Virtual fencing in cattle production

A literature review on the technology and its impacts on animal welfare

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Virtuell stängsling inom nötkreatursproduktion: En litteraturöversikt om tekniken och dess påverkan på djurvälfärd

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Keywords:	virtual fencing, cattle, heifers, animal welfare, stress, cortisol, behaviour, pasture, grazing management

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Abstract

Virtual fencing is an increasingly utilized technology in pasture-based livestock systems, offering opportunities to reduce labour demands and improve management efficiency. Currently virtual fencing has been adopted in several countries, including Australia, New Zealand, the United States of America and Norway. Sweden has adopted the use of virtual fencing as of January 2026, following legislation making it illegal prior to this date due to concerns from the general public and various industry stakeholders regarding its use and the impacts on animal welfare. The aim of this literature review is therefore to review existing scientific literature on virtual fencing in cattle production, with a focus on how system characteristics may influence animal welfare.

The most prominent concern regarding animal welfare and the use of virtual fencing is an animal's ability to learn the technology. However, the current reviewed literature shows that cattle generally learn to associate the audio cues given by the virtual fencing technology with the electrical pulse administered within a few days of training. Thus, allowing them to avoid further electrical stimuli by responding to the audio cues with direction changes away from the virtual boundaries. Nevertheless, individual variation in learning and uncertainty regarding long-term memory retention of this learning highlights the importance of appropriate training, reinforcement and understanding the technology learning process thoroughly.

Virtual fencing is primarily adopted to improve grazing flexibility, reduce labour associated with physical fencing, improve animal monitoring and support adaptive grazing strategies. It can also be used to exclude cattle from environmentally sensitive areas and may aid in predator management through improved location tracking. However, while virtual fencing does not eliminate labour but shifts it towards collar management and digital planning, it does decrease the physical management of fencing, particularly within a rotational grazing system.

Current evidence indicates that virtual fencing does not negatively affect cattle welfare when compared to traditional electric fencing. Research generally reports no consistent negative effects on cortisol concentrations, body weight, feed intake, lying behaviour, activity or productivity. Short-term behavioural responses (e.g. vocalisation or increased activity) may occur during the initial learning phase, but these typically decrease as animals adapt. Welfare assessment should therefore consider both physiological and behavioural indicators (animal-based welfare indicators) as well as resource-based indicators such as pasture accessibility, forage availability and water intake. A comprehensive evaluation of welfare cannot be achieved without considering all these factors.

Overall, virtual fencing offers a flexible way to manage grazing without compromising animal welfare compared to traditional electric fencing. Cattle typically adapt through learning, but welfare outcomes depend on factors like individual animals' learning ability, system design, grazing intensity, stocking rates, and attentive management. The variation in welfare indicators used across studies emphasize the importance of developing more standardized assessment methods to better understand and improve outcomes.

Keywords: virtual fencing, cattle, heifers, animal welfare, stress, cortisol, behaviour, pasture, grazing management

Sammanfattning

Virtuella stängsel är en teknik som används i allt större utsträckning inom betesbaserade produktionssystem för nötkreatur och erbjuder möjligheter att minska arbetsbelastningen samt förbättra management och effektivitet. I dag används virtuella stängsel i flera länder, däribland Australien, Nya Zeeland, USA och Norge. I Sverige blev användningen av virtuella stängsel tillåten först i januari 2026, eftersom tidigare lagstiftning förbjöd tekniken till följd av oro hos både allmänheten och flera aktörer inom branschen kring dess användning och potentiella påverkan på djurvälfärden. Syftet med denna litteraturöversikt är därför att sammanställa befintlig vetenskaplig litteratur om virtuella stängsel inom nötkötts- och mjölkproduktion med särskilt fokus på hur systemens egenskaper kan påverka djurvälfärden.

Den mest framträdande djurvälfärdsrelaterade frågan kring användningen av virtuella stängsel är djurens förmåga att lära sig tekniken. Den granskade litteraturen visar dock att nötkreatur generellt lär sig att associera ljudsignalerna från systemet med den elektriska impuls som ges inom några dagars träning. Detta gör att djuren kan undvika ytterligare elektriska stimuli genom att reagera på ljudsignalen och ändra riktning bort från den virtuella gränsen. Samtidigt visar individuella skillnader i inlärning och osäkerhet kring långtidsminnet av denna inlärning vikten av lämplig träning, förstärkning och en god förståelse för själva inlärningsprocessen.

Virtuella stängsel används främst för att förbättra flexibiliteten i betesdriften, minska arbetsinsatsen kopplad till fysiska stängsel, förbättra övervakningen av djur och stödja adaptiva betesstrategier. Tekniken kan även användas för att hålla nötkreatur borta från miljökänsliga områden och kan bidra till rovdjurshantering genom förbättrad positionsövervakning. Även om virtuella stängsel inte eliminerar arbetsbehovet, utan snarare flyttar fokus till hantering av halsband och digital planering, minskar det behovet av fysisk stängselhantering, särskilt i rotationsbetessystem.

Nuvarande forskning tyder på att virtuella stängsel inte påverkar nötkreaturs välfärd negativt jämfört med traditionella elektriska stängsel. Studier rapporterar generellt inga konsekventa negativa effekter på kortisolnivåer, kroppsvikt, foderintag, liggbeteende, aktivitet eller produktivitet. Kortvariga beteendemässiga reaktioner, såsom vokalisering eller ökad aktivitet, kan förekomma under den initiala inlärningsfasen men tenderar att minska när djuren anpassar sig till systemet. Bedömning av djurvälfärd bör därför inkludera både fysiologiska och beteendemässiga indikatorer (djurbaserade välfärdsindikatorer) samt resursbaserade indikatorer, såsom tillgång till bete, fodertillgång och vattenintag. Detta eftersom en heltäckande bedömning av välfärd kräver att samtliga av dessa faktorer beaktas.

Sammanfattningsvis kan virtuella stängsel stödja en flexibel betesförvaltning utan att kompromissa med djurvälfärden jämfört med traditionella elektriska stängsel. Nötkreatur anpassar sig generellt till tekniken genom inlärning, men välfärdsutfallen påverkas av individens inlärningsförmåga, systemets utformning, betesintensitet, beläggningsgrad och noggrant management. Variationer i vilka välfärdsindikatorer som används mellan olika studier visar samtidigt på behovet av mer standardiserade metoder för välfärdsbedömning.

Nyckelord: virtuell stängsling, nötkreatur, kvigor, djurvälfärd, stress, kortisol, beteende, bete, betesdrift

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Abbreviations

Abbreviation	Description
AC	Audio cue
BCS	Body condition score
EF	Electric fencing
EP	Electrical pulse
FCM	Faecal cortisol metabolites
GNSS	Global navigation satellite systems
GPS	Global positioning system
NZ	New Zealand
PB	Physical boundary
UK	United Kingdom
US	United States of America
VF	Virtual fencing

1. Introduction

Virtual fencing (VF) has emerged as an increasingly utilised technology in pasture-based livestock systems, offering opportunities to reduce labour demands and improve management efficiency. The technology was first used on livestock (goats) in 1987 (Fay et al. 1989; Anderson 2007) but was not commercially available until 2011 (Innovation News Network n.d.). In conventional grazing systems, physical electric fences (EF) are used to manage animals within desired areas. However, these require regular inspection, maintenance, and manual adjustment, tasks that are often time-consuming and particularly challenging in remote or rugged terrain. In contrast, VF enables farmers to establish and modify pasture boundaries virtually via satellite navigation-based systems (e.g. GPS and GNSS), allowing for instantaneous adjustments through mobile applications. This technology not only simplifies fencing management but also introduces advanced monitoring tools, such as heat maps that visualize animal distribution and grazing patterns, facilitating more informed and responsive decision-making (Petters & Wahlund 2025).

As a precision livestock farming tool, VF uses audio cues (AC) and electrical pulses (EP), controlled via satellite navigation, to keep animals within predefined areas without the need for physical barriers (Campbell et al. 2019). Managing grazing livestock traditionally involves multiple labour-intensive tasks, including daily supervision, ensuring adequate forage availability, and maintaining infrastructure such as fences and water sources (Jamieson & Hessle 2021). These requirements can limit the efficiency and scalability of pasture-based systems.

A key driver for the adoption of VF is its potential to improve labour efficiency, particularly in rotational and strip grazing systems (Hoag et al. 2024). Such systems often depend on frequent reallocation of animals, which in conventional setups necessitates repeated manual changes of EF. Virtual fencing eliminates this constraint by allowing boundaries to be adjusted virtually, thereby increasing flexibility in paddock design and grazing management. Furthermore, farmers can rapidly respond to changing conditions, such as variations in forage availability, weather events, or the need to protect environmentally sensitive areas, without the need for physical intervention. This capacity for real-time adaptation can substantially reduce labour inputs while enhancing the precision and effectiveness of pasture management (Campbell et al. 2019; Jamieson & Hessle 2021; Petters & Wahlund 2025).

The adoption of VF varies considerably across countries. While some nations have embraced the technology, it remains prohibited or unexplored in several others. Most recently, in January 2026, its use has been permitted in Sweden, following a regulatory change in Chapter 2, Section 17 of the Ordinance amending the Animal Welfare Ordinance (2019:66) (SFS 2025:948). The slow adoption of VF technology in Sweden and other countries is caused by public and industry stakeholder concern regarding VF and the impacts on animal welfare. These concerns have been raised both by consumers (Stampa et al. 2020) and by authorities such as Animal Welfare Committee (2022). The concerns are primarily linked to the use of EPs and animals' learning ability.

1.1 Purpose and research questions

The purpose of this study is to review and synthesize the existing scientific literature on VF in cattle production, with a focus on how system characteristics influence animal welfare. To address this aim, the review examines the technologies and collar systems currently used in VF, the management contexts that motivate adoption of the technology, animal welfare concerns, potential benefits of VF use, findings reported in the literature, and the animal-based/ resource-based indicators used to assess animal welfare in VF systems.
The review is guided by the following research questions:

- Which commercial VF systems are currently in use, and how do they differ in design, cue delivery and intended application?
- In which management contexts is VF adopted, and what are the reported drivers of adoption?
- What welfare concerns and potential benefits of VF use have been reported in the scientific literature on cattle?
- Which animal-based and resource-based welfare indicators have been used in VF research, and consistency across literature?

2. Methodology of the literature review

This narrative literature review synthesizes studies describing commercial VF systems used for managing cattle and related ruminants, focusing on animal- and resource-based welfare indicators used to assess stress and welfare. A narrative approach was chosen given the recent popularity of VF as a research field and the different indicators used in published literature.

2.1 Search strategy and data collection

The review protocol was not preregistered. The overall topic and research focus were defined at the outset, in consultation with the supervisors, before literature searching began. However, the specific scope and emphasis of the review developed iteratively as the student's understanding of the field deepened during the writing process, with refinements made in dialogue with the supervisors throughout. Time constraints and this evolving focus meant that a formal protocol was not registered in advance with a repository such as PROSPERO or the Open Science Framework. Inclusion and exclusion criteria were, however, defined before full-text screening commenced and applied consistently throughout the process.

Electronic searches were conducted between [January, 2026] and [May, 2026] in the databases Web of Science (https://www.webofscience.com/wos/woscc/basic-search), Scopus (https://www.scopus.com/pages/home?display=basic#basic) and Google Scholar (https://scholar.google.com/). Keywords used for searching in databases were *virtual fencing*, *cattle*, *heifers*, *animal welfare*, *stress*, *cortisol*, *behaviour*, *pasture* and *grazing management*. Different combinations of these keywords were used in each database to identify studies addressing the use of VF in cattle and its welfare-related outcomes. Reference lists of relevant papers and review articles were also screened to identify additional sources. Searches were limited to publications in English and Swedish, with no restriction on publication year.

Studies were included if they were peer-reviewed (primary research or reviews), addressed virtual fencing in cattle, and were published in English or Swedish. Studies on other ruminants (sheep and goats) and selected studies on welfare in other species were included where they provided supporting evidence for the welfare indicators discussed in the sourced cattle literature. Manufacturer documentation and other grey-literature sources were included specifically to describe commercial VF systems (Section 3.2) and were not used as evidence for welfare claims. Conference abstracts without accompanying full text were excluded.

References were grouped into studies of VF in cattle and supporting literature on welfare indicators, stress physiology, and assessment frameworks as presented on Table 1 in Appendix 1.

2.2 Data analysis

A qualitative and descriptive comparative analysis was conducted to examine key aspects of different VF systems, as well as animal-based and resource-based welfare indicators reported in the literature. Data from the included studies were extracted and organized in a spreadsheet according to system characteristics, welfare outcomes and the types of indicators used. Extracted variables included author and year, country in which the study was conducted, study design, animal category (dairy or beef, age, sex, breed), sample size, type and brand of VF system, duration of exposure to the VF, training protocol, and the welfare indicators measured. Welfare indicators were further identified as animal-based (behavioural, physiological or production-related) or resource-based.

To support comparison and synthesis, references were grouped into two categories: studies directly investigating or describing VF in cattle, and supporting literature drawn upon for welfare indicators, stress physiology and welfare assessment frameworks (Table 1 in Appendix). Where available, statistically analysed results from the original studies were used to identify similarities and differences in the effects of VF on animal welfare indicators. Where studies reported differing results, possible methodological explanations, for example, differences in animal age, training duration, collar system or grazing context, were considered before drawing conclusions. Findings were synthesized and interpreted narratively across studies.

2.3 Limitations

As this study is based on a narrative synthesis of existing literature rather than a meta-analysis, the findings rely on the interpretation of reported results rather than quantitative aggregation, which may introduce a degree of subjectivity.

3. Literature review

3.1 Virtual fencing: principles and operation

Virtual fencing is a technology that restricts animal movement to within a specified boundary using collars with Global Positioning System (GPS) or Global Navigation Satellite System (GNSS)-controlled signals rather than physical boundaries (PB). The technology works by providing a series of cues that, through associative learning, train the animals to stay within a designated inclusion zone (Campbell et al. 2019; Goliński et al. 2022). Figure 1 presents a detailed schematic representation of the most adopted virtual fencing concept.

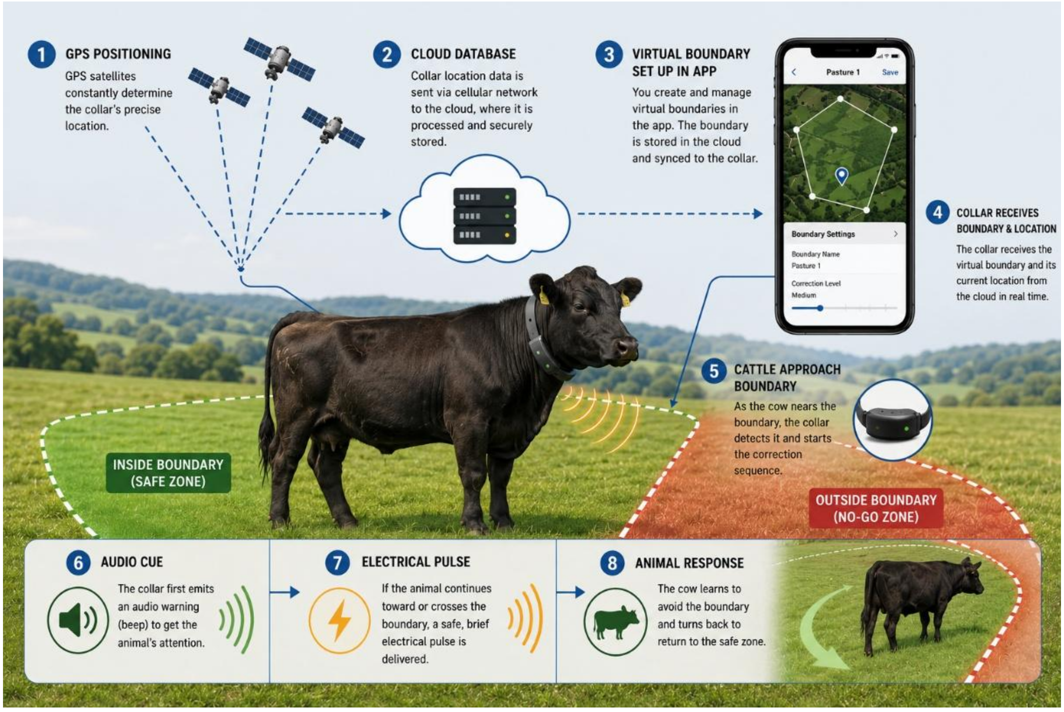

Figure 1. AI-generated - Detailed schematic representation of the most adopted virtual fencing concept, including the components used.

The virtual fencing automated system continuously monitors the animal's position, direction, and speed in real time using a collar and GPS or GNSS connected to cellular systems. When the animal approaches or crosses the virtual fence boundary (depending on the system), the collar emits an AC. If the animal stops or turns away from the boundary after hearing the AC, no further stimulus is applied. If the animal instead continues moving forward, the collar delivers a short EP. To ensure welfare, collars are configured to deliver a maximum of three EPs in one instance of boundary approaching/crossing. If three EPs are given the collar will cease to administer more until the animal re-enters the boundary and the collar resets (Campbell et al. 2019).

3.2 Types of virtual fencing collars and their use worldwide

A range of commercial VF systems have been developed over the years, with ongoing technological improvements and new companies continually emerging (Table 1). All systems typically consist of two main components. A software interface allowing users to draw VF boundaries and a GPS/GNSS-enabled collar fitted around the animal's neck. These systems differ in collar design, signal delivery and additional features, which may influence their practical application and their uptake by industry.

3.2.1 eShepherd

The eShepherd® system developed by Gallagher is currently used in Australia, New Zealand, and the northern United States (eShepherd®, Gallagher, Hamilton, New Zealand). The system is available in two communication models, the LoRa eS1 neckband and the cellular eS1 neckband. The LoRa version communicates via long-range LoRa radio signals to an on-farm base station, which then connects to a cellular network. The cellular eS1 neckband instead uses a global SIM card to connect directly to local cellular networks, thereby removing the need for additional on-farm infrastructure.

The system supports VF, livestock training and herd movement management and is primarily intended for cattle weighing more than 200 kg. It is powered by solar energy and is designed to have an operational lifespan of approximately 7 to 10 years.

3.2.2 Halter

The VF system developed by Halter® is currently used in New Zealand, Australia and the United States of America. The system combines virtual fencing with animal monitoring and health management functions (Halter®, Halter, Auckland, New Zealand).

The system comprises solar-powered GPS collars, LoRaWAN transmission towers installed across the farm, and a mobile application integrated with satellite imagery. The collars communicate with on-farm towers, which relay data to the application, while commands from the application are transmitted back to the collars over the same network. The infrastructure typically requires multiple base stations and a service contract lasting three to four years. The collars are estimated to have a lifespan of approximately five years.

When animals approach a virtual boundary, the collar first emits a directional AC intended to guide the animal back toward the designated grazing area. If the cue is ignored the system delivers an EP. In addition, the collars can generate vibration signals to indicate access to fresh pasture and to promote herd movement in a desired direction.

Beyond fencing functions, the Halter system also provides continuous health and behavioural monitoring. The accompanying data analysis tools include reproductive monitoring, such as heat detection, cycling rates, return-to-estrus intervals and mating performance benchmarking. The system also supports grazing management through features including rotation planning, fertilizer application records, pasture performance benchmarking and forage growth rate estimates. Herd monitoring functions further provide insights into individual animal behaviour, rumination activity and health-related alerts.

3.2.3 Nofence

The VF system developed by Nofence® is currently used in Norway, United Kingdom, United States of America, Spain, Ireland and Sweden (Nofence®, Nofence AS, Molde, Norway). The system is available for cattle, goats and sheep and consists of a solar-powered collar with a rechargeable battery in combination with a mobile application.

The collars use satellite-based positioning through GPS and other GNSS technologies to determine the animal's location in relation to user-defined virtual boundaries. Communication between the collars and the mobile application occurs over 2G or 4G mobile networks. However, the fencing function itself relies on satellite positioning rather than mobile coverage. The collars transmit updates every 15 minutes, including battery status, location, operating mode, and emitted cues. Bluetooth connectivity enables local troubleshooting and the temporary removal of pasture boundaries even in areas without mobile network access. In addition, the system includes the HerdNet function, which allows nearby collars to share updates locally so that herd movement can continue collectively even if only one collar has network connectivity.

The manufacturer does not specify a minimum age or weight requirement for use. Instead, suitability is considered to depend on the animal's cognitive maturity and physical ability to wear the collar without behavioral impairment. Animal owners are therefore responsible for monitoring the animal's adaptation to the system.

The system operates in three sequential audio zones, in which the AC intensity increases as the animal moves closer to or beyond the virtual boundary. The duration and escalation of the cue are influenced by the animal's movement speed, with faster movement resulting in more rapid escalation. If the animal ignores all ACs, an EP of up to 0.7 joules may be delivered through metal chains that maintain contact with the neck. If the animal continues beyond the boundary after passing through all three audio zones the fencing function is temporarily deactivated.

System performance depends on GPS accuracy, meaning that cues may occasionally be triggered earlier or later than intended. If positional accuracy decreases below approximately 3.5 meters, neither ACs nor EPs are emitted. Roofed structures and walls can further degrade signal quality and reduce positioning accuracy. To address this, a shelter Beacon can be installed to temporarily disable the collar's operating mode in designated areas.

The collars are estimated to have a lifespan of approximately five to ten years.

3.2.4 Vence

The Vence® VF system is currently only used in the United States of America (Vence®, Merck Animal Health, Madison, NJ, USA). The system relies on solar-powered base stations designed to operate in remote and rugged terrain. Depending on the topography, a single base station can provide coverage for approximately 5.000-10.000 acres. These base stations connect collar data to the internet and enable remote programming and software updates of the collars.

The collars communicate with the base stations via a LoRaWAN transceiver that transmits position data derived from GPS satellite coordinates. Unlike several other VF systems, the Vence collars use single-use batteries rather than rechargeable or solar-powered units. Battery life is estimated to range from six months to two years, depending on factors such as pasture configuration and grazing management plans.

As animals approach a virtual boundary the collar first emits a sequence of ACs intended to encourage the animal to change direction. If the animal continues toward or beyond the boundary, the collar escalates the warning by combining ACs with EPs. The system also allows users to create and schedule multiple virtual fences that automatically activate or deactivate based on predefined grazing plans, thereby facilitating rotational grazing management.

3.2.5 Monil

The VF system developed by Monil® is currently used by farmers in Norway, United Kingdom, Sweden and United States of America (Monil®, Monil AS, Lysaker, Norway). The system consists of solar-powered GNSS collars connected to a mobile application that enables users to monitor animals and manage virtual boundaries remotely.

When an animal approaches or crosses a virtual boundary the collar initiates a warning sequence consisting of up to three escalating rounds of ACs. If the animal does not respond to these cues, an EP is delivered. The AC intensity increases progressively before the EP is activated. If the animal continues beyond the boundary after the complete warning sequence it is classified as “escaped” and the user receives a push notification through the application. Once the animal is registered as escaped, the collar stops delivering cues but continues transmitting positional information. The fencing function is automatically reactivated once the animal has moved at least 0.5 meters back within the designated area.

The collars transmit positional data approximately every 20 minutes and rely on both mobile network connectivity and GNSS signals to operate. If GNSS accuracy becomes insufficient, the fencing function is temporarily paused to reduce the risk of inappropriate cue delivery. The collars are powered by integrated solar cells designed to maintain operation throughout the grazing season, although battery performance may vary depending on weather conditions, sunlight exposure, fence size, and animal movement patterns.

In addition to virtual fencing functions, the application includes an activity heatmap feature in which colour intensity reflects the amount of time an animal has spent in a specific area during the previous hour. The system is not recommended for animals younger than six months of age, due to considerations related to learning ability and adaptation to the technology.

Table 1: Different VF systems and their specifications.

Collar Brand	Weight/age restrictions	What countries	Communication	Energy source
eShepherd	>200kg	Australia, New Zealand (NZ), United States of America (US) and Canada	GPS, base station	Solar powered
Halter		NZ, Australia, US	Base station, mobile network needed, GPS	Solar powered
Nofence		Norway, United Kingdom (UK), US, Spain, Ireland and Sweden	Mobile network (2G and 4G), Bluetooth, GPS	Solar powered & chargeable battery
Vence		US	Base station, GPS, radio frequency transceiver	Battery
Monil	>6 months	Norway, UK, Sweden, US	Mobile network coverage and GNSS (GPS) signals	Solar powered, can be charged via charger

3.3 Drivers of virtual fencing adoption

3.3.1 Farmer adoption, animal management and monitoring

Research has identified several practical, environmental and management-related motivations that influence farmers' adoption of VF (Hoag et al. 2024; Schillings et al. 2024). Labor efficiency and improved grazing control have been highlighted as two of the most important perceived advantages of the technology by farmers (Goliński et al. 2022; Hoag et al. 2024). By reducing reliance on physical fences, VF may lower labor demands associated with fence construction, inspection and maintenance, while also extending the functional lifespan of existing fencing infrastructure. At the same time, VF offers increased flexibility in grazing management, allowing farmers to rapidly modify grazing boundaries in response to changing conditions, establish temporary enclosures, exclude livestock from environmentally sensitive areas, or create virtual lanes to guide animal movement

(Hoag et al. 2024; Wilms et al. 2024). These features are particularly relevant in systems where adaptive pasture use and rotational grazing are central management objectives.

In addition to its role in grazing management, VF is frequently described as a tool that can enhance animal monitoring. Through animal-mounted GPS-equipped collars, the technology provides continuous location data that allow farmers to supervise livestock remotely, locate animals more quickly, and respond more rapidly to injuries, mortalities, or predation events (Hoag et al. 2024; Petters & Wahlund 2025). This functionality may be especially valuable in extensive production systems or rugged terrain, where traditional supervision is more time-consuming and logistically challenging (Goliński et al. 2022; Hoag et al. 2024). Although similar tracking functions are available in other GPS-based monitoring systems, VF differs in that all animals are typically fitted with collars, enabling identification of individuals that have separated from the group rather than relying on a subset of tracked animals (Petters & Wahlund 2025).

The literature also identifies environmental considerations as a relevant factor in the adoption of VF (Bennett et al. 2026). Reducing or removing physical fencing may improve landscape connectivity and facilitate wildlife movement, thereby reducing the risk of injury or mortality from fence entanglement (Hoag et al. 2024). Although these environmental benefits are often difficult to quantify, they are still considered meaningful in farmers' decision-making processes. VF may also indirectly support predator management by enabling closer monitoring of livestock behavior and improving documentation of predation events, which may strengthen farmers' ability to participate in compensation schemes (Jamieson & Hessle 2021; Hoag et al. 2024).

Despite these advantages, the literature consistently shows that VF does not eliminate labour requirements altogether but rather transforms them. While virtual boundary design may reduce the time and personnel needed compared with constructing and maintaining physical fences, new forms of work emerge (Goliński et al. 2022; Hoag et al. 2024). These include fitting and removing collars, checking collar placement, adjusting collars for growing animals, replacing batteries, locating lost collars, planning virtual paddocks, and handling escaped livestock (Hoag et al. 2024; Petters & Wahlund 2025). Some of these tasks may also introduce additional practical and occupational challenges. For example, collar adjustment often needs to be carried out in the field and may be difficult without restraining the animal, which can increase the risk of injury of both farmers and livestock if not performed properly.

In the survey by Petters & Wahlund (2025), farmers identified animal supervision as the most time-consuming task in livestock management, followed by fence maintenance. Against this background, the ability to monitor animal positions in real time via a mobile application was seen as a major advantage, as it enabled rapid location of animals and reduced the time needed to retrieve escaped animals. Escapes were reported to occur in both traditional and VF systems, but VF users generally perceived them as less frequent. However, the causes differed between systems: in EF, escapes were often linked to low voltage or external disturbances, whereas in VF they were more commonly associated with animals being startled or insufficiently familiar with the system. Although VF may reduce some of the limitations of physical fencing, it also introduces new forms of management risks, including those associated with technical failures such as battery depletion.

Another challenge highlighted in the literature concerns the learning process associated with using the technology (Hoag et al. 2024). The implementation of VF requires adaptation not only by the animals, which must learn to respond to the system, but also by farmers and farm workers, who must develop both technical competence and new management routines. In this sense, adoption is not merely a matter of learning how the technology operates, but also of rethinking how livestock can be managed through virtual rather than physical boundaries. This challenge may be compounded by the rapid pace of technological development in the field, as new functions and system updates require continuous learning and operational adjustments over time.

Importantly, the literature also indicates that farmers are generally reluctant to rely on VF as a stand-alone solution in situations without physical borders. Hoag et al. (2024) report that farmers typically would not adopt VF without physical borders, particularly in contexts where strict containment is necessary. In such cases, VF is instead discussed as a complementary technology, rather than a replacement for conventional fencing. Hybrid systems that combine virtual and physical fencing have therefore been proposed as a more reliable strategy, allowing some reduction in physical infrastructure while maintaining a higher degree of containment security.

Overall, the literature suggests that adoption of VF is motivated by a combination of expected gains in labour efficiency, greater flexibility in grazing management, improved animal monitoring and potential environmental benefits (Hoag et al. 2024; Gadzama et al. 2025; Petters & Wahlund 2025). At the same time, these benefits are moderated by practical constraints, learning demands and continued concerns about containment reliability. Virtual fencing should therefore not be classified as a straightforward substitute for traditional fencing but rather as an emerging management tool whose value depends on the specific production context in which it is implemented.

3.3.2 Grazing systems

Virtual fencing provides producers with a flexible tool for adaptive and precision grazing management (Brier et al. 2020; Goliński et al. 2022). By creating and adjusting virtual boundaries on a computer or mobile device, producers can easily implement rotational or strip grazing and move animals between specific enclosures, thereby increasing feed efficiency (Langworthy et al. 2021; Goliński et al. 2022). The technology enables higher stocking rates over shorter periods to manage vegetation and achieve specific land management objectives (Hoag et al. 2024).

Grinnell et al. (2025) evaluated VF as an alternative to physical EF in rotational grazing systems, specifically assessing whether VF can effectively manage cattle while safeguarding animal welfare. The results showed that VF can contain and manage cattle without adversely affecting stress levels. The study found no significant effects of the fencing system on faecal cortisol metabolites (FCM), body weight gain and herbage selection. However, stocking rate was moderately positively associated with the frequency of audio cues (AC) and electrical pulses (EP) in cows with calves, whereas grazing pressure was weakly positively associated with EP frequency. No such correlations were observed in heifers (Harland et al. 2025). Higher stocking rates can accelerate forage depletion, encouraging animals to spread out in search of feed and thereby increasing the likelihood of interacting with the virtual boundary. From a management perspective, this highlights the importance of considering grazing intensity when implementing VF, as it can influence animal-boundary interactions.

From practical, environmental, and management perspectives, VF offers several advantages for adoption in rotational and strip grazing systems. Practically, it reduces labour demands and enables more precise and flexible pasture allocation. Environmentally, it supports adaptive grazing strategies that optimize forage utilization, reduce overgrazing, and protect ecologically sensitive areas without the need for permanent infrastructure. From a management standpoint, research shows that animal welfare and productivity are maintained even with frequent paddock transitions (Grinnell et al. 2025; Harland et al. 2025).

However, it should be noted that areas closest to the virtual boundary in strip grazing were found to be underutilized relative to other parts of the inclusion zone, which may indicate an aversion to the stimuli and could affect the spatial distribution of grazing (Lomax et al. 2019). This is an important consideration when planning and implementing VF in practice.

3.3.3 Managing sensitive or protected areas

Virtual fencing can also be useful for excluding livestock from environmentally sensitive areas, such as riparian zones or habitats with rare plant species, without the labour-intensive construction of physical fences (Hoag et al. 2024; Bennett et al. 2026).

A study by Campbell et al. (2020) demonstrated that cattle could be excluded from a regenerating area 99.8% of the time. The animals rapidly learned to respond to the AC alone, allowing the VF to effectively restrict access even with a more complex fence line (not a straight line). By the end of the trial, the grazing zone had decreased from an average biomass of 0.50 ton/ha to 0.31 ton/ha, whereas the non-grazed exclusion zone had an average biomass of 0.59 ton/ha by the end of the trial. The exclusion zones also had significantly higher dry matter digestibility (DMD) and crude protein (CP) than the inclusion zone (mean ± SE DMD inclusion zone: 31.6 ± 1.1%, exclusion zone: 53.6 ± 3.8%; CP inclusion zone: 6.1 ± 0.7%, exclusion zone: 20.7 ± 2.1%). These results indicate that VF can protect environmental assets within a paddock from grazing pressure, even when a substantial feed differential exists across the fence. However, the study was conducted on a single group of animals in a single paddock, highlighting the need for replication with more diverse groups of animals and across different paddock sizes and configurations.

The pasture differential at the end of the trial further showed that VF could maintain animal exclusion under high grazing pressure. Nevertheless, the feed differential likely motivated some individuals to attempt entry into the exclusion zone, especially as animals experienced weight loss during the trial due to limited feed supplementation. At least one animal crossed into the exclusion zone on every day of the trial except two, with a mean daily number of incursion events greater than 2 m into the exclusion zone across all animals of 2.7 ± 3.5 SD (Campbell et al. 2020). Although no damage to saplings was observed during the animals' brief interactions with the excluded area, it is important to note that VF does not guarantee 100% exclusion, similar to standard EF. For practical application, it is recommended to position the virtual boundary some distance away from the sensitive area to create a buffer zone.

An earlier study by Campbell et al. (2018a) tested a prototype automated VF collar to temporarily exclude a small group of ten cattle from a riparian zone on a commercial property in Australia. During VF activation, all animals interacted with the fence and received collar cues, though the number of interactions, ACs, and EPs varied among individuals. The VF successfully prevented access to a previously frequented water resource for approximately ten days. Some animals attempted to push through the boundary, particularly during the first few days, indicating continued motivation to access the river. Nevertheless, the VF was sufficient to deter them. After deactivation, all animals accessed the previously excluded riparian area within approximately two hours, including portions of the riverbank they had not used before VF activation. This study therefore indicates that VF may be effective for short-term exclusion of cattle from sensitive riparian areas.

Overall, these studies demonstrate that VF can effectively protect environmentally sensitive areas while allowing flexible livestock management. The technology provides a non-physical means of exclusion, but practical implementation should account for buffer zones and potential variation in individual animals' responses to ensure reliable protection of protected areas.

3.3.4 Predator management

Virtual fencing has been proposed as a tool to support predator management in extensive grazing systems, with several proposed mechanisms by which this may occur, although the supporting evidence remains largely indirect and based on producer perspectives rather than experimental studies (Hoag et al. 2024; Bennett et al. 2026). Producers may use virtual boundaries to exclude cattle from known predator habitats or hotspots, reducing the likelihood of encounters (Hoag et al. 2024). The absence of physical barriers may also allow cattle to flee predators more easily, since traditional fences can inadvertently trap livestock against perimeter boundaries, increasing predation risk. Continuous GPS tracking provided by VF collars further enables producers to locate injured or dead animals more quickly and to document predation events, which can be important for participation in livestock indemnity or compensation programmes.

Producers have also expressed interest in future technological developments such as predator-alert functionality, which would notify them of unusual herd movements that may indicate a predator's presence (Jamieson & Hessle 2021; Hoag et al. 2024). Despite these potential advantages, producer surveys indicate that VF is not yet widely regarded as a reliable defensive strategy against predators. Many farmers view it more as an internal management tool than as a perimeter solution (Hoag et al. 2024).

Beyond direct effects on predation, VF may also have indirect benefits for wildlife. By reducing reliance on physical fencing, VF can decrease wildlife-fence conflicts and entanglement injuries, support landscape connectivity, and facilitate the maintenance of wildlife corridors (Goliński et al. 2022; Wilms et al. 2024; Bennett et al. 2026). Overall, predator management appears to be one of the most contextually variable applications of VF. Its relevance depends heavily on the predator species present, the grazing system, the size of the area, and the farm's topography.

3.4 Public perception and ethical concerns

Public perception of VF is characterized by ambivalence, with attitudes polarized between its potential to improve animal welfare and biodiversity conservation and concerns about its ethical implications (Stampa et al. 2020; Labarthe 2023). Public perception is often shaped by a widespread lack of knowledge about modern agricultural practices and animal welfare.

Generally, the idea of cattle pasturing to promote animal welfare by enabling natural behaviours is supported, but some concerns are being raised about the technology's effects on animal welfare. Consumers generally associate pasture access with better animal health, freedom of movement and higher product quality, thereby improving animal welfare in the eyes of the consumer (Brier et al. 2020; Stampa et al. 2020). This view aligns with the use of VF which promotes increased grazing through ease of use and access to difficult to fence grazing areas. However, the use of VF also faces criticism similar to that of stock contained by conventional EF, which uses aversive electrical stimuli to contain animals with the only difference between the two being the visual cue rather than the AC. For VF to be ethically justifiable, the aversive stimuli must provide a clear welfare benefit that cannot be realistically delivered by a non-aversive method. Virtual fencing and the monitoring associated with it increase farmers' ability to exercise their duty of care to their stock and improve grazing while also protecting environmentally sensitive areas.

The use of VF may also face increasing public pressure as the technology evolves including the use of a VF as a herding tool. This may come under scrutiny as the VF learning process for individuals is not yet well understood, and there may be limitations on how the technology works at both the individual and herd levels (Lee & Campbell 2021). However, a study by Verdon et al. (2024) using the Halter technology (the only one with directional cues) showed that animals in a herd were able to exit paddocks and navigate laneways to the milking parlour unassisted by humans, after four days of training using the Halter technology's directional cues. The largest cause of an increased ratio of AC:EPs was human error, e.g. failing to open a physical gate or temporary electric fence. To mitigate this VF systems include safeguards that automatically disable stimuli if an animal fails to respond after a certain number of cues, preventing unnecessary stress and safeguarding welfare.

Virtual fencing is seen as a possible tool to support biodiversity and conservation, enabling protection of environmentally sensitive areas, such as rare plant species or the nests of endangered birds, by excluding cattle without needing physical barriers (Bennett et al. 2026). Some people perceive VF as more sustainable because they can be reused and do not disturb the natural landscape the way erecting physical electric fences does (Stampa et al. 2020; Labarthe 2023). But despite the environmental positives some of the general public fear that the electronic signals or irradiation could harm humans or insects, however, this has not been well studied or documented for the use of VF (Stampa et al. 2020; Hoag et al. 2024).

Technical and practical doubts also influence public acceptance. There are worries about battery life and GPS signal failure where there are doubts whether the system can effectively control cattle during stampedes (Schillings et al. 2024).

This is not only a worry shared by the general public, but also industry (Hoag et al. 2024), where when surveyed many farmers would not use VF alone as a boundary fence, perhaps limiting its use and environmental positive impacts by this viewpoint.

Virtual fencing forms part of a shift in livestock management practices towards greater automation. If used in combination with other systems, such as automated milking, automated feed dispensing systems and drone observation, it may contribute to a highly technological management infrastructure in which ingoing contact with humans is reduced. This may have unintended negative livestock welfare impacts which need to be furthered studied. But currently it appears to have net positive welfare impacts, improving the usage of stockperson time, reducing the time spent on locating/ monitoring animals and increasing targeted engagement with health problems through individual animal monitoring (Hoag et al. 2024; Petters & Wahlund 2025).

3.5 Animal welfare implications of virtual fencing

Animal welfare is a complex concept that encompasses physical health, behavioural expression and subjective mental experiences. It is increasingly recognized that welfare cannot be assessed solely through productivity or absence of disease and an animal's ability to cope with its environment, but with a focus on agency and natural behavioural expression (Hemsworth et al. 2015; Mellor 2017).

Welfare assessment is often indirect and currently it is not possible to identify an individual animal's emotional state (Hemsworth et al. 2015), where we rely on a combination of physiological, behavioural and environmental indicators to infer how an animal is thinking or feeling. However, it is important to remember that physiological responses often related to stress are not necessarily negative and the emotional valence of the animal should be inferred from not just physiological indicators but in combination with behavioural. Where a stress response may reflect adaptive processes that help support survival and goal-directed behaviour (Koolhaas et al. 2011).

In addition to scientific measures, animal welfare is shaped by ethical considerations and public perception, particularly in relation to new technologies in livestock management (Stampa et al. 2020). This highlights the need for structured approaches that integrate multiple dimensions of welfare.

3.5.1 Welfare is multidimensional

Animal welfare is a multidimensional concept that has many definitions and welfare is evaluated through a combination of physiological stress indicators, behavioural patterns, physical health and cognitive factors such as predictability and controllability based on individual animal assessment (Hemsworth et al.

2015; Gadzama et al. 2025). One assessment of animal welfare is the use of the Five Domains Model which is a systematic framework used to facilitate a structured and comprehensive assessment of animal welfare (Mellor 2017).

The Five Domains Model consists of the domains nutrition, physical environment, health, behavioural interactions and mental state. The nutrition domain focuses on the animal's internal physical and functional state in relation to food and water intake, including both negative experiences such as hunger and thirst and positive experiences associated with pleasant tastes and feeding opportunities (Mellor et al. 2020). The physical environment domain evaluates how external conditions, including temperature, light, air quality and noise levels, affect the animal's welfare and comfort. The health domain considers the presence of disease, injury, pain, or functional impairment, while also recognizing positive states associated with good health, vitality, and physical fitness (Mellor 2017; Mellor et al. 2020).

Unlike the first three domains, which primarily address internal survival-related conditions, the behavioural interactions domain focuses on the animal's ability to express voluntary and goal-directed behaviours. This includes behaviours such as exploration, social interaction, play, and other activities that reflect agency and behavioural freedom (Mellor 2017; Littlewood et al. 2023). The fifth domain, mental state, integrates the subjective experiences inferred from the previous four domains. These experiences may include negative affective states such as pain, fear, thirst or breathlessness, as well as positive states including calmness, comfort, playfulness and maternal reward (Mellor 2017; Littlewood et al. 2023).

The Five Domains Model operates by assessing both internal physiological states and external environmental conditions, from which likely mental experiences are cautiously inferred. The cumulative affective experiences represented within the mental state domain are considered indicative of the animal's overall welfare status (Mellor 2017). Although the model provides a valuable framework for scientific welfare assessment, its application in public evaluation and communication remains challenging. This is largely because mental states cannot currently be measured directly and must be inferred from observable positive or negative experiences. Such interpretations may contribute to uncertainty and misunderstanding, particularly in discussions surrounding emerging technologies and novel animal management systems.

3.5.2 Associative learning

The effectiveness of VF relies on the principles of associative learning through operant conditioning. Animals learn to associate the non-aversive stimulus (AC), with the aversive stimulus (EP). Through repeated exposure, the animal learns that the AC precedes the EP. The goal is for the animal to develop an associative behaviour where they respond to the AC alone, to avoid the EP (Campbell et al. 2019; Lomax et al. 2019).

The system relies on predictability and controllability. The AC acts as a warning, making the subsequent EP predictable. Since the animal can stop or turn away to prevent the EP, the environment remains controllable (Lee et al. 2018; Campbell et al. 2019). Research shows that cattle learn this association rapidly, often within two to five days (Confessore et al. 2024; Liffen et al. 2026). Evidence of successful learning is seen in a significant reduction on the number of EPs received over time and a corresponding increase in ACs (Campbell et al. 2019). This technology operates under the same learning principles as traditional EF, where a visual stimulus, the fence itself, is paired with an electrical shock. In VF, the AC replaces the visual cue of the physical fence (Campbell et al. 2019).

While the technology is highly effective on a herd level, containing animals 99% (Lomax et al. 2019), there is significant individual variation in how quickly animals learn and how frequently they interact with the virtual boundary (Campbell et al. 2019; Lomax et al. 2019). While individual variation is present in learning VF technology age as a factor does not appear to affect how well an animal learns; primiparous and multiparous cows have been shown to adapt to the system with equal speed (Confessore et al. 2024).

3.5.3 Retaining learning

The retention of understanding the VF technology cues is an important aspect of VF to consider, since the learning period is one of the most labour- and resource-intensive phases of VF implementation due to the time and labour required to enclose cattle in small paddocks, progressively adjust VF boundaries and closely observe animals during training (Harland et al. 2025). This period is also among the most stressful for the animals (Verdon & Rawnsley 2020). Research has shown varying findings on this topic, suggesting that retention depends heavily on the intensity of initial training and the number of pairing events experienced by the animal (Verdon & Rawnsley 2020; Harland et al. 2025).

Cattle retain learning differently based on their age and the complexity of the task. While younger heifers often learn new tasks more quickly, older cows are generally found to have a more stable long-term memory (Kovalčik & Kovalčik 1986). In tests involving food location in a maze, multiparous cows showed better retention than heifers after a six-week break, where approximately 77% of the multiparous cows went directly to the correct feeders, whereas only 46% of heifers did so without error (Kovalčik & Kovalčik 1986).

A study by Verdon & Rawnsley (2020) on VF suggests that cattle do not retain associative learning over very long periods without reinforcement. There were no beneficial effects of previous training at an early age on the responsiveness of heifers to the AC and EP when re-trained at 22 months. Compared to naïve 22 months old heifers, animals that were initially trained at 6 and 9 months required more interactions with the VF before responding to the AC alone, with 9 months heifers requiring the highest number of interactions (Verdon & Rawnsley 2020).

In comparison, Harland et al. (2025) showed significant learning retention over long periods. In the multi-year study, yearling beef heifers were trained and managed with VF showing retention when they returned as first-calf cows after a 300-day break. While naïve heifers typically require a 5- to 7-day training period to associate ACs with EPs, reintroduced cows showed no clear learning curve upon re-exposure and minimized EPs from the first day of re-training.

Overall, while cattle possess memory capabilities, the stability of what they retain is influenced by their developmental stage and frequency of reinforcement (Kovalčik & Kovalčik 1986; Verdon & Rawnsley 2020)

3.5.4 Stress and its interpretation

The concept of stress is often misunderstood as being synonymous with any physiological arousal often related to a negative experience. However, based on Koolhaas et al. (2011) stress is more accurately defined and interpreted through the lens of controllability, predictability and adaptive capacity and is not necessarily negatively correlated.

While stress has been traditionally defined as a non-specific response to a "noxious stimulus" or a threat to homeostasis (Chrousos 2009), it could be argued that this definition is too broad (Del Giudice et al. 2018). Instead, it is proposed that stress be restricted to conditions in which environmental demands exceed an organism's natural adaptive capacity. Central to the interpretation of stress are two psychological factors: predictability and controllability. True stress is a cognitive perception of these two factors, which then manifests in a physiological and behavioural response (Koolhaas et al. 2011). The review by Koolhaas et al. (2011) highlights that the physiological reactions labelled as stress responses, are not inherently harmful or negative. These systems primarily function to mobilize energy and redistribute resources, such as oxygen and nutrients, to support physical activity. This is a mandatory metabolic function for survival and goal-directed behaviour. Physiological responses to appetitive or rewarding stimuli can be just as strong as those to aversive ones. For instance, studies have shown that horses and rats exhibit similar levels of corticosterone, a stress hormone, during rewarding activities, such as sexual behaviour or winning a social interaction, as they do during aversive experiences (Colborn et al. 1991; Koolhaas et al. 2011).

When an environment provides challenges that fall within an organism's regulatory range, the resulting physiological activation is considered physiological support of behaviour rather than stress. These challenges can be adaptive, helping the individual to optimize their responses to future events. The key differentiator between a healthy physiological response and a negative stress response is not the magnitude of the initial reaction, but the speed of recovery. In controllable/predictable situations the physiological response declines rapidly once the activity is over, while in uncontrollable/unpredictable situations the response is characterized by delayed recovery or the absence of an anticipatory response. It is this failure to shut off the physiological response or return to baseline that can lead to maladaptation, rather than the activation of the stress system itself (Koolhaas et al. 2011).

3.5.5 Welfare impairment when comparing virtual fencing with traditional electric fencing

Based on the available research, VF compares favourably with traditional EF in terms of animal welfare, learning, and productivity outcomes (Campbell et al. 2019; Langworthy et al. 2021; Verdon et al. 2021; Hamidi et al. 2022; Aaser et al. 2022; Marini et al. 2022; Fuchs et al. 2024).

Both VF and EF systems appear to elicit similar behavioural and physiological responses with no long term welfare impairment. Aaser et al. (2022) reported that cows exhibited clear signs of learning the VF cues, with a reduction in both ACs and EPs over time, and no evidence of negative welfare impacts from behavioural observations. Similarly, Fuchs et al. (2024) found that milk cortisol concentrations, body weight, feed intake, activity, and lying behaviour did not differ significantly between VF and EF groups throughout a 56-day period. Short-term stress-related behavioural responses, such as running away from the virtual boundary, were observed initially after receiving EPs but decreased as cows gained experience with the VF system. Overall, these findings indicate that VF does not induce higher stress levels than EF and that cows adapt well to the system.

In terms of exploratory behaviour, which may indicate positive welfare in cattle (Proudfoot et al. 2025), one study cows remain engaged with virtual fencing boundaries, exploring throughout the trial period rather than actively avoiding it (Campbell et al. 2019). Similar to, Fuchs et al. (2024) who noted a higher number of displacements in VF groups initially, reflecting exploration and learning, but cows progressively kept a greater distance from exclusion zones while still interacting with the system. This demonstrates that VF promotes behavioural adaptation without inducing excessive stress responses. In contrast, EF creates a permanent physical barrier that limits exploratory behaviour and requires no adaptation (Jachowski et al. 2014).

While EF provides reliable physical containment, it lacks adaptability. VF allows dynamic adjustment of paddock boundaries, facilitating rotational or strip grazing without manual fence relocation. This flexibility does not appear to compromise welfare or productivity and can be particularly advantageous in complex or variable landscapes (Fuchs et al. 2024).

Overall, based on presented literature, VF and EF perform similarly in terms of animal welfare, stress indicators, behavioural adaptation, and productivity. Virtual fencing introduces the additional benefits of flexible, adaptive boundary management and supports herd-level learning, while maintaining welfare and production comparable to EF.

3.6 Welfare indicators used (and potentially useful) in virtual fencing research

Animal welfare is a central concern in VF research, making the identification of appropriate welfare indicators which are useful in field assessment vital. The choice of indicators effects not only how welfare is measured, but also how findings are interpreted and compared across studies. Indicators can broadly be divided into two categories 1. Animal based welfare indicators and 2. Resource based welfare indicators. Where animal-based welfare indicators relate directly to the animal (e.g. behaviour, blood) and resource based are what is provided to the animal (e.g. shelter, food).

3.6.1 Animal-based indicators

Hair cortisol

Hair cortisol metabolites are increasingly recommended as measures of chronic stress over periods of several weeks or months, as they provide an integrated, long-term record of cortisol (Wilms et al. 2024). As a non-invasive method, hair sampling causes minimal disturbance to the animals and is therefore particularly suitable for welfare assessments. Hair cortisol analysis also represents a valuable complementary tool for monitoring stress, since it captures systemic cortisol exposure over prolonged periods (Tarantola et al. 2020). Furthermore, the determination of corticosteroids in hair reduces the confounding effects of restraint and handling, thereby offering a more representative measure of long-term cortisol levels. In contrast to other sampling matrices, hair cortisol is not influenced by the circadian rhythm of hormone secretion. Hair samples are also easy to collect, preserve, and store. Collectively, these characteristics make hair a promising alternative for evaluating prolonged stress exposure, as it may preserve the exposure history of the animals and, through bioaccumulation, enable extended detectability of stress-related biomarkers and other substances over time.

In the context of VF, Confessore et al. (2024) in grazing beef cattle where samples were taken with non-exposure to VF and exposure to VF there were no reported changes in hair cortisol concentrations over time and the result were also not effected by age or sampling times.

Blood cortisol

Measuring cortisol concentrations via blood is a standard method used to identify stress responses and assist in the assessment of animal welfare. These measures are fundamentally useful for establishing that the HPA axis has been activated in response to a stimulus (Ralph & Tilbrook 2016).

Research in species like sheep and pigs has shown that stressors yield species specific ranges of glucocorticoid concentrations in the blood, (Turner et al. 2005; 2010). Cortisol concentration is also impacted by exercise, isolation and immune challenges which have been found to induce predictable peaks in cortisol, which can help researchers interpret the relative impact of different stressors on an animal (Ralph & Tilbrook 2016).

Specific to VF a study by Ranches et al. (2025) evaluating the physiological stress response of 40 mature beef cows during a five-day VF training phase, found that no significant changes in plasma cortisol concentrations occurred between the start of the study (mean plasma cortisol 2.70 µg/dL) and the end of the training phase (2.50 µg/dL). This lack of difference suggests that the use of VF does not trigger a major or lasting stress response via the HPA-axis.

Faecal cortisol metabolites

Faecal cortisol metabolites are a useful indicator of animal welfare since they provide a non-invasive tool for monitoring an animal's endocrine status and physiological stress levels (Hamidi et al. 2022; Wilms et al. 2024). Unlike blood sampling, which can cause acute stress responses due to the handling required, faecal samples can be collected without disturbing the animal, making them non-invasive to obtain (Tarantola et al. 2020; Wilms et al. 2024).

In cattle, the concentration of metabolites found in the faeces reflects the cortisol secretion from approximately 12 to 24 hours earlier. This allows researchers to link physiological responses to specific events or management changes that occurred earlier in the day (Hamidi et al. 2022).

For FCM to be an effective indicator, researchers must account for factors such as diurnal rhythms, excretion times, and the animal's gradual acclimation to its environment, as concentrations often naturally decrease over time as animals become used to handling or their surroundings (Wilms et al. 2024).

Studies indicate that VF does not result in higher FCM concentrations compared to physical EF, suggesting that the technology does not impose additional physiological stress on cattle (Campbell et al. 2019; Hamidi et al. 2022). In a 4 week study by Campbell et al. (2019) on angus steers, it was shown that no difference in FCM concentrations was present between those contained by virtual fences and those contained by electric tape fences. Similarly, a study on Fleckvieh heifers found no significant effect of the fencing system on FCM concentrations. The means were slightly lower in the VF group (14.3 ± 7.11 ng/g) compared to the physical fence group (16.4 ± 12.6 ng/g), but the difference was not significant (Hamidi et al. 2022).

Milk cortisol

Milk cortisol is used as a non-invasive biomarker to assess the welfare of lactating dairy cows by measuring their adrenocortical response to environmental challenges (Verkerk et al. 1998; Fuchs et al. 2024; Wilms et al. 2024). Since milk collection is a routine operation on dairy farms, it allows for the monitoring of stress levels without confounding factors often caused by other more invasive procedures, such as blood sampling (Verkerk et al. 1998).

Cortisol concentrations in milk correlate highly with those found in blood plasma, as free cortisol moves between these compartments via simple diffusion (Verkerk et al. 1998). While the transfer between blood and milk is nearly instantaneous, milk cortisol concentrations generally reflect plasma levels accumulated during the interval of milk synthesis prior to milking (Verdon & Rawnsley 2020). It is a sensitive measure for detecting acute stress responses occurring shortly before milking. Research indicates that composite milk cortisol accurately reflects plasma elevations that occur within one to two hours of collection. Foremilk, milk stripped manually before machine milking, may be an even better medium for assessing the impact of stressors acting up to two hours prior to sampling.

When using milk cortisol as a welfare indicator, it is essential to account for diurnal variation, as concentrations are naturally higher in the morning than in the evening (Fuchs et al. 2024). Additionally, researchers must control for exogenous stressors than can influence cortisol levels independently of the specific factor being studied, such as heat stress, flies or handling intensity (Verkerk et al. 1998; Fuchs et al. 2024).

Specifically for VF, milk cortisol does not seem to be significantly higher compared to traditional EF, suggesting that VF does not cause lasting or increased physiological stress (Verdon et al. 2021; Fuchs et al. 2024). One eight-week study showed that activating the VF system did not cause a significant rise in cortisol, even during the periods when cows were first introduced to the technology or moved to new paddocks (Fuchs et al. 2024).

Salivary cortisol

Salivary cortisol is a non-invasive method of stress assessment that is favoured for its ease of collection and similarities to blood (Dzviti et al. 2019). Saliva can often be collected at specific time points with minimal interference, providing a clearer picture of acute stress responses (Schwinn et al. 2016; Chmelíková et al. 2020). However, it is important to take the circadian rhythm into account. Cortisol levels naturally fluctuate throughout the day, typically peaking in the morning

(Chmelíková et al. 2020). Factors such as age, sex and temperament can also significantly influence baseline levels and the magnitude of the stress response (Chmelíková et al. 2020).

In a study on dogs by Chmelíková et al. (2020) unanticipated stimuli, such as sound blasts and electric shocks tended to increase cortisol response. Similarly in a study on sheep procedures such as shearing or facing a predator caused rapid and significant elevations in salivary cortisol (Contreras-Aguilar et al. 2019). As salivary cortisol is a non-invasive measure which correlates to blood cortisol it is often a preferable collection method which provides accurate assessment with limited confounding factors.

Body weight/body weight gain/Body condition score

Body condition score (BCS), body weight and body weight gain can be used as animal-based outcome measures in welfare assessments since they reflect an animal's physical health, nutritional status and response to environmental stressors (Cook 2018).

Body condition score is a subjective assessment of the proportion of body fat on an animal and is widely adopted in welfare audits since it reflects historic feed intake and the animal's ability to buffer against physical challenges, such as severe cold (Cook 2018). Thin cows face elevated welfare risks, including a lack of body reserves, potential hunger and a significantly higher risk of lameness and mastitis (Cook 2018; Van Eerdenburg et al. 2021). Managing BCS within a tight range is critical to minimizing metabolic disorders. For instance, over-conditioned cows at calving are at a greater risk for ketosis in early lactation. Industry recommendations suggest maintaining a score of 2.75-3.25 at calving for optimal health and productivity (Cook 2018).

Body weight change is a valuable, non-invasive indicator of the "biological cost" of stress (McLaren et al. 2004). To meet the energetic cost of a stress response, an individual must utilize stored reserves, fat, or divert resources from other functions like growth or lactation. Consequently, stress often manifests as body weight loss (McLaren et al. 2004). In commercial settings, weight gain is a crucial economic indicator (Grinnell et al. 2025). Welfare assessments that correlated positive weight outcomes with higher economic returns are often more readily accepted by producers (Van Eerdenburg et al. 2021). Weight gain is considered a reliable welfare indicator primarily under controlled research conditions, as it can be easily influenced by external factors like feed quality and availability rather than stress alone (Wilms et al. 2024).

Regarding VF, multiple studies, conducted across various cattle types and grazing systems consistently report that VF is comparable to traditional EF regarding body weight gain (Campbell et al. 2018; Fuchs et al. 2024; Grinnell et al. 2025). Several trials found that live weight and daily weight gain did not differ significantly between virtually fenced groups and control groups using physical electric fences (Hamidi et al. 2022; Fuchs et al. 2024; Grinnell et al. 2025). In many instances, animals in VF trials instead increased in body weight throughout the experimental period. For example, one study observed dairy cows increasing from a mean weight of 697 kg at the start of the trial to 717 kg by the final period (Fuchs et al. 2024). Research specifically examined whether receiving EPs from the collars negatively affected growth. These studies found no significant correlation between the number of EPs an individual animal received and its daily weight gain (Grinnell et al. 2025), suggesting that VF does not impose a significant welfare risk (McLaren et al. 2004; Ranches et al. 2025). The lack of negative impact on performance indicates that the technology does not divert critical energetic resources away from maintenance and growth, even during the initial learning phases (Hamidi et al. 2022; Fuchs et al. 2024; Grinnell et al. 2025).

Behaviour

Behavioural observations are widely recognised as important animal-based welfare indicators, as they provide a result-oriented assessment of how individual animals respond to and cope with their environment (Campbell et al. 2019; Linstädt et al. 2024). While physical health constitutes an important dimension of welfare, behavioural measures offer additional insight into affective states, comfort, and the animal's ability to adapt to environmental conditions (Confessore et al. 2024). In cattle kept at pasture, normal behaviour is typically characterised by grazing, ruminating, resting, and engaging in social interactions with herd mates (Campbell et al. 2019). Among these behaviours, lying time is commonly regarded as a particularly relevant indicator of comfort and well-being. Dairy cattle generally require approximately 12 hours of lying time per day, and deviations from this pattern, such as reduced lying duration, may indicate discomfort, restlessness, fear, or exposure to environmental stressors (Campbell et al. 2019; Linstädt et al. 2024).

In addition to lying behaviour, activity-based measures such as step counts, standing time, walking distance, motion indices, and rumination patterns are frequently used to assess welfare and create behavioural time budgets (Confessore et al. 2024; Gadzama et al. 2025). Alterations in these parameters may indicate stress, pain, or physical impairment. For example, lame cows have been shown to differ from healthy individuals in feeding behaviour, activity levels, and lying patterns (Linstädt et al. 2024). Other behavioural indicators may reflect more acute states of distress. Increased vocalisations, as well as elevated frequencies of urination and defecation, have been associated with stressful situations such as novelty or social isolation (Fuchs et al. 2024).

Social behaviour also represents an important dimension of welfare assessment. Higher frequencies of agonistic interactions, including displacements and chases, may reflect frustration or reduced capacity to cope with environmental challenges (Fuchs et al. 2024). At the same time, herd behaviour may also play an adaptive role, as cattle can learn from conspecifics and modify their responses through social facilitation or shared avoidance (Campbell et al. 2019; Hamidi et al. 2022; Fuchs et al. 2024). In addition, the distance an animal maintains from humans has been identified as a validated indicator of the human–animal relationship (Confessore et al. 2024; Linstädt et al. 2024). Increasingly, such behavioural measures are monitored using technologies such as accelerometers and GPS collars, which allow for continuous and objective welfare assessment while reducing labour demands and observer bias (Campbell et al. 2019; Confessore et al. 2024; Wilms et al. 2024).

Within the context of VF, behavioural observations are particularly relevant because they can be used to assess both the immediate aversiveness of the system and the animals' learning process. Responses to the AC and EP provide insight into how cattle perceive, interpret, and adapt to the boundary system. Typical reactions to the AC include stopping or turning away, whereas the EP may elicit stronger responses such as flinching, bucking, head tossing, or running forward (Lee et al. 2008; Wilms et al. 2024). The time taken to resume grazing following a stimulus has also been used as an indicator of how disruptive the cue is to natural behaviour and how well the animal has learned the association between the warning signal and the boundary (Wilms et al. 2024).

Studies based on activity sensor data indicate that VF does not substantially disrupt core daily behaviours once adaptation has occurred. Most studies report no significant differences in step counts between cattle managed with VF and those kept behind physical fences (Campbell et al. 2019; Hamidi et al. 2022; Fuchs et al. 2024). Likewise, daily lying time is generally reported to be similar between fencing systems (Hamidi et al. 2022; Fuchs et al. 2024). Although, Campbell et al. (2019) found that cattle in the VF treatment spent approximately 20 minutes less per day lying down than cattle in the physical fencing treatment, total lying time still exceeded 11 hours per day and thus remained within a range considered normal for cattle comfort. Some studies have also reported slight reductions in lying time or temporary alterations in grazing and walking behaviour, for example following the removal of visual cues or under conditions of pasture depletion. However, these changes have generally been difficult to interpret as unequivocally negative when overall behavioural time budgets remained within normal limits (Campbell et al. 2019; Gadzama et al. 2025). In terms of space use, cattle typically appear to utilise the full inclusion zone and do not consistently avoid areas close to the virtual boundary. Overall, the literature suggests that VF may induce short-term behavioural changes during the initial learning phase, whereas long-term effects on normal behavioural time budgets appear limited and broadly comparable to those observed under physical EF (Campbell et al. 2019; Hamidi et al. 2022; Fuchs et al. 2024).

The available evidence further suggests that behavioural adaptation to VF does not occur at the expense of productivity or general physical health, as no consistent negative effects have been reported on milk yield or live weight gain. Nevertheless, some practical concerns remain. One such issue is the risk of skin abrasions on the neck or jaw associated with prolonged collar wear or poor collar fit, which may in turn influence grazing behaviour if not carefully monitored. Behavioural responses to VF should also be interpreted in relation to individual animal characteristics and management conditions. For example, age has been shown to influence activity levels, lying behaviour, and social status within the herd, with younger cows generally being more active and older cows spending more time lying and less time standing or walking (Confessore et al. 2024). Consequently, behavioural responses observed in VF studies should be evaluated with consideration of both individual variation and the broader environmental context.

3.6.2 Resource-based indicators

Access to pasture

Access to pasture is considered a resource-based indicator of animal welfare since it represents an environmental provision that facilitates a wide range of positive animal-based outcomes (Blaga Petrean et al. 2024). Within the welfare quality protocol, it is explicitly utilized as a measure under two key principles, good housing and appropriate behaviour (Welfare Quality Network 2023).

Access to pasture provides the space and environment necessary for cows to express their full behavioural repertoire, which is often restricted in indoor housing (Crump et al. 2019). Pasture also allows for increased walking, which is considered a behavioural need, with cows being motivated to walk even when their external needs for food and water are met indoors (Crump et al. 2019). Since pasture provides ample space and reduces competition for resources, it allows the herd to synchronize their activities, such as lying down or grazing at the same time. Synchronized behaviour is a characteristic of cattle in semi-natural environments and is often used as a signal of good welfare (Crump et al. 2019).

Not only does pasture access often promote positive behaviours the physical characteristics of pasture directly influence welfare measures relating to cow comfort. Pasture is generally a more comfortable and less abrasive surface for lying and locomotion compared to indoor substrates like concrete or cubicle mats. Cows with pasture access exhibit fewer but longer lying bouts and fewer transitions, which indicates they are more comfortable and less restless than cows indoors (Crump et al. 2019; Blaga Petrean et al. 2024).

The importance of this resource is reflected in the high level of motivation cows show for it. Studies show that cows are prepared to “pay a price” for pasture access, such as walking a long distance (Charlton et al. 2013). This motivation and ability to choose or “pay a price” promotes animal agency, allowing cows to make choices about where and when they want to eat or rest, which is a modern pillar of positive animal welfare (Crump et al. 2019).

A study by Campbell et al. (2019) indicates that VF can effectively restrict animals to designated areas while still allowing them to make full use of the available space. Where cattle utilized the entire inclusion zone, suggesting minimal avoidance of areas within the prescribed boundary.

Forage quality and quantity

Forage quality and quantity directly impact the animal’s ability to meet physiological demands for protein, energy and minerals. This can be evaluated in forage with potential yield, botanical composition and chemical analysis of the sward (Kulik et al. 2023). The quantity of available biomass, measured as dry matter yield indicates whether a pasture can support the stocking density of the herd.

Virtual fencing may impact forage quality and quantity by serving as a highly flexible management tool that allows for precise control over livestock distribution and paddock allocations (Hamidi et al. 2022; Harland et al. 2025). By utilising GPS technology to set boundaries, farmers can optimize how herbage is consumed and preserved without the physical constraints of traditional fencing (Harland et al. 2025). Virtual fencing systems are highly effective at containing animals within designated zones, which prevents overgrazing in sensitive or depleted areas while ensuring the herd utilises the available biomass in targeted zones (Harland et al. 2025). Farmers can shift virtual boundaries in real-time to provide livestock with immediate access to fresh biomass when existing areas become depleted. Virtual fencing technology is more responsive to the spatio-temporal dynamics of pasture conditions than physical fences (Hamidi et al. 2022; Harland et al. 2025). Boundaries can be adjusted remotely to move herds to areas where forage quality, such as protein content or palatability, is currently at its peak (Hamidi et al. 2022; Harland et al. 2025). By simplifying the implementation of rotational grazing, VF makes it easier to provide pastures with the rest and recovery periods necessary to maintain high quality species compositions (Harland et al. 2025).

Research indicates no significant differences in herbage consumption when comparing VF to EF (Hamidi et al. 2022).

Water intake

The absence of prolonged thirst is considered an important animal welfare indicator because continuous access to enough clean and good-quality water is essential for maintaining normal physiological function, health, and productivity (Beggs et al. 2019; Welfare Quality Network 2023). This criterion can be assessed through water provision, cleanliness of water points, and the number of animals sharing access to each water source.

Studies consistently show that cattle provided with clean water achieve higher weight gains than those drinking from contaminated sources such as ponds. This effect has been observed across different age groups, including calves, yearlings, and cows. Reduced performance is largely explained by decreased palatability caused by contaminants such as manure, algae, and high salinity levels. Lower palatability leads to reduced water intake, which is closely linked to decreased feed intake and grazing activity, ultimately resulting in lower weight gain (Willms et al. 2002).

4. Discussion

This review examines the use of VF technology in cattle management through four research questions addressing system design, management applications, welfare outcomes and welfare assessment tools. The findings demonstrate that VF systems are not uniform technologies but vary substantially in their communication infrastructure, cue delivery mechanisms and additional applications. At the same time, the reviewed literature suggests that welfare outcomes must be assessed within the management context in which the VF is implemented. This is because management factors including stocking density, training procedures, forage availability and human supervision all impact welfare regardless of individual animal welfare. Together, these findings indicate that the welfare implications of VF are shaped by both technological design and practical application rather than by the technology alone.

The following discussion critically interprets these findings. Section 4.1 examines how differences in VF system design may influence animal welfare outcomes, while Section 4.2 discusses how management context shapes the effects of VF implementation. Section 4.3 critically evaluates the reported welfare concerns and potential benefits identified in the literature, including areas where evidence remains limited, and relates these findings to ongoing public concerns regarding VF technology. Section 4.4 then considers the adequacy and consistency of the welfare indicators currently used in VF research. Finally, Section 4.5 addresses limitations within the existing evidence-based literature, and Section 4.6 outlines implications for future research, practical implementation, and policy development.

4.1 System design as a determinant of welfare outcomes

The reviewed VF systems show considerable variation in collar design, communication infrastructure, additional applications and stimulus delivery, all of which may have implications for animal welfare. However, all collars are consistently based on GNSS/GPS positioning and deliver a combination of ACs followed by EPs when animals approach or cross virtual boundaries. Differences in how these cues are structured, triggered and supported by system architecture are likely to influence animal responses and welfare outcomes.

One key distinction between systems lies in their communication models and infrastructure requirements. For example, Gallagher's, eShepherd and Halter systems rely on LoRa-based communication with on-farm base stations or towers, while Nofence and Monil primarily depend on cellular networks combined with satellite positioning. Systems using local infrastructure often offer more stable communication in remote areas, while cellular-based systems provide greater flexibility but are dependent on network coverage. Notably, systems using mobile coverage still maintain fence functionality through satellite positioning even when mobile connectivity is limited. From a welfare perspective, interruptions in communication or positioning accuracy may lead to inconsistent cue delivery, potentially causing stress in animals. However, the collars have safety measures preventing this scenario where the collars are temporarily deactivated if the signal is not sufficient and reactivated when the signal returns, preventing incorrect stimuli delivery. For example, Nofence and Monil temporarily disable fence functions when positional accuracy falls below a defined threshold. Nofence also recommends using a beacon near objects that could disturb positioning accuracy and turn off the VF. While such features reduce the risk of unjustified stimuli, they may also allow animals to move beyond boundaries without feedback, potentially affecting management control.

Another important aspect is the design and escalation of the stimuli. All reviewed systems apply a sequential warning principle, in which an AC precedes an EP. The structure of these warning systems varies. For instance, Nofence, Monil and Vence apply escalating warning rounds before delivering an EP. Halter uses directional ACs that guide animals back into the permitted area and incorporates vibration signals to encourage forward movement.

Some systems also offer extended monitoring and management functions. For example, Halter includes continuous behavioural and health monitoring, heat detection and activity alerts. Similarly, Monil provides activity heatmaps. These additional functionalities may indirectly support animal welfare by enabling earlier detection of health or behavioural issues.

4.2 Management context shapes welfare more than the technology itself

Virtual fencing appears to influence animal welfare less through the technology itself and more through the management context in which it is applied. Although VF is based on associative learning principles, where cattle learn to respond to an AC to avoid an EP, studies consistently show that cattle are generally able to learn this association quickly and reduce their exposure to EPs over time (Campbell et al. 2019; Lomax et al. 2019; Confessore et al. 2024). This suggests that the system can provide predictable and controllable interactions, which are typically considered beneficial for welfare. However, the consistency of these outcomes depends heavily on how the system is implemented and managed in practice.

One important aspect is the role of training and reinforcement. While cattle often adapt rapidly at the herd level, several studies report considerable individual variation in learning ability and boundary interactions (Campbell et al. 2019; Lomax et al. 2019). Animals that require repeated exposure to EPs during training may experience the system differently from individuals that learn more quickly. In addition, evidence suggests that VF-specific learning may weaken over time without continued reinforcement (Verdon & Rawnsley 2020). This indicates that welfare outcomes are not solely determined by the technology but by management factors such as training protocols, supervision and the frequency of animal interactions with the system. The same VF system may therefore produce different welfare outcomes depending on how animals are introduced to and managed with it.

The importance of management context is also evident in grazing systems. Virtual fencing enables flexible grazing management, including rotational and strip grazing as well as excluding cattle from environmentally sensitive areas (Hoag et al. 2024). However, studies indicate that grazing intensity and paddock design strongly influence how often animals interact with virtual boundaries. Higher stocking rates have been associated with increased frequencies of ACs and EPs, likely because animals move more actively in search of forage under high grazing pressure (Harland et al. 2025). Similarly, cattle may avoid areas near virtual boundaries after learning the association between cues and boundaries, which can contribute to uneven pasture utilization if boundaries are poorly positioned (Lomax et al. 2019). Complete exclusion from sensitive areas may also become less effective when forage availability is limited or grazing pressure increases (Campbell et al. 2020). These findings suggest that welfare implications arise not only from the VF technology itself but also from how grazing systems are structured around it.

The adoption of VF also appears to be driven primarily by management objectives rather than welfare considerations alone. Farmers adopt VF to increase flexibility, reduce labor associated with physical fencing and improve livestock monitoring and control (Hoag et al. 2024; Petters & Wahlund 2025). In this sense VF changes the nature of livestock management by shifting control from physical infrastructure to digital supervision. However, this does not necessarily reduce the need for management, but instead requires continuous monitoring of collars, system functionality and animal behaviour. The effectiveness of VF therefore depends not only on technological performance but also on farmers' ability to integrate the system into existing management routines.

Taken together these findings suggest that VF should not be understood as inherently good or bad in the sense of welfare. Instead, welfare outcomes are highly context dependent. Factors such as stocking density, forage availability, paddock design, training protocols and human supervision appear to shape animal experiences more strongly than the technology itself.

4.3 Welfare concerns and benefits: what the evidence shows and what remains contested

The findings in this review suggest that the current evidence base supports the conclusion that VF does not impair cattle welfare any more than conventional EF. Across multiple studies, cattle managed with VF showed physiological and behavioural responses comparable to those observed under physical EF (i.e. adult beef cattle and nonlactating dairy cows). Measures including FCM, milk cortisol, body weight gain, activity levels and lying behaviour were reported to remain within normal ranges and did not differ significantly between VF and physically fenced groups (Campbell et al. 2019; Hamidi et al. 2022; Fuchs et al. 2024; Grinnell et al. 2025). These findings suggest that cattle can adapt to VF systems through associative learning and that the predictable relationship between the AC and EP allows the animals to maintain a degree of environmental controllability. This is important because predictability and controllability are considered central factors in distinguishing adaptive physiological activation from harmful stress responses (Koolhaas et al. 2011).

Evidence of successful associative learning was particularly consistent across studies. Most cattle learned to respond to the AC alone within a relatively short period, leading to reduced exposure to EPs over time (Campbell et al. 2019; Aaser et al. 2022; Fuchs et al. 2024). Behavioural responses associated with the initial learning period, such as running, head tossing or increased vocalisations, generally decreased as animals gained experience with the system (Lee et al. 2008; Wilms et al. 2024). These findings indicate that VF can function as a predictable and learnable system rather than a continuous source of uncontrollable aversive stimulation. Furthermore, studies comparing VF and EF found no consistent negative effects on productivity indicators such as milk yield, feed intake or body weight gain (Fuchs et al. 2024; Grinnell et al. 2025). Together, these findings strengthen the argument that VF does not affect welfare outcomes and is comparable to the use of traditional EF.

Despite these findings, several important limitations and understudied areas remain in the evidence base. Most studies have been relatively short-term, often lasting only a few days or weeks, making it difficult to assess whether repeated exposure to VF may produce longer-term welfare consequences. Existing welfare assessments have largely focused on acute stress indicators, such as cortisol concentration and activity budgets, which may be less sensitive to chronic low-grade stress. In addition, much of the available research has been conducted in adult beef cattle or non-lactating dairy cows under relatively controlled grazing conditions, limiting the generalisability of findings to other production systems or animal categories.

There is currently very limited evidence on younger cattle, despite suggestions that age and developmental stage may influence learning ability, behavioural responses and long-term retention of VF associations (Verdon & Rawnsley 2020). Research is also lacking regarding VF use under conditions of high stocking density, restricted forage availability or more complex grazing environments, where motivation to cross boundaries may increase and interactions with the virtual fence may become more frequent (Campbell et al. 2020; Harland et al. 2025). These contextual factors are important because several studies have indicated that increasing grazing pressure or pasture depletion may increase the frequency of ACs and EPs, potentially altering the system's welfare implications.

4.4 Are the welfare indicators used in virtual fencing research adequate?

Animal welfare is a multidimensional concept that cannot be comprehensively assessed with a single indicator. Therefore, welfare assessment requires a combination of physiological, behavioural and environmental measures, while also considering predictability and controllability from the animal's perspective (Hemsworth et al. 2015; Mellor 2017; Gadzama et al. 2025). In VF systems this is particularly important since welfare outcomes depend on whether animals successfully learn to respond to the audio cue and thereby maintain control over the environment.

The literature suggests that VF does not impair welfare when compared with traditional EF when assessed using the indicators most commonly used in current research. Across studies, no clear differences have been reported in faecal cortisol metabolites, milk cortisol, body weight, feed intake, lying behaviour or activity levels between VF and EF systems (Campbell et al. 2019; Aaser et al. 2022; Fuchs et al. 2024). Behavioural observations indicate that cattle may show short-term reactions during the learning phase, such as running or increased vigilance, but that these responses generally decrease once animals adapt to the system (Fuchs et al. 2024; Wilms et al. 2024). This suggests that welfare assessment in VF must consider both short-term adaptation and longer-term responses.

However, the indicators currently used in VF research are largely focused on detecting acute physiological stress and major behavioural disruption. Measures such as circulating cortisol concentrations and activity patterns are useful for identifying immediate stress responses but may be less sensitive to chronic low-grade stress responses. From the perspective of the Five Domains framework, most VF studies focus mainly on the physical and behavioral domains, while the mental state domain (domain 5) is rarely assessed directly (Mellor 2017; Mellor et al. 2020). As a result, important aspects of emotional welfare may remain insufficiently explored. As the science of animal welfare continues to explore how domain 5 may be adequately assessed with the current limited understanding of how to assess animal emotions (Mellor 2017), this will become an increasingly important topic regarding welfare and individual animal learning of VF.

The welfare indicators used also vary considerably across studies. Common animal-based measures include cortisol measured in hair, blood, faeces or milk, along with behavioural observations, activity monitoring and body weight. Resource-based indicators such as pasture access and forage availability are also frequently included. While this reflects the complexity of welfare assessment, it also makes comparisons between studies more difficult and highlights the need for a more standardised and integrated approach to welfare evaluation in VF research.

Finally, welfare assessment in VF extends beyond scientific measurements to include ethical and societal considerations. Despite findings in the scientific literature indicating that VF does not negatively impact animal welfare, public concern remains regarding the use of EPs and the growing technological control over animals (Stampa et al. 2020; Animal Welfare Committee 2022). This suggests that the acceptability of VF depends not only on measurable welfare outcomes but also on how the technology is perceived and implemented in practice.

4.5 Limitations of the evidence base

There is also considerable variation in study design and methodology across the reviewed literature. Differences in factors such as animal age, sex, breed, grazing system and collar brand make direct comparisons between studies challenging. In addition, variation in the selection and measurements of welfare indicators may further limit the comparability of the results.

4.6 Implications for practice and future research

The findings of this review suggest that the welfare implications of VF depend more on how the technology is implemented in practice than on the technology itself. For producers, this highlights the importance of careful training protocols, appropriate stocking densities and continued human supervision during implementation. Since animals differ in how quickly they adapt to VF systems, individual-level monitoring remains important, particularly during the initial learning phase. The literature also suggests that hybrid systems combining VF with physical fencing may provide a more reliable management strategy in situations where strict containment is required or where technical failures could pose welfare risks (Hoag et al. 2024).

For researchers, several important knowledge gaps remain. Current evidence is largely based on short-term studies, and research involving younger animals and long-term exposure remains limited. Future research should therefore prioritise long-duration studies and a broader range of production systems. There is also a need for more assessment of welfare indicators that can assess emotional states and chronic stress, including cognitive bias testing, qualitative behavioural assessment and heart rate variability. In addition, direct comparisons between different commercial VF systems are currently lacking, despite substantial variation in system design, cue delivery and safeguard mechanisms.

The review also has implications for policy and regulation. Since welfare outcomes appear highly context-dependent, future regulation should not focus solely on approving or rejecting VF technology but should also consider how systems are managed in practice. This includes factors such as training procedures, supervision requirements, stocking density and the use of safeguard mechanisms designed to reduce unnecessary exposure to aversive stimuli. Evidence-based guidelines addressing these management factors may therefore be essential to ensure both effective implementation and acceptable welfare outcomes in VF systems.

Conclusions

The study aimed to examine how system aspects of VF influence animal welfare in cattle production and which indicators are used to assess these effects. Overall, the findings suggest that VF does not adversely affect animal welfare compared with traditional EF, but outcomes depend largely on system design and management context.

Cattle generally adapt to VF through learning, thereby reducing their exposure to EPs over time. However, factors such as stocking rate and grazing intensity influence how frequently animals interact with virtual boundaries, highlighting the importance of appropriate management.

The results also confirm that animal welfare is assessed using a wide range of behavioural, physiological and resource-based indicators, reflecting its multidimensional nature. At the same time variation in assessment methods across studies limits comparability.

In conclusion, VF can support effective and flexible grazing management without compromising animal welfare, if it is carefully implemented and managed.

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Popular science summary

Interest in virtual fencing has emerged, with commercial systems available in countries like Australia, New Zealand, Norway, US, and Sweden. The technology offers flexible grazing management, as farmers can adjust boundaries virtually via phone or computer instead of laying physical fences. This reduces labour, enhances management, and helps protect sensitive areas such as rivers, forests, or habitats with rare plants.

Virtual fencing utilizes GPS collars and virtual boundaries to control cattle, replacing physical fences. When cattle near virtual boundaries, collars emit audio cues and may deliver electric pulses, teaching cattle to associate the sounds with the stimulus. Over time, cattle respond to warnings alone, allowing virtual fences to partially replace traditional fences. The main advantage of virtual fencing is animal monitoring through GPS collars, enabling real-time location tracking and quick detection of injured or separated animals, particularly in large or remote grazing areas. Some systems also track health and behaviour, such as activity levels and heat.

While virtual fencing relies on audio cues and electric pulses, raising animal welfare concerns, scientific studies indicate it does not harm cattle welfare more than traditional electric fences. No significant differences have been found in stress indicators like cortisol, body weight, feed intake, activity, or lying behaviour. Research shows most cattle learn how the system works within a few days. As they adapt, electrical pulses decrease because they respond to the audio cue alone. Initially, cattle might react with running, head tossing, or vocalizing, but these behaviours lessen over time, indicating that predictability and controllability are crucial for welfare. If animals understand how to avoid pulses, the environment becomes less stressful and easier to manage. Proper implementation and management are essential, as factors like stocking density, grazing pressure, pasture type, and collar design influence welfare. Poor management may lead to increased aversive stimuli, harming animal well-being. Virtual fencing does not eliminate labour but shifts it toward managing collars, digital grazing plans, and monitoring via apps. Overall, animal welfare is complex and cannot be measured by a single indicator. Researchers use various measures such as cortisol levels in hair, blood, milk, or faeces, behaviour, body weight, grazing patterns and access to pasture, forage, and water.

Differences in methods between studies complicate comparisons and highlight the need for standardized welfare assessments in future research. When used correctly, virtual fencing appears promising for flexible, sustainable grazing management that supports cattle welfare, enhances livestock management, and protects the environment. Success depends on proper implementation, training animals, and continuous welfare monitoring.

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Appendix 1

Part A. Studies using virtual fencing systems					
Article	**Title**	**VF system / brand**	**Country**	**Welfare indicators**	**Animal category**
Aaser et al. (2022)	*Is Virtual Fencing an Effective Way of Enclosing Cattle? Personality, Herd Behaviour and Welfare*	Nofence	Denmark	Behaviour, personality, herd dynamics	Beef cattle
Anderson (2007)	*Virtual fencing — past, present and future*	Conceptual / multiple	USA	Conceptual review of VF	Cattle (general)
Campbell et al. (2018)	*Temporary Exclusion of Cattle from a Riparian Zone Using Virtual Fencing Technology*	eShepherd (Agersens)	Australia	Behaviour, exclusion success, area use	Beef cattle
Campbell et al. (2019)	*Virtual Fencing Is Comparable to Electric Tape Fencing for Cattle Behavior and Welfare*	eShepherd (Agersens)	Australia	Behaviour, plasma cortisol, body weight	Beef cattle
Campbell et al. (2020)	*Virtual Fencing Technology Excludes Beef Cattle from an Environmentally Sensitive Area*	eShepherd (Agersens)	Australia	Behaviour, exclusion success, GPS use	Beef cattle
Confessore et al. (2024)	*A matter of age? How age affects the adaptation of lactating dairy cows to virtual fencing*	Nofence	Switzerland	Learning, behaviour, age effects	Dairy cow
Fuchs et al. (2024)	*Stress indicators in dairy cows adapting to virtual fencing*	Nofence	Switzerland	Faecal cortisol metabolites, behaviour, milk yield	Dairy cow
Gadzama et al. (2025)	*Influence of Virtual Fencing Technology in Cattle Management and Animal Welfare*	Multiple (review)	Australia	Review of welfare outcomes	Cattle (review)

Goliński et al. (2022)	*Virtual Fencing Technology for Cattle Management in the Pasture Feeding System — A Review*	Multiple (review)	Poland	Review of VF systems & outcomes	Cattle (review)
Grinnell et al. (2025)	*Supporting rotational grazing systems with virtual fencing: paddock transitions, beef heifer performance, and stress response*	Nofence	Germany	Faecal cortisol metabolites, performance, behaviour	Beef heifer
Hamidi et al. (2022)	*Heifers don't care: no evidence of negative impact on animal welfare of growing heifers when using virtual fences compared to physical fences for grazing*	Nofence	Germany	Faecal cortisol metabolites, behaviour, body weight	Beef heifer
Harland et al. (2025)	*Evaluating virtual fencing as a tool to manage beef cattle for rotational grazing across multiple years*	Vence	Canada	Performance, behaviour, exclusion success	Beef cattle
Hoag et al. (2024)	*Beef Cattle Producer Perspectives on Virtual Fencing*	Multiple (survey)	USA	Producer attitudes, adoption	Beef cattle
Lomax et al. (2019)	*Does Virtual Fencing Work for Grazing Dairy Cattle?*	eShepherd (Agersens)	Australia	Behaviour, learning, exclusion success	Dairy cow
Petters & Wahlund (2025)	*Virtuella stängsel — en ny era ur ett arbetsmiljöperspektiv?*	Multiple (Swedish context)	Sweden	Work environment, farmer perspectives	Cattle (general)
Ranches et al. (2025)	*Evaluation of blood markers of stress in beef cows during exposure to virtual fence stimuli*	Vence	USA	Blood cortisol, haptoglobin, NEFA, behaviour	Beef cow

Stampa et al. (2020)	*Insights into German Consumers' Perceptions of Virtual Fencing in Grassland-Based Beef and Dairy Systems*	Multiple (consumer survey)	Germany	Consumer perception, ethics	Beef & dairy (consumer)
Verdon et al. (2021)	*Virtual fencing technology to intensively graze lactating dairy cattle. II: Effects on cow welfare and behavior*	eShepherd (Agersens)	Australia	Behaviour, milk yield, plasma cortisol	Dairy cow
Verdon et al. (2024)	*The effectiveness of a virtual fencing technology to allocate pasture and herd cows to the milking shed*	eShepherd (Agersens)	Australia	Behaviour, milk yield, exclusion success	Dairy cow
Verdon & Rawnsley (2020)	*The Effects of Dairy Heifer Age at Training on Rate of Learning and Retention of Learning in a Virtual Fencing Feed Attractant Trial*	eShepherd (Agersens)	Australia	Learning rate, retention, age effects	Dairy heifer
Wilms et al. (2024)	*How do grazing beef and dairy cattle respond to virtual fences? A review*	Multiple (review)	Germany	Behaviour, learning, welfare (review)	Beef & dairy (review)

Part B. Supporting literature (welfare indicators, stress physiology, assessment frameworks)					
Article	**Title**	**Reason for inclusion**	**Country**	**Topic / indicators**	**Animal category**

Beggs et al. (2019)	*The effects of herd size on the welfare of dairy cows in a pasture-based system using animal- and resource-based indicators*	Welfare indicators in pasture systems	Australia	Animal- & resource-based welfare indicators	Dairy cow
Blaga Petrean et al. (2024)	*Pasture Access Effects on the Welfare of Dairy Cows Housed in Free-Stall Barns*	Pasture access & welfare	Romania	Animal-based welfare indicators	Dairy cow
Charlton et al. (2013)	*The motivation of dairy cows for access to pasture*	Motivation & preference for pasture	United Kingdom	Behaviour, motivation testing	Dairy cow
Chmelíková et al. (2020)	*Salivary cortisol as a marker of acute stress in dogs: a review*	Salivary cortisol methodology	Czech Republic	Salivary cortisol (review)	Dogs (methodology)
Colborn et al. (1991)	*Responses of cortisol and prolactin to sexual excitement and stress in stallions and geldings*	Stress physiology reference	USA	Plasma cortisol, prolactin	Horses (physiology)
Contreras-Aguilar et al. (2019)	*Evaluation of new biomarkers of stress in saliva of sheep*	Salivary stress biomarkers	Spain	Salivary biomarkers of stress	Sheep (physiology)
Cook (2018)	*Assessment of cattle welfare*	Welfare assessment framework	USA	Welfare assessment frameworks	Cattle (general)
Crump et al. (2019)	*Pasture Access Affects Behavioral Indicators of Wellbeing in Dairy Cows*	Pasture access & behaviour	United Kingdom	Lying time, activity, behaviour	Dairy cow

Dzviti et al. (2019)	*Relationship between saliva and blood cortisol in handled cows*	Cortisol biomarker validation	South Africa	Salivary vs blood cortisol	Cow (physiology)
Hemsworth et al. (2015)	*Scientific assessment of animal welfare*	Welfare assessment principles	Australia / New Zealand	Welfare assessment principles	General
Jamieson (2021)	*Hinder och möjligheter för ökad naturbetesdrift ur ett lantbrukarperspektiv: en kunskapsöversikt*	Swedish grazing context	Sweden	Farmer perspectives on grazing	Cattle (general)
Koolhaas et al. (2011)	*Stress revisited: A critical evaluation of the stress concept*	Conceptual stress framework	Netherlands	Stress concept (review)	General (physiology)
Kovalčik & Kovalčik (1986)	*Learning ability and memory testing in cattle of different ages*	Cattle learning & memory	Slovakia (Czechoslovakia)	Learning, memory, age effects	Cattle
Kulik et al. (2023)	*The Impact of Rotational Pasture Management for Farm-Bred Fallow Deer (Dama dama) on Fodder Quality in the Context of Animal Welfare*	Rotational grazing & resource quality	Poland	Fodder quality, resource-based indicators	Fallow deer
Lee et al. (2008)	*The effect of low energy electric shock on cortisol, β-endorphin, heart rate and behaviour of cattle*	Electrical pulse physiology	Australia	Plasma cortisol, β-endorphin, heart rate, behaviour	Cattle
Linstädt et al. (2024)	*Animal-based welfare indicators for dairy cows and their validity and practicality: a systematic review of the existing literature*	Welfare indicator review	Germany	Animal-based welfare indicators (review)	Dairy cow (review)

McLaren et al. (2004)	*Body weight change as a measure of stress: a practical test*	Body weight as stress indicator	United Kingdom	Body weight change	Small mammals (methodology)
Mellor (2017)	*Operational Details of the Five Domains Model and Its Key Applications to the Assessment and Management of Animal Welfare*	Five Domains framework	New Zealand	Five Domains welfare framework	General
Ralph & Tilbrook (2016)	*INVITED REVIEW: The usefulness of measuring glucocorticoids for assessing animal welfare*	Glucocorticoid methodology	Australia	Glucocorticoids in welfare (review)	General (physiology)
Schwinn et al. (2016)	*Suitability of saliva cortisol as a biomarker for hypothalamic–pituitary–adrenal axis activation assessment, effects of feeding actions, and immunostimulatory challenges in dairy cows*	Salivary cortisol validation	Switzerland	Salivary cortisol biomarker	Dairy cow (physiology)
Tarantola et al. (2020)	*Beef cattle welfare assessment: use of resource and animal-based indicators, blood parameters and hair 20β-dihydrocortisol*	Welfare indicator combination	Italy	Animal- & resource-based indicators, hair cortisol	Beef cattle
Turner et al. (2005)	*Susceptibility of reproduction in female pigs to impairment by stress or elevation of cortisol*	Cortisol & reproduction	Australia	Cortisol & reproduction	Pigs (physiology)
Turner et al. (2010)	*Stressor Specificity of Sex Differences in Hypothalamo-Pituitary-Adrenal Axis Activity*	HPA axis & stressor specificity	Australia	HPA axis, cortisol, sex differences	Sheep (physiology)

Van Eerdenburg et al. (2021)	*A New, Practical Animal Welfare Assessment for Dairy Farmers*	Practical welfare assessment	Netherlands	Welfare assessment indicators	Dairy cow
Verkerk et al. (1998)	*Characterization of Milk Cortisol Concentrations as a Measure of Short-Term Stress Responses in Lactating Dairy Cows*	Milk cortisol biomarker	New Zealand	Milk cortisol	Dairy cow (physiology)
Willms et al. (2002)	*Effects of Water Quality on Cattle Performance*	Resource-based indicator (water)	Canada	Water quality, performance	Beef cattle

Note. Country indicates where the study was conducted (or, for reviews and methodological references, the country of the corresponding author's affiliation). Commercial websites and manuals (Nofence, Halter, Vence, Gallagher, Monil), regulatory documents (Defra, Regeringen) and assessment protocols (Welfare Quality Network) were used as descriptive sources to characterise commercial systems and the regulatory context, and are not listed here.