on 51 commercial KC cattle (49 yearling heifers and two breeding bulls) naïve to VF. The training phase was 11 days long with an average pasture size of 6.5±3.1 ha, and composed of four progressive phases: i) an initial 24-hour acclimation period during which collars were turned off; ii) a five-day period when collars were activated and virtual boundaries coincided with existing physical fences; iii) a two-day period when one virtual boundary was moved 50 m inward from the physical fence ; and iv) a three-day period during which the virtual boundary was moved to exclude cattle from half of the physical pasture area. Training was followed by a 56-day rotational grazing trial to test the capabilities of Nofence VF to confine heifers within and rotate them between designated inclusion zones. The average grazing period length, grazing area, and stocking rate were 7.3±1.5 days, 4.7±0.9 ha, and 2.4±0.8 AUM ha^{-1}, respectively.
6) The second rotational grazing trial ran from June 27 to August 16, 2023, with 39 of the original 49 heifers from Trial 1 returning as first-calf cows with calves at side, and thus with previous exposure to VF. Cows were joined by three KC bulls (naïve to VF), and all calves remained uncollared. A six-hour acclimation period was followed by a three-day re-training phase with an average pasture size of 7.15±3.1 ha, where VF boundaries aligned with physical fences for one day, VF boundaries were moved inwards 50 m for one day, and then VF was used to exclude access to half of the pasture for a final day. This was followed by a 46-day rotational grazing period similar to that described in Trial 1. The average grazing period length, grazing area, and stocking rate were 6.1±0.6 days, 3.7±1.5 ha, and 2.6±1.3 AUM ha^{-1}, respectively.

3.3.6. Pedometers and Cattle Activity

All heifers and cows were fit with an IceQube+ pedometer (Peacock Technologies, Stirling, Scotland, UK) at the start of the grazing period as part of another ongoing investigation into cattle activity. Pedometers were placed onto the lower left rear leg and collected continuous data on the proportion (%) of time cattle spent lying down and standing, as well as movement patterns through step counts in 15-minute binned intervals. Here, we utilized information on lying time (as lying time and standing time are inversely related) and step counts to relate these behaviors to interactions with the VF boundary. Pedometers were removed at the end of each grazing trial, and data downloaded for analysis.

3.3.7. Data and Statistical Analysis

All data processing and statistical analyses were performed using the program R (version 4.4.0) in R Studio (R Core Team 2024). Data from Nofence VF collars were compiled throughout training and rotational grazing. Collars transmit data via the mobile network to an online cloud, from which data were downloaded. As described in Staahltoft et al. (2023), collars report five types of messages. '*Warning'* and '*Zap'* messages were sent every time an animal received an audio cue (AC) or electrical shock (ES), respectively, and were used to count the number of VF stimuli that cattle received. '*Status*' messages were sent whenever the fence or collar status changed and were used to count the number of escapes and their duration. '*Poll'* messages were received every 15 minutes and were used, in conjunction with *Warning, Zap,* and *Status* messages, to calculate the amount of time cattle were contained by VF boundaries. Data were checked for duplicates, and 0.28% of data were removed. Outliers for all data were identified as observations more or less than 4 standard deviations away from the mean.

3.3.7.1. Virtual fence collar data

VF data were compiled from *Zap* and *Warning* messages as the number of ESs and ACs received by each animal per day, and approximately 2.3% of data were removed as outliers. The E:A ratio is the number of shocks divided by the number of audio cues received by cattle (head^{-1}day^{-1}). Audio cue duration was averaged per head per day, and approximately 0.12% of data were removed as outliers. The distribution of VF stimuli data was inspected using the *fitdistrplus* package (Delignette-Muller and Dutang 2015) and visually through histograms, and was observed to fit a Poisson distribution. The frequency of time spent within inclusion zones (IZF) was compiled per head per day, as seen in Staahltoft et al. (2023) where "*FenceStatusNormal*", "*Escaped*", and "*MaybeOutOfFence*" observations were used to calculate the IZF such that "*FenceStatusNormal*" observations represented time spent within inclusion zones. The number and duration of escapes were summarized and presented as raw data due to their small sample size.

Throughout both grazing trials there were instances of planned (e.g., animal handling, field tours) and unplanned (e.g., removing cattle from an incorrect pasture) human disturbances that impacted cattle behaviour. For the purposes of this study, all collar and pedometer data were removed for: 1) handling and weighing events; 2) periods when cattle needed to be moved without using the VF; and 3) anomalous disturbance events, such as field tours and a severe summer storm. Bulls were excluded because of their small sample size, one heifer was removed during the training phase because of handling difficulties, and another was removed because of a VF collar connection malfunction. Once data were removed as indicated, VF stimuli counts were standardized over the hours of data inclusion per day. Training phase records were excluded for any summaries or analyses that did not require training data, as indicated.

3.3.7.2. Learning and individual behaviour

The means and standard deviations of the number of ESs and ACs (head^{-1}day^{-1}) and the E:A ratio, and the mean and standard error of the mean of AC duration, are reported for the training and rotational grazing phases of each trial, and across cohorts within each trial.

The ability of cattle, both naïve to and experienced with VF, to learn to avoid crossing VF boundaries was investigated through the change in ESs, ACs, and the E:A ratio over time, where a decrease in ESs and the E:A ratio indicated that associative learning took place (Aaser et al. 2022; Hamidi et al. 2024). Means and standard deviations of daily ESs, ACs, and E:A ratios were presented graphically to visualize change over time. Audio cues, ESs, and E:A ratios were summed over the training and rotational grazing periods for each animal. All three values were compared between training and rotational grazing using the Wilcoxon signed rank test for paired, non-parametric data. To further represent the change in VF stimuli over time, sums of ESs and ACs for each animal were plotted over five distinct time periods for each trial, including the following: training (11 days in 2022 and 3 days in 2023), the first 14 days of rotational grazing, the middle of rotational grazing (28 days in 2022 and 19 days in 2023), the last 14 days of rotational grazing, and for the entirety of rotational grazing. The number of ACs, ESs, and the E:A ratios for heifers in 2022, and cows with calves in 2023, were also compared using Wilcoxon signed rank tests and visualized using scatterplots. The effects of prior VF experience and uncollared offspring are confounded, limiting the interpretation of these results.

Individual cattle in each trial were ranked by the total number of ESs they received from most to fewest. These data were visually inspected to reveal distinct groups of VF behaviour, and cattle were categorized into high stimuli (HS), moderate stimuli (MS) and low stimuli (LS) cohorts. These cohorts describe the number of ESs and ACs received by each individual animal relative to the other individuals in each trial. Information about virtual fence stimuli ranks and cohorts for every animal are available in Table S3.1. Differences in ESs, ACs, and E:A ratios received by cattle between cohorts, were investigated using the Kruskal-Wallis rank sum test for non-parametric data. Significant Kruskal-Wallis results were followed by post-hoc pairwise comparisons using Dunn's test from the R package *FSA* (Ogle et al. 2023).

3.3.7.3. Virtual fencing and rotational grazing

The effectiveness of using VF to contain cattle within virtual sub-pastures was investigated using IZF, the number of escapes in total and expressed per animal and day, the duration of escapes, and the animal performance metrics of average daily gain (ADG) and pregnancy rate. The animal performance metrics were included to assess the productivity of both herds while under the management of researchers using VF. The mean IZF ($head^{-1}$) for training and rotational grazing periods were compared using Wilcoxon signed rank tests, and the Kruskal-Wallis rank sum test followed by Dunn's test was used to investigate whether the likelihood of being outside of the VF inclusion zone during rotational grazing differed between cohorts. Spearman's rank correlation from the R package *rstatix* (Kassambara 2023) was used to investigate relationships between cow and calf ADG, pregnancy rate, and mean rib fat depth (RD) of individual animals and the ESs, ACs, and E:A ratios ($head^{-1}trial^{-1}$) received throughout the rotational grazing trials. Cow and calf ADG, pregnancy rate, and RD were compared between cohorts using Kruskal-Wallis and Dunn's tests. The Mann-Whitney U test for unpaired, non-parametric data was used to compare the number of ESs and ACs received by pregnant and open cattle, excluding data from the training phase.

3.3.7.4. Factors affecting virtual fence outcomes

Behaviour metrics and select inherent cattle characteristics were used to investigate possible factors associated with the behavioural variation observed between individuals within a VF system. Spearman's rank correlation was used to investigate possible relationships between ESs and ACs ($head^{-1}$ day^{-1}), the E:A ratio, AC duration (sec), step counts ($head^{-1}$ day^{-1}), lying time (min $head^{-1}$ day^{-1}), pedometer-calculated motion index, and inherent animal characteristics. These animal characteristics include feed efficiency quantified previously as residual feed intake corrected for backfat (RFI_{fat}) and measured in drylot as a heifer (Basarab et al. 2011), and the fraction of Angus in the breed composition (BC_{angus}), which refers to the proportion of different breeds that contribute to the genetics of a crossbred animal (Akanno et al. 2018; Zhang et al. 2020). Means and standard deviations of behaviour and inherent cattle characteristics are presented.

Additionally, stocking rate and grazing pressure were used to investigate possible effects of grazing management strategies on VF success. Stocking rate, which describes the relationship of the number of animals utilizing a specific area of land over a specified time (Allen et al. 2011), was calculated as animal unit months (AUM) per hectare for each rotational grazing period. Grazing pressure is an instantaneous relationship between animal live weight, and therefore forage intake, and the forage mass available in the specific area of land being grazed (Allen et al. 2011). Grazing pressure was calculated for each rotational grazing period as the forage demand of the herd with bulls included, divided by the forage mass available in the VF sub-pasture. Demand was based on dry matter intake (DMI), which was assumed to be 2% of bodyweight for heifers and bulls, and 2.4% of bodyweight for lactating cows (Agriculture and Food 2008). An estimated bodyweight (EWT) was calculated whenever a scheduled weighing session did not fall within a grazing period. Bulls, ranging in age from one to three years, were weighed throughout both trials, but the frequency was inconsistent due to the nature of the other ongoing investigation. All bulls used in these trials were weighed at least once, and these measurements were used to estimate the weights of the yearling, two-year-old, and three-year-old KC bulls as 454 kg, 544 kg, and 635 kg respectively. Furthermore, in 2023 calves were included in the calculation of forage demand, with the assumption that calves of median frame size, nursing at median milk yield, each consume approximately 2 kg day^{-1} of dry matter at 4 months old and 3.6 kg day^{-1} of dry matter at 5 months old (Fox et al. 1988).

Spearman's rank correlation tests were used to investigate possible relationships between stocking rate (AUM hec^{-1}), grazing pressure, ESs and ACs, E:A ratios, and AC duration (sec). Virtual fence stimuli data were summed per head over each grazing period. Summary statistics describing the grazing periods, stocking rate, grazing pressure, forage supply and utilization are presented.

3.4. Results

3.4.1. Learning the Virtual Fence System

3.4.1.2. Naïve heifers in 2022

Audio cues, ESs, and E:A ratios are presented for heifers naïve to VF in Tables 3.2 and 3.3. The E:A ratio received by heifers declined over the course of training and rotational grazing (Figures 3.2 and S3.2-C). Compared to day one, the first day of training, the mean E:A rate per day decreased 15.9% by day three, 55.4% by day five, and 93.6% by day 11, the first day of rotational grazing. Heifers experienced a significantly lower E:A ratio while rotational grazing than during training (Table 3.3). There was no significant difference in E:A ratio between cohorts (Table 3.2). Electrical shocks received per day decreased over time for MS and LS heifers, reaching a stable and low level by day five, apart from day eight that occurred during the training phase and was the first day that VF boundaries were used to exclude cattle from half of a physical pasture (Figure S3.2-A). In contrast, the mean ESs ($head^{-1}day^{-1}$) received by HS heifers fluctuated over time with no clear decrease (Figure S3.2-A). Mean ACs ($head^{-1}day^{-1}$) received by heifers fluctuated for all cohorts, remaining approximately the same for MS and LS heifers, and increasing after the training phase for HS heifers (Figure S3.2-B).

3.4.1.3. Experienced cows with calves at side in 2023

Audio cues, ESs, and E:A ratios for cows with uncollared calves at side and prior VF experience, are presented in Tables 3.2 and 3.3. The E:A ratio demonstrated by cows remained consistently low and relatively stable during both the re-training and rotational grazing phases (Figures 3.2 and S3.3-C). There was no difference (Kruskal-Wallis, $p \geq 0.05$) in E:A ratio between cohorts (Table 3.2) and a small increase in the E:A ratio from retraining to rotational grazing was observed (Table 3.3). The mean number of ESs ($head^{-1}$ day^{-1}) received by cows fluctuated in no clear pattern over the 2023 trial, although they trended higher for HS cows than MS and LS cows (Figure S3.3-A). In addition, HS cows received more ACs ($head^{-1}$

day^{-1}) than MS and LS cows, and experienced distinct periods of high and low numbers of ACs (Figure S3.3-B).

The mean number of ESs (head^{-1} day^{-1}) received during rotational grazing were significantly different between heifers and cows, being lower for cows (mean ±SEM, heifers = 0.76 ±0.09, cows = 0.53 ±0.05; Wilcoxon signed rank test, $p = 0.02$). In contrast, the mean number of ACs (head^{-1} day^{-1}) received during rotational grazing were significantly greater for cows than as heifers the year before (mean ±SEM, heifers = 17.2 ±2.2, cows = 34.4 ±5.2; Wilcoxon signed rank test, $p < 0.001$), as were E:A ratios (mean ±SEM, heifers = 0.052 ±0.003, cows = 0.021 ±0.002; Wilcoxon signed rank test, $p < 0.001$). When ESs, ACs (head^{-1} trial^{-1}) and E:A ratios were presented graphically for heifers and cows, the MS and LS heifer groups in 2022 appeared to receive similar numbers of ESs upon return to the VF system in 2023, while HS heifers received fewer ESs upon return in 2023 (Figure 3.3-A). In contrast, HS and MS heifers received more ACs upon return in 2023 than in 2022, while LS heifers remained the same (Figure 3.3-B). Finally, all animals demonstrated lower or similar E:A ratios in 2023 compared to 2022 (Figure 3.3-C).

3.4.2. Virtual Fencing and Rotational Grazing

Escape events are summarized in Table 3.3. Briefly, heifers and cows with uncollared calves at side spent more than 99% of their time within VF sub-pasture inclusion zones during both rotational grazing trials (Table 3.3), and heifers escaped for shorter durations compared to cows (Table 3.3). The E:A ratio during rotational grazing was not significantly different between cohorts for heifers or cows (Table 3.2). Three of 49 heifers (1 MS and 2 LS) and four of 38 cows (all MS; the pregnancy status of one cow was not recorded in 2023) were diagnosed as open during pregnancy checks in late fall of each year (Table 3.4). The number of ESs and ACs (head^{-1} trial^{-1}) received, and the E:A ratio demonstrated by cows and heifers, were not correlated with ADG, calf ADG (2023 only), mean rib fat depth, or pregnancy rate ($p \geq 0.05$). Heifers exhibited greater mean rib fat depth than cows with calves (2.6 ±0.9 mm and 2.2 ±0.5 mm respectively, $p = 0.01$). Differences in pregnancy status between years was not significant ($p \geq 0.05$).

3.4.3. Factors Affecting Virtual Fence Outcomes

3.4.3.1. Behaviour cohorts

Cattle were categorized into VF behaviour cohorts based primarily on the number of ESs, and secondarily on the number of ACs (Figures 3.2, 3.3, S3.1; Table S3.1), received over the course of each trial. More specifically, 1) High stimuli (HS) cattle were those that received a higher number of ESs and ACs; 2) moderate stimuli (MS) cattle were those that received high to moderate ACs and moderate to low ESs; while 3) low stimuli (LS) cattle were those that received low numbers of ESs and ACs (Table 3.1). Heifers and cows within HS groups received proportionally twice as many ESs and ACs while rotational grazing, in comparison to MS and LS cattle (Table 3.1). The total E:A ratio for cattle over each trial was negatively associated with the total number of ACs received ($r = -0.65$, $p < 0.001$ in 2022; $r = -0.78$, $p < 0.001$ in 2023). The average E:A ratio per day for cattle over each trial was not correlated with the total number of ACs received by heifers in 2022 ($p > 0.05$) but was negatively associated with ACs received by cows in 2023 ($r = -0.61$, $p < 0.001$). Ten heifers did not return for the 2023 trial, and of the remaining 39, 50%, 77%, and 50% of HS, MS, and LS heifers, respectively, were categorized to the same cohort class as cows in 2023, with a total of 67% of animals being categorized as the same cohort in both years (Table S3.1).

3.4.3.2. Animal factors

Significant correlations between ACs, ESs, E:A ratio, and behavioural factors are summarized in Table 3.6 for both heifers and cows. Residual feed intake (RFI_{fat}) and BC_{angus} were not correlated with the number of ESs or ACs received by cattle ($p > 0.05$). No significant differences in step counts, lying time, and motion index were observed between cohorts and trial years (Table 3.5).

3.4.3.3. Grazing management factors

The duration of ACs for heifers in 2022 was negatively correlated with cattle stocking rate ($r = -0.13$, $p < 0.001$) but positively correlated with grazing pressure ($r = +0.24$, $p < 0.001$). Neither stocking rate nor grazing pressure were correlated with the number of ESs or ACs received per head during each grazing period, or the E:A ratio ($p \geq 0.05$). Stocking rate for cows with calves in 2023 was positively correlated with ESs and ACs, AC duration, and the E:A ratio ($r = +0.36$, $+0.25$, $+0.25$, and $+0.33$ respectively, $p < 0.001$). Grazing pressure was positively correlated with ESs, AC duration, and the E:A ratio ($r = +0.094$, $r = +0.093$, and $r = +0.29$ respectively, $p < 0.05$).

3.5. Discussion

3.5.2. Heifers Naïve to Virtual Fencing

Heifers, naïve to VF technology, quickly learned to navigate VF boundaries using ACs to avoid ESs. The mean number of ESs received by the heifers ($head^{-1}day^{-1}$) was lower during rotational grazing than training, while the mean daily E:A ratio declined throughout the training phase and into rotational grazing, and the overall mean E:A ratio during rotational grazing was distinctly, visually lower than that during training. A 'learning curve' was evident from the decrease in the mean daily E:A ratio over time as seen in Figure S3.2-C, and indicates that most of the naïve heifers had learned to avoid receiving ESs by day 5 of the trial.

These results are consistent with many previous VF studies that observed a decrease in the number of ESs and the E:A ratio received during successive days or trial phases. Although the lengths of observed learning periods vary among studies, some reported that learning had occurred after two to six days of continuous VF exposure (Campbell et al. 2017; Lomax et al. 2019; Verdon et al. 2021; Confessore et al. 2022), one study reported that 40 mins of training spread over four VF test events was sufficient to observe learning had occurred (Colusso et al. 2020), another reported a two-week long learning period (Aaser et al. 2022), and one did not report a specific learning period but indicated that the number of ESs and the E:A ratio decreased over time (Staahltoft et al. 2023). It has been noted that learning period length depends on the individual animals' capacity to learn, and that individual learning should be tracked to analyze sufficient training time (Hamidi et al. 2024).

It is notable that the 'learning curve' observed in the current study was interrupted by a sudden, short-lived spike in the E:A ratio on day 8 (Figure S3.2-C), which coincided with the first incidence that a VF boundary did not overlap with a physical fence during training. Hamidi et al. (2024) reported a similar phenomenon where the only time a heifer escaped across a VF boundary occurred when one of the physical fences was removed from the VF boundary. In the present study, it is possible that the association between ESs and ACs made by heifers during the training phase was initially confounded by the visual cue of the physical fence, such that when the visual cue of the physical fence was removed the heifers may not have recognized the AC as the conditioned stimulus. This observed phenomenon was short lived, and by day 9 heifers were avoiding ESs, such that ESs were at similar levels to those observed prior to the day 8 disturbance. Considering the limited duration of the E:A ratio increase observed in the present study, and with no further escapes reported by Hamidi et al. (2024), these results collectively demonstrate that heifers were able to avoid ESs by responding to audio cues without the assistance of visual cues, which is supported by similar conclusions drawn by early VF research (Lee et al. 2007, 2009). Ultimately, the results discussed above lead to the conclusion that the naïve beef heifers observed in this study learned to navigate a VF system within five days, although their learning was enhanced by additional time and the ability to experience audio cues that did not coincide with a physical fence.

3.5.3. Cows With Prior Virtual Fence Experience

Heifers from the 2022 trial returned to the VF system in 2023 as cows with uncollared calves at side, after a 300-day period since their last exposure to VF. Despite the presence of uncollared calves the cows were successful at avoiding ESs from the first day of the re-training period and throughout the subsequent rotational grazing period. Cows received fewer ESs ($head^{-1}day^{-1}$) than they did as heifers, and the E:A ratio was observed to be half of what they received during their prior exposure to VF. There was no ‘learning curve’ where the E:A ratio declined over time, as seen in naïve heifers from the previous year. The low E:A ratio observed during the 2023 trial was driven by an increase in ACs and a decrease in ESs received, compared to the 2022 trial wherein ES levels generally declined over time.

While the current study observed the persistence of the AC and ES association over time, such that cattle avoided receiving ESs upon hearing ACs 300 days after their last exposure to VF, other research did not report similar findings. Verdon and Rawnsley (2020) initially trained heifers naïve to VF at six, nine, and 12 months of age, re-exposed those heifers to a VF system at 22 months, and compared the behaviour of re-exposed heifers to others that were initially trained at 22 months. They observed that previous training had no effect on the behaviour of heifers that were later re-exposed to VF, concluding that heifers did not retain their associative learning. This inconsistency between the results of the two studies could be due to differences in the number of AC-ES pairing events. In the current study, naïve heifers were continuously exposed to VF for 67 days, and individuals experienced a range of 30 to 124 ESs, i.e. AC-ES pairing events. Verdon and Rawnsley (2020) exposed naïve heifers to VF stimuli throughout four training sessions held over the course of two days, during which heifers interacted with the fence an average of 10 to 15 times in total, receiving an ES in 70% to 90% of these interactions, meaning that heifers experienced an average of 7 to 13.5 AC-ES pairing events.

It is possible that the limited number of AC-ES pairing events experienced by the heifers in Verdon and Rawnsley (2020) resulted in a weak or incomplete association between ACs and ESs. Additionally, the association between a conditioned stimulus (AC) and the conditioned response (flight or freeze) has been shown to be persistent across time, if the last experience of the conditioned stimulus was paired with the unconditioned stimulus (ES) (Malone 1990). This means that after a period without VF exposure cattle should react to the AC and avoid the ES, if there was an established AC-ES association, and an AC was paired with an ES before the break from VF exposure. This suggests that cattle could be ‘primed’ for success after a break from VF exposure by ensuring that they experience a sufficient AC-ES pairing event at the conclusion of grazing and before the VF break.

It is important to understand how cattle react to VF after an extended break, and how to minimize the amount of re-training that is necessary. Many beef cattle producers in Canada do not graze their cattle for some or all of the winter season due to cold temperatures and a build up of snow (Sheppard et al. 2015). It is likely that producers who wish to utilize VF for grazing management in western Canada will go weeks or months without exposing their cattle to VF stimuli, between periods of extensive grazing. The time and labour that is required to enclose cattle in a small paddock, progressively change VF boundaries, and observe cattle during training means that the training period is one of the most resource intensive aspects of VF. Information about how much re-training is required, best practices while re-training, and potentially insight into how to ‘prime’ animals in preparation for the next grazing season, could assist producers in implementing this new technology. The results of this study on the persistence of the AC-ES association over 300 days are encouraging, but more research on the nature of the association over time is needed.

3.5.4. Virtual Fencing and Rotational Grazing

Within the context of the pastures and rotational grazing strategies utilized in this study, both naïve heifers and experienced cows with uncollared calves at side were successfully contained within targeted grazing areas by VF. It has been well documented that heifers, steers, dry cows, and lactating dairy cows can be effectively contained by static VF boundaries for over 99% of the time while grazing (Lomax et al. 2019; Campbell et al. 2020; Langworthy et al. 2021; Fuchs et al. 2024). Despite this documented success, effective containment was not universal; one study experienced failure when using VF to contain cattle within inclusion zones, but the authors noted this was likely caused by the experimental design, which attempted to contain several groups of cattle in different areas using VF but ran concurrent trials with each group, placing them within close contact to each other (Verdon et al. 2021).

Rotational grazing of cattle using VF requires that animals respond to audio cues rather than learning the “location” of each virtual boundary, and thus can adapt to dynamic VF boundary lines. Previous studies have shown that cattle learn to react to audio cues rather than depending solely on visual cues or a boundary “location” to avoid electrical shocks (Campbell et al. 2017; Marini et al. 2018). Heifers and cow-calf pairs in the current study displayed this ability as they were effectively ‘herded’, albeit passively, between sub-pastures in four-to-eight-day intervals using VF technology. These results are supported by other research demonstrating that VF can be used to passively herd cattle and sheep over short distances, to strip graze dairy cows, and to holistically graze bull calves (Marini et al. 2018; Colusso et al. 2021b; Campbell et al. 2021; Staahltoft et al. 2023). The VF management in these examples is similar to the VF rotation method adopted by the current study (see section *3.3.5: Rotational Grazing Trials*), where herding and rotation between sub-pastures relied on the animals’ own movement and the subsequent changing of front and/or rear VF boundaries that prevented movement in the wrong direction.

There are few studies that address the ability of VF to contain cow-calf pairs in comparison to those which have utilized steers or females unaccompanied by offspring. Many beef operations raise cow-calf pairs (Statistics Canada 2024a), and it is reasonable to assume that some producers who wish to utilize VF will be placing collars on cows and leaving their offspring uncollared. The user manual from Nofence Ltd. (2023) states that a VF collar must be placed on every adult animal in a herd, but also that an animal must have sufficient mental development to understand the VF system, meaning that VF is not appropriate for young calves. It was observed that cows with calves at side escaped more times (head^{-1}day^{-1}) than they did the previous year as heifers; despite this, however, VF was more than 99%

effective at containing these cows. We are not able to draw direct comparisons between the effectiveness of VF in the heifer and cow trials due to study design and resource limitations, which led to confounding effects of VF experience and the presence of uncollared offspring. Ultimately, the high IZF reported here during the 2023 cow-calf trial indicates cows were effectively contained despite the presence of their uncollared calves, and this is supported by Nyamuryekung'e et al. (2023) who concluded that nursing Brangus cows were able to learn and be effectively contained by VF despite the behaviour of their uncollared offspring. More research onto the impact that uncollared offspring have on cows within a VF system will help shed light on best management practices for the use of VF on cow-calf pairs.

The containment of animals within targeted grazing areas is an indication of VF success, but it is also important to consider possible impacts of VF on animal performance when assessing the overall utility of a technology. While we were not able to compare animal performance metrics to a non-VF control, results of this study indicate that within each herd there were no apparent correlations between the number of VF stimuli received and the cattle performance parameters of pregnancy rate, ADG, and calf ADG. Pregnancy rates during both trials were the same as, or better than, the average Alberta provincial benchmark of 86% from 2018 to 2022 (Agriculture and Irrigation 2024). Results of the current study indicate that average rib fat depth was similar across cohorts within both years, with the exception of the MS cows in 2023, which had less rib fat accumulation (i.e. a negative change in rib fat depth) relative to the HS and LS heifers (Table 3.4). The cause of the latter remains unclear, however, particularly as rib fat accumulation was similar across cohorts in 2022. This is consistent with other research reporting that VF had no affect on ADG or live weight gain (Verdon et al. 2021; Vandermark 2023; Wilms et al. 2024), or milk yield and milk cortisol levels for dairy cattle (Fuchs et al. 2024).

3.5.1. Individual Variation in Behaviour

While all individual animals were able to learn the VF system, a high degree of individual variation was observed in the number of ACs and ESs received by heifers and cows with calves (Figure S3.1). This is consistent with other research reporting that specific individuals are more likely to interact with the VF, i.e. receive an AC, than others, and that the E:A ratio received by cattle depends on the individual animal (Campbell et al. 2018, 2019b; Lomax et al. 2019; Aaser et al. 2022). In this study, the HS cohort was composed of animals that were more likely to interact with the VF boundaries and to receive an ES as a result, similar to the animals identified as "leaders" of VF interactions by other studies (Campbell et al. 2019a; Keshavarzi et al. 2020). Cattle in the MS cohort were more likely to interact with VF boundaries, but were less likely to receive ESs, and the cattle in the LS cohort were less likely to interact with the VF boundaries in general, and also less likely to receive an ES when they did.

Interestingly, it was observed that two thirds of cattle were classified as the same cohort in both years of rotational grazing trials, which suggests that characteristics specific to each animal may play a role in how, and how often, cattle interact with VF boundaries. Differences in the number of ACs received by cattle, i.e. the number of VF boundary interactions, may be related to how cattle are spatially distributed. Factors that may affect the spatial distribution of individuals, and therefore their likelihood of interacting with VF boundaries, include personality or temperament, social position, age, the presence of offspring, nutritional status, and activity levels (Campbell et al. 2018; Ramos et al. 2021). For example, bolder animals may be more likely to explore their environment, and therefore encounter VF boundaries more often, while cautious cattle may avoid receiving audio cues by responding to the behaviour of, and VF stimuli received by, their bolder counterparts (Keshavarzi et al. 2020; Colusso et al. 2020). In this study cattle within each trial were similar in age, production status (gestating, lactating), and the presence or absence of offspring, suggesting that these were unlikely to cause the variation in ACs observed among individuals.

The results of this study also found that step count and motion index were positively correlated with the number of ACs received by heifers and cows, albeit the association was weak between step counts and ACs for cows. This suggests that more active animals may have been more likely to interact with VF boundaries, and is supported by Staahltoft et al. (2023) who found a moderate, positive correlation between activity and the total number of audio cues received by each bull calf in a holistic, i.e. rotational, grazing system. In contrast, other studies have concluded that VF has little to no impact on resting or walking behaviour, and therefore the connection between animal activity and VF interactions should be further investigated (Hamidi et al. 2022; Vandermark 2023; Wilms et al. 2024; Fuchs et al. 2024). While no correlation was found between the RFI_{fat} or BC_{angus} of individual animals and the number of ACs received, values for both these variables fell within narrow ranges, which may have limited their explanatory ability. Thus, further research should investigate a wider range of RFI and BC in cattle to assess whether there are relationships between feed efficiency, breed composition, and the number of VF boundary interactions.

The likelihood of an animal receiving an ES following an AC depends on the saliency of the AC, the strength of the association between ACs and ESs, and the reactivity of that animal to the AC. Cattle that have not interacted with the VF boundary very often may not have a strong association between ACs and ESs, whereas cattle that receive more ACs have had more opportunities to experience an AC-ES pairing event. This is supported by our results as shown by higher numbers of total ACs received over the course of each trial being associated with a decrease in the daily average and total E:A ratios. The strength of the reaction of each animal to the AC and whether they are more likely to 'flee' or 'freeze' may also affect how likely they are to receive an ES. Further research could address possible relationships between the reactivity of cattle to un-paired audio cues and shocks, and their interactions with VF boundaries after training. Similar to ACs, this study did not find a correlation between the number of ESs received, and either RFI_{fat} or BC_{angus}. While there were positive correlations between ESs and movement behaviour such as step counts and motion index in 2022, and a very weak positive correlation between ESs and motion index in 2023, the mechanism behind these associations is unclear and could be revealed by further research.

Although VF has already been demonstrated to be highly successful at managing cattle distribution, insight into the factors affecting the number of VF boundary interactions and ESs received by individual cattle may help producers select cattle that are more likely to be successful within a VF system. Temperament and personality are already criteria used to breed and cull cows, and understanding how these factors influence behaviour under VF may allow producers to select animals that are more likely to succeed in VF systems. Additionally, cattle temperament and reactivity could be used as a tool to assess whether new animals may be a good fit within a VF system. Finally, producers may be able to use data about the number of VF interactions each cow experiences to assess their behaviour within VF systems, and remove cattle that are not well suited to the technology.

3.5.2. Effects of grazing management factors

The results of this study show that stocking rate and grazing pressure had some effect on cattle interactions with VF boundaries. Stocking rate had a moderate positive correlated with ACs and ESs, and grazing pressure was weakly, positively correlated with ESs for cows with calves in 2023, although neither were correlated with ACs or ESs for heifers in 2022. Stocking rate and grazing pressure had variable effects on AC duration between both trials, suggesting that other factors may have been influencing possible interactions with VF boundaries. Nevertheless, stocking rate influences the spatial distribution of cattle in a pasture, such that an increase in stocking rate means that more animals are occupying a unit of land and may seek to spread out and distribute themselves more widely, thereby increasing the number of times they interact with a VF boundary. Additionally, it has been noted that increases in stocking rate may lead to enhanced competition for resources and agressive interactions between cattle (Teixeira et al. 2017), and an increase in grazing pressure, which represents the instantaneous amount of forage demand of the herd relative to the forage available (Allen et al. 2011), may increase the motivation of cattle to find areas of pasture with more available forage. Both factors may decrease the saliency of ACs in the face of competing motivation, explaining the relationships between stocking rate, grazing pressure, and ESs received by cows during 2023.

The results discussed above are consistent with previous research indicating that while feed attractants, restricted feed rations, and increased grazing pressure are generally associated with more VF boundary interactions, VF still effectively contains cattle in target inclusion zones (Campbell et al. 2018, 2020; Colusso et al. 2021b, 2021a). Additionally, Vandermark (2023) reported that containment rates of steers using VF were similar across most stocking rates (light, moderate, and heavy), with the exception of a heavy stocking rate in 2022. This unexpected reduction in containment rate may have been due to drought in 2021 and 2022 reducing forage quality and quantity (Vandermark 2023). Further research should investigate the effects that a wider range of stocking rates have on VF success. Ultimately, despite the effects that grazing pressure and stocking rate had on cattle interactions with VF boundaries, in the current study VF remained effective at controlling the spatial distribution of cattle.

3.6. Conclusion

This study has shown that heifers naïve to VF technology are able to learn to comply with VF boundaries within five to seven days, and that the learned association between audio cues and shocks can persist for 300 days without VF exposure. While there is a high degree of variation in individual behaviour under VF, this technology successfully managed rotational grazing systems for heifers and cows, despite the presence of uncollared calves in the latter case. There is no evidence that VF stimuli were associated with cow-calf production parameters. Further areas of research include the effects of higher stocking rates on VF success, the influence of temperament and other intrinsic or heritable factors, and the possibility that herds of livestock may be controlled by using VF collars on a specific subset of animals. Ultimately, the potential management flexibility of VF, and therefore efficient resource utilization, means it could be a revolutionary technology for cattle industries. The usefulness of this technology depends on access to high quality information about best practices for selecting animals, training, and deployment of virtual fencing to address specific producer goals.

<u>3.7. List of Tables</u>

Table 3.1. Characteristics of cattle virtual fencing behaviour cohorts, detailing the proportions of each group by the percentage of animals in the herd and the percentage of total electrical shocks and audio cues received, and the average number of audio cues and electrical shocks received ($head^{-1}day^{-1}$).

Year and animal class (no)	------------- 2022 Heifers (49) -------------			------- 2023 Cows with calves (39) ------		
Entire trial length (d)	67			50		
Cohort	High stimuli	Moderate stimuli	Low stimuli	High stimuli	Moderate stimuli	Low stimuli
Number of cattle (% of herd)	7 (14.3%)	20 (40.8%)	22 (44.9%)	5 (12.8%)	23 (59.0%)	11 (28.2%)
Virtual fence stimuli						
ESs[1] received (% of total)	32.5	40.9	26.5	26.2	59.0	14.9
Mean (±SD) ESs received ($head^{-1}$)	124.0 (±28.8)	55.6 (±16.0)	30.9 (±7.7)	48.8 (±5.3)	23.5 (±7.9)	13.5 (±3.9)
ACs[2] received (% of total)	28.3	52.0	19.7	29.4	59.5	11.1
Mean (±SD) ACs received ($head^{-1}$)	1862.4 (±564.4)	1228.5 (±697.4)	379.0 (±78.8)	3549.8 (±1072.0)	1646.7 (±1266.9)	443.8 (±80.4)

[1] *ES: electrical shock*

[2] *AC: audio cue*

Table 3.2. Virtual fence (VF) compliance and VF stimuli data compared between cohorts throughout training and rotational grazing phases. Cohorts were compared within each year using the Kruskal-Wallis rank sum test for non-parametric data, followed by Dunn's test for pairwise comparisons. Means with different letters differ, $p < 0.05$. Descriptive statistics for escape numbers and duration are presented.

Year and Animal Class (no)	---------- 2022 Heifers (49) ----------				------ 2023 Cows with calves (39) ------			
Cohort and Animals (no)	High Stimuli (7)	Moderate Stimuli (20)	Low Stimuli (22)	Kruskal-Wallis H (p-value)	High Stimuli (5)	Moderate Stimuli (23)	Low Stimuli (11)	Kruskal-Wallis H (p-value)
Training Period Length (d)			11			3		
Virtual Fence Stimuli								
Mean (±SD) ES[1] ($head^{-1}day^{-1}$)	2.7^{A} (±2.2)	1.8^{B} (±1.7)	1.5^{C} (±1.6)	14.7 ($p > 0.001$)	0.6 (±1.1)	0.2 (±0.5)	0.2 (±0.4)	*NS*
Mean (±SD) AC[2] ($head^{-1}day^{-1}$)	14.4^{A} (±9.7)	12.5^{A} (±8.3)	8.7^{B} (±6.0)	17.5 ($p > 0.001$)	23.2^{A} (±16.1)	13.6^{AB} (±11.6)	8.5^{B} (±5.8)	8.0 ($p = 0.02$)
Mean (±SD) E:A[3] ratio (%)	20.3 (±16.7)	17.3 (±17.8)	17.7 (±19.4)	*NS*	1.7 (±3.5)	1.7 (±4.8)	1.2 (±2.9)	*NS*
Virtual Fence Compliance								
Mean (±SD) IZF[4] (%)	99.42 (±2.68)	99.62 (±2.24)	99.58 (±2.23)	*NS*	99.38^{A} (±1.86)	100^{B} (±0.00)	99.96^{AB} (±0.25)	9.5 ($p = 0.009$)
Number of escapes	5	8	10	-	10	0	0	-
Mean (±SD) ESC[5] duration (min)	98.5 (±99.8)	122.5 (±96.5)	116.8 (±93.6)	-	1.4 (±0.7)	NA	NA	-

Table 3.2. Continued.

Year and Animal Class (no)	---------- 2022 Heifers (49) ----------				------ 2023 Cows with calves (39) ------			
Cohort and Animals (no)	High Stimuli (7)	Moderate Stimuli (20)	Low Stimuli (22)	Kruskal-Wallis H (p-value)	High Stimuli (5)	Moderate Stimuli (23)	Low Stimuli (11)	Kruskal-Wallis H (p-value)
Rotational grazing length (d)	56				47			
Virtual Fence Stimuli								
Mean (±SD) of ES ($head^{-1}day^{-1}$)	2.0^{A} (±2.1)	0.7^{B} (±1.2)	0.4^{C} (±0.8)	29.5 ($p < 0.001$)	1.1^{A} (±1.3)	0.5^{B} (±0.9)	0.3^{C} (±0.7)	23.0 ($p < 0.001$)
Mean (±SD) of AC ($head^{-1}day^{-1}$)	35.9^{A} (±28.4)	21.6^{A} (±22.5)	7.0^{B} (±6.1)	27.0 ($p < 0.001$)	80.4^{A} (±54.1)	33.9^{B} (±39.3)	13.5^{B} (±12.5)	11.4 ($p = 0.003$)
Mean (±SD) E:A ratio (%)	6.7 (±8.6)	4.8 (±10.5)	5.1 (±12.6)	2.2 ($p = 0.3$)	1.4 (±1.9)	2.2 (±5.6)	2.0 (±6.8)	1.8 ($p = 0.4$)
Virtual Fence Compliance								
Mean (±SD) IZF (%)	99.73 (±1.42)	99.82 (±1.07)	99.81 (±1.08)	*NS*	99.75 (±1.76)	99.67 (±3.09)	99.88 (±1.04)	*NS*
Number of escapes	10	14	8	-	4	28	7	-
Mean (±SD) ESC duration (min)	116.4 (±283.0)	79.2 (±233.4)	15.3 (±11.1)	-	153.3 (±238.0)	149.1 (±259.7)	80.1 (±117.6)	-

[1] *ES: electrical shock.*

[2] *AC: audio cue.*

[3] *E:A ratio: a metric describing the frequency of electrical shocks delivered when an audio cue is triggered.*

[4] *IZF: inclusion zone frequency, describing the amount of time cattle spent within inclusion zones.*

[5] *ESC: escape event.*

Table 3.3. Summary and descriptive statistics for time cattle spent within inclusion zones, number of escapes, and virtual fence (VF) stimuli received by heifers and cows. Data are summed as VF stimuli and time spent within inclusion zones ($head^{-1}day^{-1}$) and were compared between training and rotational grazing phases within each year using Wilcoxon signed-rank tests for paired, non-parametric data. Means with different letters differ ($p < 0.05$). Escapes and escape duration are compiled for each trial phase.

Year and Animal Class (no)	2022 Heifers (49)		2023 Cows with calves (39)	
Trial Phase (number of days)	Training (11)	Rotational grazing (56)	Re-training (3)	Rotational grazing (47)
Virtual Fence Compliance				
Mean (±SD) IZF[1] (%)	99.6 ^{A} (±2.3)	99.8 ^{A} (±1.1)	99.9 ^{A} (±0.7)	99.7 ^{B} (±2.5)
Escapes, total (no)	23	32	3	39
Escapes ($head^{-1}day^{-1}$)	0.043	0.012	0.026	0.021
Cows escaped (% of herd)	22 (44.9%)	21 (42.9%)	2 (5.1 %)	22 (56.4%)
Mean (±SD) escape duration (min)	114.8 (±91.8)	74.9 (±218.2)	1.4 (±0.7)	137.1 (±235.2)
Virtual Fence Stimuli				
Mean (±SD) active data hours (day^{-1})	22.0 (±4.9)	22.1 (±3.8)	18.0 (±8.3)	23.0 (±2.4)
Mean (±SD) ES[2] ($head^{-1}day^{-1}$)	1.8 ^{A} (±1.8)	0.76 ^{B} (±1.3)	0.26 ^{A} (±0.58)	0.52 ^{B} (±0.94)
Mean (±SD) AC[3] ($head^{-1}day^{-1}$)	11.1 ^{A} (±7.9)	17.3 ^{B} (±21.1)	13.4 ^{A} (±11.8)	34.1 ^{B} (±41.5)
Mean (±SD) E:A[4] ratio (%)	17.9 ^{A} (±18.4)	5.2 ^{B} (±11.2)	1.6 ^{A} (±4.2)	2.1 ^{B} (±5.7)
Mean (±SEM) AC duration (sec $head^{-1}day^{-1}$)	7.7 ^{A} (±0.1)	6.0 ^{B} (±0.05)	4.0 ^{A} (±0.1)	6.4 ^{B} (±0.06)

[1] *IZF: inclusion zone frequency, describing the amount of time cattle spent within inclusion zones.*

[2] *ES: electrical shock.*

[3] *AC: audio cue.*

[4] *E:A ratio: a metric describing the frequency of electrical shocks delivered when an audio cue is triggered.*

Table 3.4. Cattle production parameters summarized by cohorts for each of the heifers and cows with calves at foot. Cohorts were compared within each year using the Kruskal-Wallis rank sum test for non-parametric data, followed by Dunn's test for pairwise comparisons. Means with different letters differ, $p < 0.05$.

Year and Animal Class (no)	---------------- 2022 Heifers (49) ----------------				--------- 2023 Cows with calves (39) ---------			
Cohort and Animals (no)	High stimulus (7)	Moderate stimulus (20)	Low stimulus (22)	Kruskal-Wallis H (p-value)	High stimulus (5)	Moderate stimulus (23)*	Low stimulus (11)	Kruskal-Wallis H (p-value)
Animal Performance								
Number of cattle pregnant (rate)	7 (100%)	19 (95%)	20 (91%)	*NS*	5 (100%)	18 (82%)	11 (100%)	*NS*
Mean (SD) ADG[1] (kg)	0.62 (0.19)	0.56 (0.13)	0.54 (0.16)	*NS*	0.46 (0.19)	0.47 (0.30)	0.51 (0.23)	*NS*
Mean (SD) ADG_{calf} (kg)	NA	NA	NA	NA	1.13 (0.11)	1.13 (0.16)	1.07 (0.12)	*NS*
Mean (SD) RD[2] (mm)	3.2 (0.9)	2.5 (0.9)	2.6 (0.9)	*NS*	1.9 (0.4)	2.3 (0.5)	2.1 (0.7)	*NS*
Mean (SD) RD_{change} (mm)	0.14 (0.9)	-0.10 (0.7)	-0.45 (0.9)	*NS*	1.0 (0.7)^{A}	-0.17 (0.7)^{B}	0.18 (0.8)^{AB}	8.6 (p = 0.01)

[1] *ADG: average daily gain.*

[2] *RD: rib fat depth.*

**One cow in 2023 did not have a pregnancy status recorded.*

Table 3.5. Summary statistics of grazing management and animal factors that may affect cattle behaviour under a virtual fencing grazing system.

Year and Animal Class (no)	2022 Heifers (49)	2023 Cows with calves (39)
Grazing Management Factors		
Mean (±SD)		
Grazing days (no)	7.3 (±1.5)	6.1 (±0.6)
Grazing area (ha)	4.7 (±0.9)	3.7 (±1.5)
Stocking rate (AUM ha^{-1})	2.4 (±0.8)	2.6 (±1.3)
Grazing pressure at start of grazing	0.050 (±0.016)	0.073 (±0.024)
Grazing pressure at end of grazing	0.10 (±0.022)	0.15 (±0.076)
Change in grazing pressure (%)	119.0 (±72.0)	107.3 (±96.8)
Mean (±SEM)		
Forage supply at start of grazing (kg ha^{-1})	1922 (±306)	2344 (±276)
Forage supply utilization (%)	48.6 (±7.5)	43.1 (±6.5)
Intrinsic Animal Characteristics		
Mean (±SD)		
BC_{angus}[1] (%)	0.39 (±0.068)	0.39 (±0.068)
RFI_{fat}[2]	0.26 (±1.5)	0.28 (±1.5)
Movement Behaviour		
Mean (±SD)		
Step count ($head^{-1}$ day^{-1})	4536 (±970)	4246 (±1266)
Lying time (min $head^{-1}$ day^{-1})	619 (±94)	367 (±292)
Motion index	200.3 (±242.5)	178.7 (±217.4)

[1] *BC_{angus}: percent of the breed composition that is red or black Angus.*

[2] *RFI_{fat}: residual feed intake adjusted for backfat, measured as heifers in drylot.*

Table 3.6. Spearman rank correlation coefficients for virtual fence stimuli and animal movement behaviour through rotational grazing in 2022 and 2023.

Year and Animal Class (no)	2022			2023		
	Motion Index	Lying time[4]	Steps[5]	Motion Index	Lying time	Steps
ESs[1] ($head^{-1}$ $trial^{-1}$)	0.17*	0.001	0.21*	0.07*	0.0064	0.045
ACs[2] ($head^{-1}$ $trial^{-1}$)	0.32*	-0.025	0.33*	0.27*	0.11*	0.087*
E:A[3] ratio	0.073*	0.0055	0.096*	0.0084	-0.011	0.047
AC duration (sec)	0.062*	-0.025	0.036	0.1*	0.036	0.082*

[1] ES: electrical shock.

[2] AC: audio cue.

[3] E:A ratio: a metric describing the frequency of electrical shocks delivered when an audio cue is triggered.

[4] Data is summed as minutes per head per day.

[5] Data is summed as number of steps per head per day.

** Denotes a significant relationship, $p < 0.05$.*

3.8. List of Figures

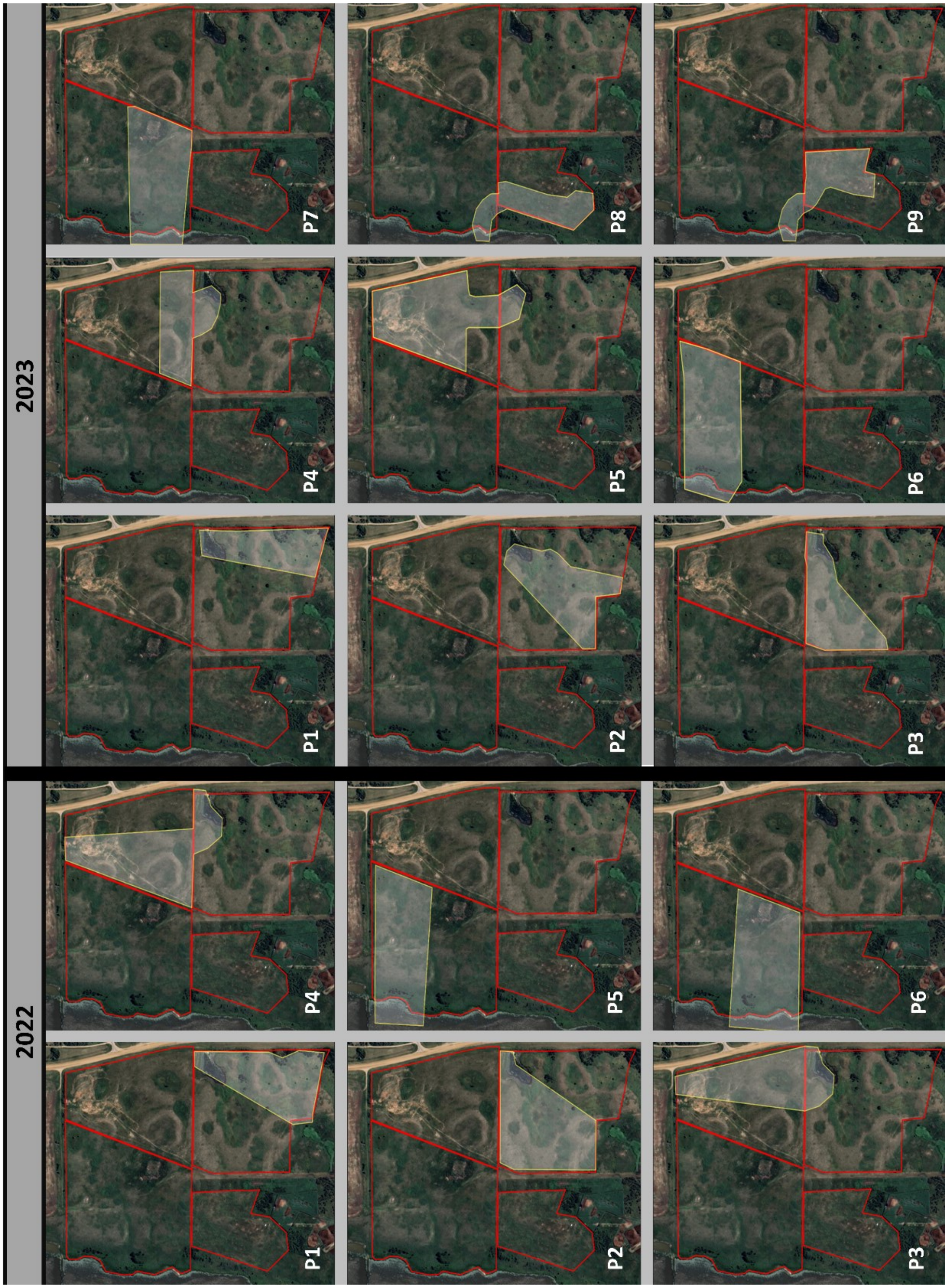

Figure 3.1. Schematic of virtual sub-pastures, identified with yellow lines and a shaded interior, used during rotational grazing trials in 2022 and 2023, overlaid on the existing permanent pastures delineated with physical fences, identified with red lines.

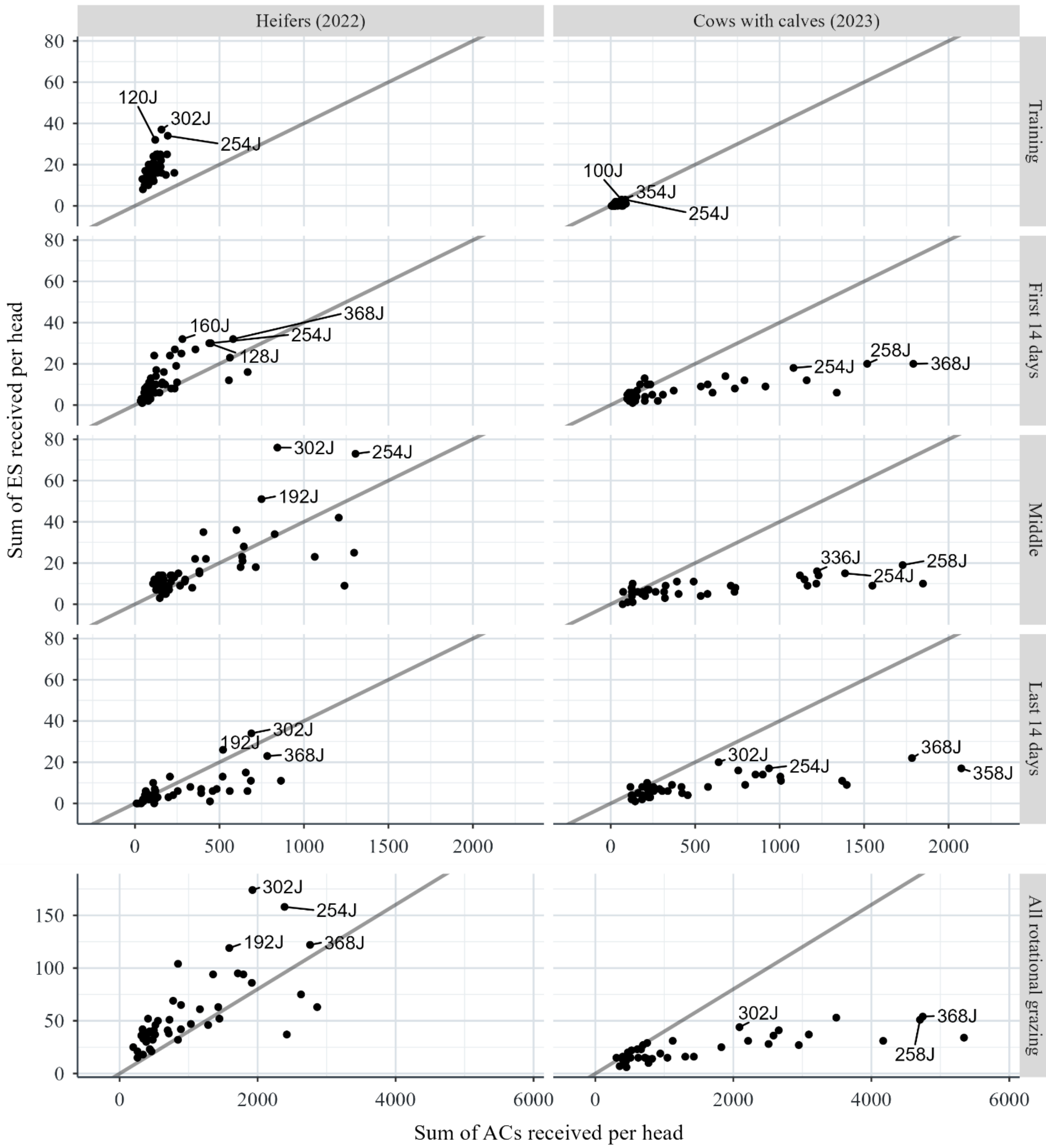

Figure 3.2. Comparison of the number of electrical shocks (ES) to the number of audio cues (ACs) received by each animal, summed over several discrete time periods throughout each trial. The grey line represents a frequency of electrical shocks cues received 4% of the time that an audio cue is received. The animals that received the three highest numbers of warnings in each time period are labelled.

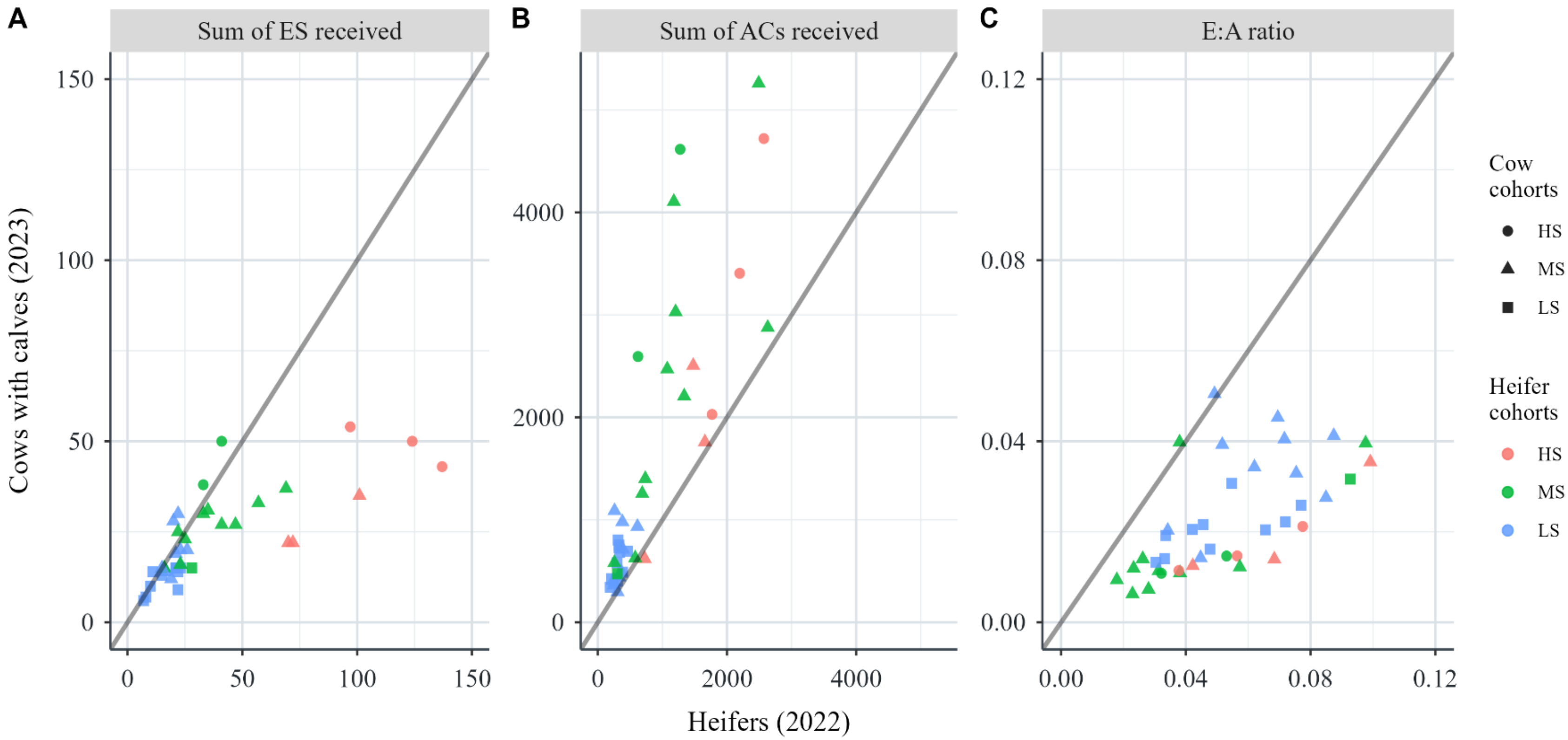

Figure 3.3. A comparison of the total number of virtual fence stimuli received by heifers in 2022 (x-axis) and cows in 2023 (y-axis). Particularly, a comparison of A) electrical shocks (ES), B) audio cues (ACs), and C) the ratio of electrical shocks to audio cues (E:A), received per head during rotational grazing. High stimuli (HS), moderate stimuli (MS), and low stimuli (LS) cohorts are identified for heifers and cows.

3.9. Appendices

3.9.1. Supplementary tables

Table S3.1. The total number of electrical shocks and audio cues summed per head over the length of each rotational grazing trial, with the associated rank of animals from most to least virtual fence stimuli received, and their designated cohort.

Heifers (2022)						Cows with calves (2023)					
Subject	Total ES[1] received	Total AC[2] received	Rank ES	Rank AC	Cohort[3]	Subject	Total ES received	Total AC received	Rank ES	Rank AC	Cohort
192J	174	1928	1	6	HS	254J*	54	4765	1	2	HS
302J*	158	2393	2	5	HS	258J	53	3502	2	5	HS
120J	123	2765	3	2	HS	368J*	52	4721	3	3	HS
160J	120	1594	4	10	HS	100J	44	2097	4	12	HS
354J	104	847	5	19	HS	302J*	41	2664	5	8	HS
368J*	95	1717	6	9	HS	296J	37	3112	6	7	MS
254J*	94	1793	7	8	HS	120J	36	2587	7	9	MS
358J	94	1356	8	13	MS	66J	34	5353	8	1	MS
384J	86	1919	9	7	MS	386J	32	2226	9	11	MS
34J	75	2631	10	3	MS	390J	31	4177	10	4	MS
258J	69	776	11	21	MS	148J	31	1123	11	16	MS
424J	65	890	12	17	MS	342J	29	3189	12	6	MS
436J	63	2868	13	1	MS	410J	29	751	13	22	MS
66J	63	1432	14	12	MS	200J	28	2512	14	10	MS
222J	61	1163	15	15	MS	188J	27	695	15	25	MS
100J	52	1446	16	11	MS	404J	25	1829	16	13	MS
296J	52	411	17	35	MS	282J	23	665	17	26	MS
364J	51	723	18	22	MS	202J	23	607	18	28	MS
24J	50	554	19	25	MS	12J	22	525	19	29	MS
410J	47	1033	20	16	MS	294J	20	471	20	32	LS
390J	46	1283	21	14	MS	354J	19	944	21	18	MS
442J	46	519	22	26	MS	358J	16	1434	22	14	MS
174J	42	887	23	18	MS	336J	16	1306	23	15	MS
386J	42	696	24	24	MS	372J	16	497	24	31	LS
422J	42	332	25	45	LS	180J	16	402	25	36	LS

Table S3.1. Continued.

Heifers (2022)						Cows with calves (2023)					
Subject	Total ES received	Total AC received	Rank ES	Rank AC	Cohort	Subject	Total ES received	Total AC received	Rank ES	Rank AC	Cohort
12J	41	498	26	28	LS	192J	15	1045	26	17	MS
348J	40	435	27	33	LS	380J	15	723	27	23	MS
148J	40	340	28	43	LS	348J	15	718	28	24	MS
336J	38	713	29	23	MS	436J	15	621	29	27	LS
372J	38	409	30	36	LS	366J	15	513	30	30	LS
420J	37	2425	31	4	MS	440J	15	306	31	39	LS
200J	37	515	32	27	LS	364J	14	827	32	19	MS
438J	36	314	33	46	LS	222J	14	753	33	21	MS
142J	35	358	34	40	LS	44J	14	428	34	35	LS
342J	34	386	35	37	LS	142J	13	401	35	37	LS
188J	33	358	36	41	LS	106J	11	441	36	34	LS
428J	33	342	37	42	LS	424J	10	773	37	20	MS
128J	32	845	38	20	MS	422J	7	352	38	38	LS
202J	32	479	39	29	LS	182J	6	450	39	33	LS
366J	31	422	40	34	LS	160J	NA	NA	NA	NA	NA
44J	31	377	41	39	LS	384J	NA	NA	NA	NA	NA
380J	30	385	42	38	LS	34J	NA	NA	NA	NA	NA
182J	25	197	43	49	LS	24J	NA	NA	NA	NA	NA
106J	23	439	44	31	LS	442J	NA	NA	NA	NA	NA
294J	23	436	45	32	LS	174J	NA	NA	NA	NA	NA
282J	21	461	46	30	LS	420J	NA	NA	NA	NA	NA
440J	21	258	47	47	LS	438J	NA	NA	NA	NA	NA
404J	18	338	48	44	LS	428J	NA	NA	NA	NA	NA
180J	15	258	49	48	LS	128J	NA	NA	NA	NA	NA

[1] *ES: the number of electrical shocks received by cattle.*

[2] *AC: the number of audio cues received by cattle.*

[3] *HS: high stimuli cohort; MS: moderate stimuli cohort; LS: low stimuli cohort.*

** Denotes HS heifers that are later identified as HS cows in 2023.*

3.9.2. Supplementary figures

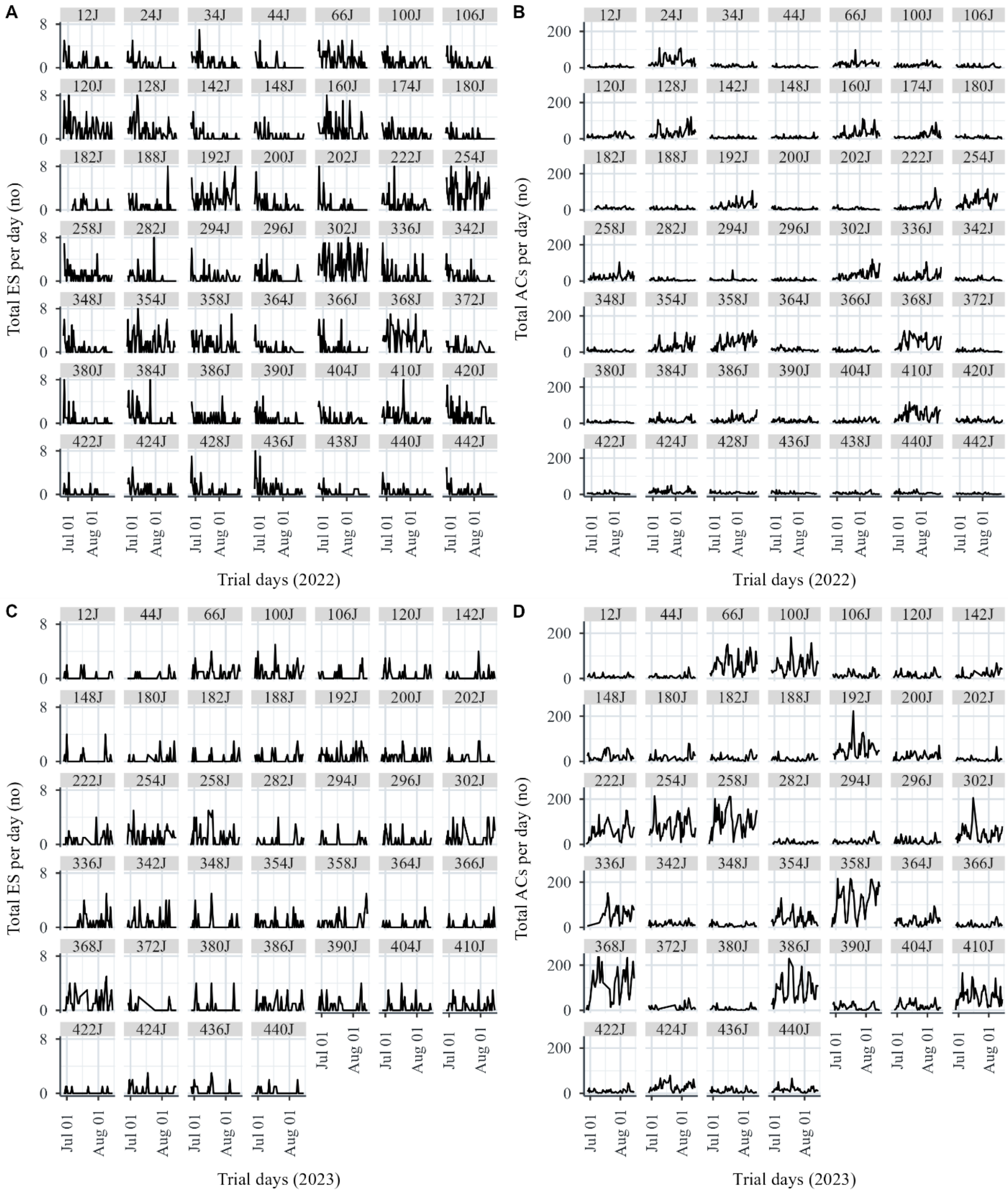

Figure S3.1. The total number of A) electrical shocks (ES) and B) audio cues (ACs) received each day by individual heifers in 2022, and subsequently in 2023 the total number of C) ESs and D) ACs received each day by individual cows with calves at side.

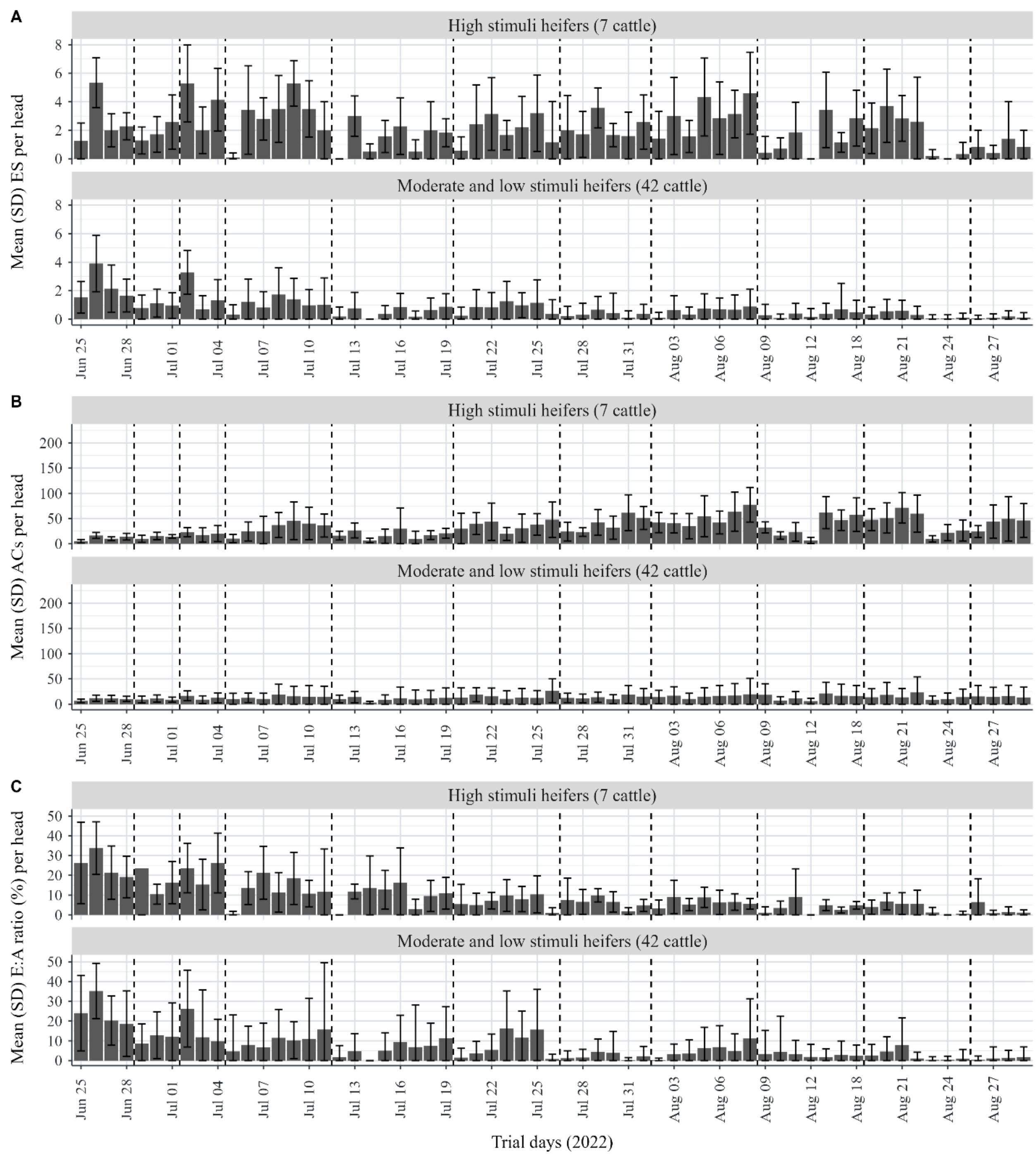

Figure S3.2. Summary of interactions for heifers naïve to VF, including A) mean (SD) electrical cues, B) mean audio cues, and C) the mean ratio of electrical shocks to audio cues, with data summed as VF stimuli per head per day during training (Jun. 25 – Jul. 4, 2022) and rotational grazing (Jul. 5 – Aug. 29, 2022).

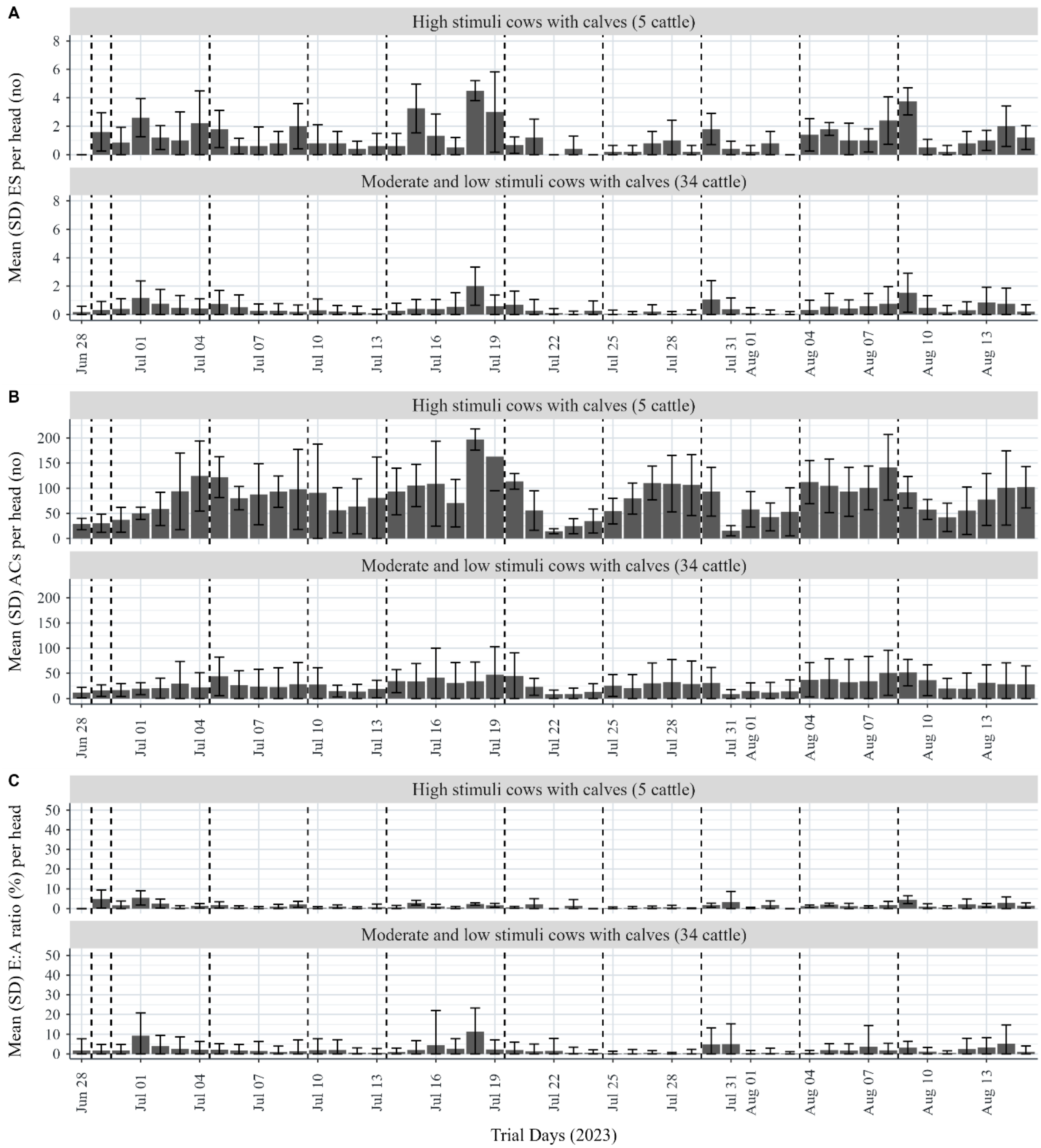

Figure S3.3. Summary of interactions for cows with calves at foot, and previously experienced with VF, including A) mean (SD) electrical shocks, B) mean audio cues, and C) the mean ratio of electrical cues to audio cues, with data summed as VF stimuli per head per day during re-training (Jun. 27 – Jun. 29, 2023) and rotational grazing (Jun. 30 – Aug. 15, 2023).

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Chapter 4: Synthesis of Virtual Fence Testing

4.1. Framing the problem and solution

The goal of this research was to investigate the efficacy of virtual fencing (VF) as a functional and practical tool for producers to face the challenges that come with modern cattle production. A significant portion of the beef cattle production system in Canada occurs while grazing on pasture, where ranchers must balance the conservation and productivity of land and soil with the seemingly opposite goal of maximizing profit (Asamoah et al. 2003; Butler et al. 2006; Teague and Kreuter 2020). Ranchers face a dynamic and increasingly unpredictable marketplace, which requires highly adaptive management to overcome obstacles such as consumer perception of cattle impacts to ecosystems (Teague and Kreuter 2020). Additionally, livestock producers are managing risk and challenges while extensively grazing their animals in remote, rugged, and often dangerous environments (Bailey et al. 2021). Despite these challenges, producers are highly innovative and thoughtful stewards of their land. While it is common for producers to search for innovative ways to balance the health of their rangelands with the profitability of their operation, there is great economic risk involved in the adoption of new systems, management strategies, and technologies. This study sought to ask, and answer, several questions about the use of VF that are highly relevant to producers who may be interested in this technology, and to add to the body of academic knowledge available on the topic of VF, as well as to inspire new questions and areas for further research.

To accomplish these goals, this study focused on the use of VF in a western Canadian Aspen Parkland environment and tested the use of VF for facilitating rotational grazing. Rotational grazing is used on 50-80% of ranches in western Canada (Chorney and Josephson 2000; Pyle et al. 2018), and is increasingly important as a strategy to obtain more efficient forage removal through grazing, while also maximizing the health of pastures. Due to the potential replacement of large amounts of cross fencing with VF technology, the latter could be an important strategy to increase the flexibility in controlling where, when and often cattle graze individual parcels of land, and in doing so adapt to changing environmental conditions such as drought and associated water and forage availability.

Additionally, two rotational grazing trials during summer were conducted, the first on heifers that were naïve to VF technology, and the second on cows with uncollared calves at side, that were previously experienced with VF. These investigations focused on training and learning, memory retention, individual animal variation within the VF system, VF success while rotationally grazing, and factors affecting VF success, such as the presence of offspring, stocking rate, animal breed composition, and feed efficiency. In addition, a winter technical trial was performed to assess the ability of Nofence VF collars to perform while rotational grazing under harsh winter conditions, specifically low temperatures and reduced hours of daylight.

Overall, it was discovered that VF technology performed well on a western Canadian commercial cow-calf operation with moderate to good quality cellular network connection during summer, and there were little to no apparent problems with VF use during the secondary winter technical trial. Despite some individualized variation among animals, all cattle were able to learn to comply with VF boundaries and displayed behaviour indicative of retained memory 300+ days later. While collars overwhelmingly performed well regarding cellular connection it is notable that some collars experienced one-off connection failures that required manual intervention to resolve. All collars remained highly charged (above 90%) during both summer and winter, and this occurred despite much lower solar charging rates in winter than in summer.

Virtual fencing provided new options to control where and when cattle grazed with potentially reduced labour and cost that is necessary to reconfigure physical fencing, and novel opportunities to move animals (albeit passively) from one area to another. While escapes from VF boundaries did occur, especially in the face of unusual environmental factors (e.g. a severe thunderstorm), in this study cattle consistently returned to inclusion zones without researcher or staff intervention, and the brief escapes did not compromise the ability of VF to manage cattle grazing and distribution. It is clear that good VF management and pasture design will be essential to animal welfare and VF success, and it is important to learn from challenges experienced by each other. Barriers to VF success may include attempting to keep separate groups of cattle that are within eye contact of each other (Verdon et al. 2021) and boundary placements alongside areas such as ditches or roads (Aaser et al. 2022). Small paddock sizes or complex designs such that animals would receive signals on multiple sides, may be confusing and stressful for animals, which could be exacerbated by collar update delays (Campbell et al. 2021). Ultimately, if cattle are set up for success with good management and thoughtful design, the potential of VF to improve management and reduce labour for ranchers is substantial.

4.2. Impact of this research

The main benefit of VF technology is the potential for major increases in management flexibility for livestock producers. Management flexibility is important for extensive cattle operations grazing large amounts of pasture, due to challenges associated with physical scale, variation of weather and plant production, and the remoteness and ruggedness of the terrain (Butler et al. 2006; Aquilani et al. 2022). In contrast to VF, physical fencing technology is resource intensive to install and maintain, and is not easily reconfigured (Butler et al. 2006), leading to limitations on management flexibility. Virtual fencing is uniquely poised to provide flexible management opportunities, including livestock monitoring, within remote or inaccessible areas. The real-time, or nearly so, location updates and wireless connection provided by the VF platform allows producers fine control over how their animals are distributed over space and time in previously inaccessible areas. Welfare outcomes of livestock raised in these remote areas may be improved by increased monitoring and producer control. The results of this study indicated that not only can VF be used to manage grazing cattle in an adaptive, dynamic way, but that Nofence VF collars are physically robust enough to withstand cold temperatures, low levels of daylight, regular animal handling through squeeze chutes, and the cattle breeding season. They are also capable of operating in a rural area with moderate, and sometimes unpredictable, cellular network connection. These conditions of use are common among cattle enterprises operating across much of western Canada, and the future success of technology adoption demonstrated in this study will depend on a minimum level of internet connectivity, which indeed may not exist everywhere at this time.

To be sustainable in the short and long term, livestock producers must maintain profitability. It has been shown that profitability is driven by rangeland condition and function, and the degree and uniformity of forage utilization (Asamoah et al. 2003; French et al. 2015; Teague and Kreuter 2020). Management strategies, such as rotational grazing, can improve pasture productivity and forage utilization (Asamoah et al. 2003; Teague and Kreuter 2020), but are difficult and can be costly to implement and maintain. The results of this study and others show that VF provides an emergent technology that can be used to manage cattle during rotational grazing, and therefore has the potential to maximize the profits of livestock producers while minimizing negative rangeland condition outcomes. For example, fences are known to pose barriers to the movement of some wildlife (e.g., pronghorn antelope), and therefore having strategies to contain cattle without physical fencing would markedly benefit wildlife (Jachowski et al. 2014). Additionally, while the initial investment cost of VF technology is high, the implementation of VF for rotational grazing may lead to direct cost savings due to the decrease in dependency on physical fences.

Finally, the pursuit of economic profitability must be accompanied by the prioritization of rangeland conservation (Asamoah et al. 2003; Teague and Kreuter 2020; Döbert et al. 2021). It is important to limit over- or under-grazing by ruminants to prevent range degradation (Stevens et al. 2021; Pyle et al. 2021), and thus, it is possible to improve rangeland condition through the increased management of grazing ruminants (Teague and Kreuter 2020). In particular, it has been shown that localized over-utilization of specific areas, or 'hot spots', can lead to marked degradation of rangeland condition (Teague and Dowhower 2003), and that under-utilization can allow the ingress of woody plants (leading to grassland loss) or increased fire risk (Stevens et al. 2021). Virtual fencing can be used to monitor cattle distribution and enable the rancher to take proactive measures to prevent over- or under-utilization. Additionally, as seen in this and prior research, VF can manage rotational grazing, which may in turn, be capable of improving conditions related to rangeland health, such as hydrologic function, soil function and stability, and biodiversity (Asamoah et al. 2003; Hillenbrand et al. 2019; Teague and Kreuter 2020; Döbert et al. 2021).

This research provided novel insight into the application of VF to manage rotational grazing with two classes of cattle that are often present within cow-calf operations: heifers, and cows with calves at side. New technologies can help livestock producers improve animal welfare, rangeland sustainability, and their own profitability (Bailey et al. 2021; Aquilani et al. 2022), but also require a significant investment of time and money. Raising awareness of new technologies and improving access to information can help overcome barriers to technology adoption (Aquilani et al. 2022). By focusing research on questions directly relevant to the practical application of VF on commercial beef cattle farms, this study strove to provide information that is valuable to any livestock producer, but particularly to western Canadian operations, who are considering implementing VF technology.

4.3. Future research needs

While conducting this research, more questions were generated than were answered. The future of VF technology is promising and provides many opportunities for further research, including foundational studies. Areas for further research include the effect of inherent individual animal characteristics on behavioural responses to VF, and the effect of higher stocking rates and stock density on VF success, i.e., understanding what herd conditions may lead to VF integrity breakdown and increased animal ‘escapes’. A better understanding is also needed on the expected longevity of VF collars, including how environmental conditions including topography, vegetation, and habitat type may affect the operation of VF technology. Additionally, the limits of the capabilities of VF technology have not yet been reached, and these possibilities should be investigated. These opportunities include the more comprehensive use of on-board accelerometer and location data to categorize animal behaviour while on pasture (Versluijs et al. 2023a), detect illness, injury, or parturition (Bailey et al. 2021), and even manage predator-livestock conflict (Bailey et al. 2021; Versluijs et al. 2023b). Finally, there is great possibility to combine VF with other technologies, such as drones, soil and nutrient sensors, extensive livestock weight sensors, and more, in order to combine the fine control over cattle distribution that VF affords with increasingly detailed and accurate information about pasture forage productivity and health status (French et al. 2015; Stevens et al. 2021; Bailey et al. 2021; Aquilani et al. 2022).

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