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The potential of virtual fencing technology to facilitate sustainable livestock grazing management

J. Schillings [a,*], C. Holohan [b], F. Lively [b], G. Arnott [c], T. Russell [a]

[a] University College Dublin, School of Agriculture and Food Science, Belfield, Dublin 4, Ireland
[b] Agri-Food and Biosciences Institute, Large Park, Hillsborough BT26 6 DR, UK
[c] Queens University Belfast, Institute for Global Food Security, School of Biological Sciences, 97 Lisburn Road, Belfast BT9 7BL, UK

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ABSTRACT

Virtual fencing (**VF**) technology is gaining interest due to its potential to facilitate sustainable grazing management. It allows farmers to contain grazing livestock without physical fences, thereby reducing the time and labour associated with the implementation of conventional fences. From a conservation perspective, some sensitive areas within uplands should not be grazed during certain periods of the year, and VF provides an invisible and moveable fence line that can exclude livestock from these areas. However, there are also concerns associated with its use, including animal welfare impacts, cost-effectiveness, and public perception. The extent to which VF can contribute to make livestock systems more sustainable remains to be investigated. To address this gap, this study investigates the potential of VF to promote sustainable grazing management using the Efficiency, Substitution, and Redesign framework, which has been used for the first time in this context. The framework is particularly relevant in taking an active and normative approach to identify key aspects to focus on to help achieve sustainability. We consulted stakeholders including farmers, wildlife inspectors, veterinarians, policy officers, researchers, NGOs, farm advisors or certification managers, through focus groups (N = 4) and in-depth, semi-structured interviews (N = 5). Stakeholders have highlighted the potential of VF to provide new opportunities to increase the efficiency and sustainability of livestock grazing systems, enabling their redesign, and contributing to improved environmental and animal welfare outcomes, as well as higher financial and social performance. However, there are important aspects that remain to be addressed to achieve such redesign, including issues of reliability due to poor network signal, animals' ability to learn, biosecurity and safety issues related to the absence of physical fences, farm suitability and farmers' ability to use the systems effectively. This study highlights the need to ensure that the development and uptake of VF are mutually beneficial to farmers, animals, and the wider farming industry. This includes a highlight on the importance of participative approaches to involve key stakeholders to address concerns and maximise the potential of the technology.

Implications

Virtual fencing has the potential to facilitate grazing management, particularly in hills and mountainous regions. The extent to which virtual fencing can help promote sustainable grazing management has been investigated using the Efficiency, Substitution, and Redesign framework. The study highlights that virtual fencing can provide new opportunities to improve financial and social performance, as long as it is designed in a way that is mutually beneficial to farmers, animals, and the industry. In this study, we provide new insights into how virtual fencing can help redesign livestock systems towards sustainability.

Introduction

In certain areas, such as on the island of Ireland, hills and upland environments account for a significant proportion of all farmed land. These are often described as high nature value (**HNV**) farmland due to the characteristics which make them environmentally sensitive, often covering a wide range of different landscapes primarily dominated by seminatural vegetation (Moran et al., 2021). In the Republic of Ireland, it is estimated that 33% of agricultural areas have HNV characteristics (Moran et al.,

* Corresponding author.
E-mail address: juliette.schillings@ucd.ie (J. Schillings).

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2021). These areas provide a range of ecosystem services with important benefits for society, including food production, the maintenance of stable and productive soils, the delivery of clean water and air, the sustenance of functional soil-biosphere, hydrological cycles, plants, animals, and other organisms that support ecosystem function and human livelihoods and well-being (Moran et al., 2021; Mcloughlin et al., 2020; Pakeman et al., 2018). Grazing livestock systems are the most common type of HNV farming system (Keenleyside et al., 2014) and are characterised by livestock (mostly ruminants) raised on natural and semi-natural vegetation that is grazed, browsed, or cut for hay (Bignal and McCracken, 2000). When managed correctly, these systems can deliver a wide range of private and public goods such as the conservation of agricultural landscapes and farm biodiversity, as well as resilience of the land to forest fires (Lomba et al., 2023). Managing these types of systems can, however, be challenging due to the often vast and remote nature of these areas, and the difficulties in managing grazing as undergrazing and overgrazing can have negative environmental impacts such as causing soil and peat erosion through defoliation and trampling (Williams et al., 2012).

Currently, increased attention is being brought to the use of digital agricultural solutions such as Precision Livestock Farming (**PLF**) technologies to respond to a range of challenges, including sustainable grazing management. Whilst most developments have focused on intensive types of systems, some tools have been developed to suit more extensive production systems (Rutter, 2014). This is the case with virtual fencing (**VF**) systems, which allow the spatiotemporal control of grazing livestock (Horn and Isselstein, 2022). Virtual fencing can offer a more cost-effective and flexible alternative to traditional fencing as it can establish boundaries without the reliance of physical objects on the landscape. Virtual fencing systems typically use Global Positioning System (**GPS**)-enabled collars and virtual platforms (e.g., mobile phone applications or computer software) that allow remote mapping of virtual boundary lines, which constitute the virtual fence. By tracking animal location, the collars emit audio cues to the animals when they approach the predefined virtual fence. If the animals cross the boundaries, electric stimuli are delivered as a pulse to encourage animals to move back to the inclusion area. There are many benefits associated with the use of VF technology, including reduced material and maintenance costs, and reduced time and labour associated with setting up physical fences, particularly on mountainous range where physical fencing is difficult, if not impossible in certain places. It can also facilitate animal herding and strategic grazing management, which in turn can contribute to enhancing biodiversity, keeping animals away from undesired areas, and directing them towards the most profitable paddocks at specific times (Jachowski, Slotow and Millspaugh, 2014; Campbell et al., 2018; Campbell et al., 2021; Langworthy et al., 2021). Exclusion zones can be mapped to restrict animals from accessing certain areas such as watercourses, sensitive habitats, or hazardous areas such as marshlands, which are often difficult to fence off. In addition, the system allows farmers to track their animals in real time, allowing them to identify possible safety or health–related problems. Thus far, virtual fences have mostly been applied to grazing cattle (Campbell et al., 2018; Lomax, Colusso and Clark, 2019; Langworthy et al., 2021; Hamidi et al., 2022) although systems have been successfully trialled in smaller ruminants, such as sheep and goats (Eftang et al., 2022; Kleanthous et al., 2022). Recent studies found that VF was highly effective in keeping livestock within a predefined zone (Campbell et al., 2018; Langworthy et al., 2021; Hamidi et al., 2022). This efficiency relies on animals' ability to learn to associate the audio cues with the electric stimuli, which varies between individuals (Campbell et al., 2018; Langworthy et al., 2021; Eftang et al., 2022; Hamidi et al., 2022).

Despite its perceived benefits, there have been concerns about its potential to have negative socio-ethical impacts (Brier et al., 2020). For virtual fencing technology to be successful at farm level and widely adopted with social licence approval from the public, evidence of acceptable animal welfare standards would be needed, such as ensuring that animals are able to learn the association between the cues and subsequently respond to the audio cue alone so that their environment is controllable and predictable. Currently, studies suggest that learning is effective in several grazing species and that minimal differences in terms of impacts on animal behaviour and welfare have been found between VF and physical fences. However, there is high individual variation, with some individuals receiving more audio warnings or electric stimuli than others (Campbell et al., 2018; Eftang et al., 2022; Verdon et al., 2020). Key barriers to virtual fencing implementation also include uncertainties regarding its reliability, challenges in training, and a lack of perceived value proposition by farmers and farmers' feed budgeting skills (Brier et al., 2020). In addition, there are concerns around potential impacts on the human-animal relationship if digital livestock technologies are used to replace farmers in certain tasks requiring human-animal interactions (Schillings et al., 2021). More generally, it has also been questioned whether these types of technologies could help facilitate more intensive types of production systems by allowing the management of larger numbers of animals with fewer stockmen to look after them. This in turn raises potential ethical challenges such as the objectification of animals and further intensification (Werkheiser, 2018). Several important aspects thus remain to be investigated to determine the possible impacts of using virtual fencing to contain grazing livestock, and the extent to which it could contribute to encouraging sustainable grazing in practice.

One way to assess how VF can contribute to making livestock systems more sustainable is the use of the Efficiency, Substitution, and Redesign (**ESR**) framework (Hill and MacRae, 1996). This framework, which has often been used in the context of organic farming and agroecology, can be used to understand pathways towards sustainability in agro-food systems (Padel et al., 2020). In the ESR framework, *efficiency* relates to better use of on-farm resources within existing farm configurations (e.g., reduction of costly or harmful inputs), *substitution* refers to the replacement of existing practices with more sustainable and more 'environmentally benign' ones, and *redesign* is a transformative stage in which new farming systems are established with an aim to achieve sustainability, where causes of issues are identified and prevented (Finger, 2023; Hill and MacRae, 1996; Pretty et al., 2018). Whilst efficiency and substitution are essential steps towards improved sustainability, these mainly focus on addressing existing issues and are often not sufficient to maximise coproduction of beneficial agricultural and environmental outcomes (Pretty, 2018). To achieve sustainability at scale, a redesign of agricultural systems is required, which usually requires more time to implement more drastic changes to the management of both human and physical resources (Hill and MacRae, 1996). In their study, Finger (2023) used the ESR framework to discuss how digitalisation could contribute to more sustainable agricultural systems. They stated that digital innovations could help increase the *efficiency* of farming systems by, for example, reducing input use or improving environmental and animal welfare outcomes without affecting productivity. Variable rate technologies, for example, allow targeted use of fertilisers or pesticides, thus reducing variable costs. They also noted that digitalisation can help farmers reduce harmful practices, such as the use of herbicides, by *substituting* these with other methods (e.g., by using weeding robots). They emphasised that for digitalisation to help contribute to sustainability, tools must enable a transformative *redesign* of agricultural systems, to ensure that the root causes of existing issues are addressed. This usually requires the combination of different tools.

Achieving transformative impacts using digital tools, however, requires an increase in cognitive labour and a paradigm shift in management that makes it unreasonable to assume that implementing these technologies in practice is straightforward. As mentioned by Rose et al. (2023, p1) "*Engagement with new technology is likely to be uneven, with benefits potentially favoring the already powerful and the costs falling hardest on the least powerful. If grand narratives of change remain unchallenged, we risk pursuing innovation trajectories that are exclusionary, failing to achieve responsible innovation*." Redesign processes can indeed present social, institutional, and agricultural challenges, highlighting the need to build social capital and to co-create knowledge to minimise socio-ethical impacts (Pretty, 2018). Brier et al. (2020) indeed emphasised the need to include relevant actors such as farmers, technology developers, NGOs, rural professionals and citizens in responsible research and innovation anticipation processes, to help develop strategies and codes of conduct that encourage the responsible use of VF. This type of involvement can help get a better understanding of the factors that encourage or prevent the adoption and effective use of digital tools, as well as acceptance from the public. As McGrath et al. (2023, p.10) suggest, *'to anticipate and be responsive to (the worlds that digital platforms create), it is important for us to understand how users interact with technologies, the social context within which technologies are used, and the wider social implications they have.'*.

The objective of this study is, therefore, to explore the role of virtual fencing technology in facilitating sustainable grazing practices with a focus on upland and hill farming, by consulting a range of stakeholders. Based on the results and the ESR framework, we make recommendations on areas of research that deserve consideration to encourage the responsible use of virtual fencing technology in a way that promotes a redesign of grazing livestock practices towards sustainability.

Material and methods

Ethical approval

Since the study involved interviews with human subjects, the research project has been reviewed according to the procedures specified by the University College Dublin Human Research Ethics Committee, which granted ethical clearance for this project (reference number LS-LR-23-21-Schillings-Russell). Participation in this research was completely voluntary. Participants were provided with an information sheet about the project, informing them with confidentiality aspects and rights. The research did not require the collection of information that may have been considered sensitive in terms of confidentiality, or that may have caused personal upset. It did not involve elements of deception, and participants were offered a guarantee of anonymity and secured data storage.

Focus groups

Stakeholders

Two focus groups (nine and eight participants) were conducted with stakeholders from the island of Ireland, who were either involved in farming or in nature conservation and included wildlife inspectors, veterinarians, policy officers, farmers, researchers, NGOs, farm advisors or certification managers. Experience with virtual fencing ranged from extensive (virtual fencing users or stakeholders working with cattle and sheep farmers using virtual fencing) to more limited (stakeholders having heard about the technology but were not involved in a virtual fencing project). Participants were recruited by email, using the research team's network and relevant websites (e.g., departments of agriculture or research institutions). Participants who were interested in being involved in the focus groups were sent an information sheet that provided them with additional information about the project. The focus groups were held online for convenience, via the video conference software Zoom (v. 5.14.7). These lasted approximately ninety minutes each.

The focus group discussions started with participant introductions, followed by a short presentation on virtual fencing technology. Then, participants had the opportunity to ask questions about the technology and to share their experience with virtual fencing. Participants were then divided into breakout groups to share their views on the benefits and risks related to VF, priority areas, and opportunities for support. Each breakout group used a digital whiteboard to take notes, which they then used as support to share their outcomes with the rest of the focus group participants.

Farmers

Two focus groups (six and four participants) were conducted with farmers who have used virtual fencing technology (n = 8) and stakeholders working with farmers who were trialing the technology (n = 2). Farmers were drystock, sheep, beef and goat farmers with low stocking intensity systems. Seven of the participant farmers were using virtual fencing with cattle, whilst one was using the technology with goats. Some of the farmers were using virtual fencing in the context of commonages, mostly in vast mountainous and hilly regions. Seven of the farmers were using the technology as part of conservation research trials, whilst one acquired the technology for their own farm. Contacts were obtained via a virtual fencing technology provider, who sent the project information sheet to their clients. Clients who were interested in participating provided their contact details, which we used to organise the focus groups. Discussions started with participant introductions, and farmers were able to share their experience using virtual fencing. These revolved around the reasons for adopting VF, the implementation process, challenges encountered, daily use, support, and impacts on livestock grazing management.

In-depth interviews

Five semi-structured in-depth interviews were conducted with three participants from the stakeholder focus groups and two participants who were unable to attend the focus group but expressed an interest in taking part in an interview. The stakeholders included a researcher, a veterinary inspector, a certification manager, an animal health officer and a farm advisor. Interviews were conducted to gain more breadth and depth into some of the topics raised during the stakeholder focus groups. The interviews lasted 47 min on average and were conducted using the conference software Zoom (v. 5.14.7).

Data analysis

Each focus group and interview were recorded using the software recording option, following approval from participants. Recordings were automatically transcribed by the software and then manually proofed by the first author using the recording. This allowed the author to get familiar with the data which was then analysed thematically. Coding of the data was performed using a qualitative data analysis software (Nvivo 12), following methods from Ritchie et al. (2014). The data were analysed inductively, allowing the identification of emerging themes and concepts (Braun and Clarke, 2006). Inductive analysis allows to get a holistic understanding of the topics under study allowing key concepts to derive from raw data whilst having the research questions as lenses (Azungah, 2018). Whilst this study focuses on a small sample size (VF is an emerging technology in the farming industry and adoption is, to our knowledge, currently low in Ireland), the richness of the data obtained through focus groups and completed with personal interviews allowed us to explore important themes and to gain a deep understanding of the topics discussed (more details can be found in the limitations section). Once sorted, each theme was reviewed individually, which sometimes resulted in the deletion, merging, or creation of new themes. Data summaries were then produced for each theme, which allowed us to draw out key elements and underlying dimensions that guided data interpretation.

Results and discussion

The potential of virtual fencing technology to enable sustainable livestock grazing systems

Discussions with a variety of farming and conservation stakeholders have highlighted the important potential of virtual fencing technology to facilitate the adoption of sustainable livestock practices. They have highlighted its potential to positively impact biodiversity, animal welfare, and livestock grazing strategies. To analyse how the use of virtual fencing technology can encourage sustainable livestock grazing systems, we used the ESR framework (Hill and MacRae, 1996).

Efficiency

The use of virtual fencing technology to contain grazing livestock was considered beneficial in increasing the efficiency of farming systems by decreasing costs and environmental impacts, increasing productivity, whilst easing management. In vast and remote regions of the island of Ireland, implementing physical electric fences represents a significant investment and can be particularly challenging. With virtual fencing, farmers can save the time required to erect, maintain, and remove physical fences. Whilst current virtual fencing systems may also be costly, in some cases, the use of virtual fencing technology can offer a more viable alternative. As one farmer stated:

'Yes, they are costly when you just look at them as an individual unit, but when you start to compare them to sheep wire or cattle fencing, it is an absolute no-brainer. Especially for us here, because it would probably cost us millions of euros to fence this place (laughs).' (farmer 1).

Better pasture productivity and gains in animal liveweight were seen as other benefits of virtual fencing since it can help improve grazing management and facilitate the adoption of practices such as mob or strip grazing. These types of grazing practices are sometimes referred to as nature-based grazing approaches as they offer a variety of benefits in terms of livestock productivity and reduced inputs, soil and ecosystem health, and animal health (Wagner et al., 2023). From an environmental point of view, discussions also highlighted the benefit of virtual fencing to improve hill and upland grazing environments and help exclude animals from environmentally sensitive areas. In addition, virtual fencing was highlighted as having an important role in wildfire management by enabling land managers to focus livestock grazing on high-risk areas of overgrown vegetation and subsequently reduce the fuel load and severity of potential wildfires. Grazing livestock can also have detrimental effects in sensitive areas by reducing water quality or damaging habitats for wildlife (Williams et al., 2012). In upland areas, undergrazing and overgrazing both reduce the availability of vegetation which serves as an important habitat for a range of rare insect and bird species (e.g., Red Grouse), while overgrazing also causes soil and peat erosion which in turn increases water pollution and leads to a decline in salmonid species in rivers and lakes (Pakeman et al. 2018). Thus, using virtual fencing to improve grazing strategies and exclude livestock from these areas whilst directing them towards desired zones (e.g., with invasive vegetation) can have positive effects on the environment and biodiversity (Campbell et al., 2018; Fuller, 1996).

Farmers viewed virtual fencing as a simple and user-friendly technology which allows them to monitor their livestock remotely, offering them peace of mind. This was considered particularly beneficial for farmers on large commonages, who live further away and may take several hours to get to their animals, sometimes being on site only a few days a week. As one farmer stated:

'I'm on the island only every, maybe 4 or 5 days, so that gives me peace of mind to know that the cattle are alright' (Farmer 2).

For another farmer, this was also perceived as beneficial during compliance inspections:

'He was accepting virtual fencing as proof that the cattle were actually where they were meant to be. Now, for me that was fantastic, because that saved a day trip up to mountain.' (Farmer 6).

By tracking their animals, farmers can identify unusual activity or behaviours within the herd or flock. One farmer, for example, was able to identify an isolated cow thanks to the tracking function of the device and react promptly as she was stuck in a lake. In their study, Brier et al. (2020) found that individual animal management was considered one of the most important benefits of virtual fencing systems, although management is likely to remain at group level unless new functions are added to the virtual fencing collars (e.g., activity monitoring). Improved livestock monitoring is a common advantage associated with digital livestock technologies (which include PLF), as it enables the prompt detection of changes in animal behaviour and early intervention with health and welfare concerns (Berckmans, 2014). Virtual fencing can also be used to keep livestock out of areas that have a high parasite burden. For example, liver fluke is associated with damp ground and advice has been to fence off access to at-risk areas, and virtual fencing can enable this to be done in a more efficient and feasible way.

The study also identified benefits for farmers, conservationists, and researchers as the technology gives them the ability to observe and record which specific areas of the grazing environment animals prefer to spend their time – making it a '*very educational*' tool according to one farmer. Learning plays a key role in decision-making and changed farm management practices (Kilpatrick and Johns, 2003), and this is particularly relevant in the context of conservation grazing as a better understanding of livestock habitat selection can help in decision-making to promote sustainable grazing and minimise damage to the land (Williams et al., 2012). With recent advances in Artificial Intelligence (**AI**), it is possible to imagine how incorporating other functions to current virtual fencing systems (e.g., accelerometers) could help farmers detect potential health and welfare compromises at an early stage. Whilst the integration of accelerometers with GPS systems is currently technically challenging due to high energy consumptions and shortening of battery life, technological advances in this area could allow for a more integrated technology (Schillings et al., 2021).

Substitution

According to stakeholders in this study, virtual fencing technology may present a more viable alternative to physical fencing, particularly in remote hill and upland regions. Often, shallow soils and rocky terrain make physical fencing difficult or impossible to instal, meaning that animals are free to roam across large areas. These environments also pose dangers to grazing livestock such as falls from heights and entrapment or drowning in peat swamps and other bodies of water. It was identified in the study that virtual fencing could help minimise such risks to animal health and welfare. According to Moss (2001), physical fences can present a danger to wildlife as animals can get entangled and injured by them, while study participants also noted that such fences can be aesthetically undesirable in high nature value areas. One stakeholder suggested, for example, that virtual fencing could facilitate the improvement of the landscape with the inclusion of features such as trees, shelters, or rocks, and have different shapes as opposed to '*square and devoid*' landscapes.

Stakeholders felt virtual fencing reduces labour thanks to the ability to locate animals and being able to use the technology as a herding tool, all of which save farmers important amounts of time and reduce costs (Campbell et al., 2021). Timesaving is a commonly cited benefit of digital innovations in livestock farming, although it is also the case that care must be taken to ensure that their use is considered an aid rather than a replacement for skilled farmers (Schillings, Bennett and Rose, 2021). Stakeholders involved in the current study similarly acknowledged that virtual fencing is not a substitute for skilled stockmanship.

It was also highlighted that virtual fencing technology has the potential to enable outwintering of livestock and minimise the requirement for winter housing which can benefit animal welfare if managed adequately (Arnott et al., 2017). One stakeholder emphasised how outdoor grazing with virtual fencing could be more beneficial than indoor housing, stating that:

'You could have a much more animal-centered grazing system with mob grazing, or similar type of systems, which are more in tune with the animal biology in terms of graze, move, graze, and move as a group rather than what is commonly happening now, being stuck in a square box that's pretty devoid, and you're just going around and around the same box.' (Stakeholder 1).

Redesign

As highlighted in the previous sections, virtual fencing technology can offer several opportunities to improve the sustainability of livestock farming systems in terms of productivity, animal welfare, and environmental impacts. These findings are supported by the work of Brier et al. (2020) in a case study of virtual fencing involving New Zealand cattle farmers. Discussions with stakeholders in our study have highlighted the potential of this technology to not only improve existing grazing management strategies but also present opportunities for new and innovative practices that could transform how grazing livestock are managed. Seen as a '*game changer*', farmers' attitudes towards this technology were largely positive. As one farmer said:

'I do think that the benefits and the potential for what can be done with cattle on the hill, with our own experience for the past couple of years, it's endless. I think it really, really needs to be much more focused on virtual fencing.' (Farmer 3).

Another farmer who welcomed the use of VF on their large upland estate which would be too expensive to fence, also said:

'It's a game changer. There's no way there'd be cattle up there without the system in place. It just wouldn't happen.' (Farmer 1).

The use of virtual fencing technology indeed allowed some farmers to '*bring cattle back onto the hills*' and to improve grazing strategies:

'What was really exciting was to see cattle grazing land that probably has not been grazed in living memory, you know. Our cattle would be on the hills anyway, but for them to have targeted grazing was a unique experience.' (Farmer 4).

Virtual fencing in the current study helped farmers who were taking part in conservation grazing initiatives, giving them better control of livestock in upland areas and improving biodiversity. The technology allowed them to impose targeted grazing pressures at different times of the year, allowing fresh regrowth of grass and flowering plants. This is also encouraging from an environmental point of view since excessive trampling from overgrazing can result in soil erosion and sediment run-off (Williams et al 2012). The reintroduction of cattle, in particular to hill and upland areas, was viewed as a significant benefit of virtual fencing. Cattle are known to be less selective in their diet than sheep and have a higher preference for fibrous vegetation such as tussock and moor grasses (Grant et al., 1985). This lower selectivity and their greater ground disturbance mean that they reduce dominant vegetation, increase diversity and have wider biodiversity impacts than sheep grazing (Rook et al., 2004). One farmer stated that changing their grazing strategies with virtual fencing allowed for new species of vegetation to appear:

'I found them great in the sense that the cattle will graze down on tougher vegetation that the sheep won't graze. I was able to fence cattle in those areas and a colleague was absolutely delighted with the work that the cattle were doing because she said she was seeing six different species of vegetation that she hadn't seen before.' (Farmer 3).

These new grazing strategies were also seen as a positive for wildlife conservation, allowing farmers to alter grazing intensity to maintain and protect certain habitats for rare bird species, such as curlews, grouse, or corncrakes. One farmer highlighted how this could potentially present an opportunity to create a new market for conservation-grazed products:

'It's great to have that objective data because it is kind of ammunition for more attention being focused on farming these types of areas.' (Farmer 4).

As previously mentioned, it was highlighted how virtual fencing could promote increased outdoor grazing of livestock. As well as improving animal health and welfare, this would also address societal demands for more pasture-based products and higher animal welfare standards (Schulze et al., 2021). It is likely to be viewed positively by the public, who may also value the absence of physical fences in high nature value areas. In a study by Sweeney et al. (2022) with citizens from the island of Ireland, it was found that animals having space and outdoor access were considered key indicators of good farm animal welfare. In addition, by allowing animals to be monitored remotely and at all times, virtual fencing technology could help farmers identify if any issues arise (e.g., isolated animals). Prompt interventions could improve animal health and have knock on effects in reducing antibiotic usage, for example.

Challenges and risks of using virtual fencing

Discussions with stakeholders have highlighted how virtual fencing technology can provide new opportunities to increase the efficiency and sustainability of grazing livestock systems, enabling a redesign of these systems and contributing to improved environmental and animal welfare outcomes, as well as higher financial and social performance. Despite the potential of virtual fencing technology, the study highlighted several challenges which require careful consideration. Inadequate use (e.g., inadequate training or boundary set-up) or failures in the system could have negative consequences for animal welfare or public safety.

Technical challenges

One of the challenges reported by stakeholders in relation to current virtual fencing systems is the reliance on mobile network signal, which in certain parts of the island of Ireland can be relatively poor. This can hinder the normal functioning of the virtual fencing system as network signal is required to facilitate the flow of information between the collars and the user's mobile application. Some farmers in the study reported difficulties in moving the boundaries due to such network issues.

Another potential challenge highlighted by participants was variation in the positioning accuracy of virtual fence collars, otherwise known as GPS drift. In a virtual fencing context, GPS drift is the difference between the actual location of the collar and the location recorded by the GPS receiver. The amount of drift a GPS system has is dependent upon several factors, including the quality of the GPS receiver and antenna, the number of satellites detected, and how much of the sky is in direct view from the ground. Factors affecting drift include proximity to buildings, heavy tree cover, steep slopes, and hilly terrain (if the animal is in a valley, the GPS receiver sees less of the sky and fewer satellites). Heavy thunderstorms may also impact satellite GPS signal. For virtual fencing systems, GPS drift may result in areas that were excluded for ecological or safety reasons becoming inadvertently accessible to animals. Such issues may restrict the adoption and efficient use of these systems, as is the case with most digital technologies (Rose et al., 2016). This was confirmed by a stakeholder:

'Some of the farmers that got the collars for precision grazing in dairy farming gave up on them because they were not fit to hold them within those small paddocks that you would if you're using an electric fence' (Stakeholder 2).

Safety issues

The study highlighted potential challenges with biosecurity due to the lack of a physical barrier between virtual fenced livestock and other animals (e.g., wildlife or animals from other farms). It was also noted that the lack of a physical barrier may result in members of the public such as walkers straying within the virtual boundaries and possibly coming in contact with livestock. Additional concerns were subsequently raised among stakeholders around the subject of contact between livestock and the public. This could result from system malfunctions, humans entering the animals' virtual grazing area, or animals simply escaping. Stakeholders were uncertain about the legislation and who would be liable in such instances:

'From an insurance point of view, if something went wrong and your 10 cows break out onto the main roads outside your house, if there's a car accident or somebody gets injured, who is liable?' (Stakeholder 3).

Animal welfare issues

Issues of GPS drift can also be ambiguous and stressful for animals, who may receive unnecessary electric pulses. Although it was reported that the intensity of the pulse delivered by virtual fencing systems is below that of a conventional electric fence, the aversiveness of the pulses administered via a neck collar was a source of concern. One stakeholder was worried about the system '*relying on fear*', with animals having to go through a certain amount of audio and electric cues to learn not to cross the boundaries. According to previous studies, there appears to be high individual variation in learning depending on sex, breed, age, or temperament (Campbell et al., 2018; Lomax, Colusso and Clark, 2019), indicating the importance of taking these aspects into consideration when implementing virtual fencing and the allowance of sufficient time periods for animals to learn the system. In addition, there were concerns about animals that are not moved frequently becoming difficult to move as they get used to a specific virtual boundary location. Whilst a study conducted by Campbell et al. (2017) suggests that animals learn to respond to audio cues rather than showing predicted learning of where the boundaries are, more research is needed to explore the impacts of using virtual fencing in different settings.

Other animal welfare concerns involved issues around fitting the collars and the practicalities of having to change them, as well as potential impacts on the human-animal relationship and stockmanship skills:

'I know farmers really speak positively about the relationship they develop with their cattle when every single day they're going out, they're moving a fence, they're opening it up. The cattle perceive all of this very positively. But obviously, if you just did that with a click of a button, you might miss some of those observational opportunities and that relationship.' (Stakeholder 1).

These issues represent potential barriers to the adoption of virtual fencing, as well as its acceptance by consumers and wider society. The adoption of digital livestock technologies depends on many factors including farm size, farmer profiles (e.g., age, education), farmers' underlying beliefs towards technologies, perceived usefulness and practicality, but also on external pressure and negative feelings (Lima et al., 2018). Shock collars for pets are not permitted or are being banned in several countries due to concerns over their efficacy, potential misuse, and ethical concerns, and so it is important that assurances and safeguards are in place which ensure that animal welfare is at a minimum maintained or enhanced when using virtual fencing systems. Concerns over impacts on the human-animal relationship have been raised before in relation to the use of precision livestock technologies (Schillings, Bennett and Rose, 2021), and care must be taken to ensure that an increase in technology use does not result in fewer positive human-animal interactions.

Farmer profiles

Other barriers to virtual fencing adoption are farmer profiles and farm suitability, as well as psychological barriers, which are often reported in relation to digital innovation in agriculture (Rose et al., 2016). Some farmers may struggle to use the device effectively or may not like the idea of the absence of physical fences:

'I think that there is a little bit of a thing within our culture; some people might be a bit apprehensive of allowing walkers through their land. People can be quite private about it or quite proud of what's theirs and they want to make sure that people know what is theirs. That might be an issue for some people.' (Stakeholder 4).

Ultimately, the impacts of using virtual fencing technology will depend on how farmers make use of them, and whether new management strategies will emerge as opposed to focusing solely on facilitating existing ones (Schillings, Bennett, Wemelsfelder, et al., 2023):

'I would really like to see how people do use it. I mean, do they just make squares on their phones, you know, the same as they would an ordinary fence or do they actually do interesting things?' (Stakeholder 1).

How the potential of digital agricultural technologies can be translated into effective use on farms has thus far been an underexamined question (Eastwood and Renwick, 2020). Studies suggest that despite numerous developments in digital agricultural technologies, most of these are not being used effectively in practice due to their complexity, cost, or the technical knowledge they require (Lundström et al., 2017). In the case of virtual fencing, Brier et al. (2020) suggest that a lack of feed budgeting skills can affect users' ability to make effective use of the technology in relation to improved grazing management. As one participant from their study mentioned: '*It's like a poor driver buying a Ferrari – you also need to help them become better drivers*'. This highlights a need for adequate training and support to ensure the responsible use of virtual fencing and enable farmers to maximise the potential of this technology. How end-users make use of Digital Livestock Technologies is important to explore, as opposed to solely focusing on the binary use or non-use of technology (Rose et al., 2023).

Key considerations for the use of virtual fencing

For the first time in this context, the ESR framework has been used to reveal the significant potential of virtual fencing systems to help redesign grazing livestock systems towards improving animal welfare and promoting biodiversity and sustainability. However, they also highlighted challenges associated with the use of these technologies which must be considered, and care should be taken to ensure that the development of virtual fencing technology and its adoption is made in a way that supports farmers, animals, as well as the farming industry.

Supporting farmers

How technological change is likely to impact farm practices widely depends on individual farmers' adaptive capacity, as some may be better able to make the most out of "agriculture 4.0 technologies" than others (Rose et al., 2022). As Rose et al. (2022) argue, it is important to explore how farmers experience technological change, and to ensure that less powerful voices are heard. In this study, discussions with participants highlighted a need for farmers to have access to adequate training that caters for the wide range of farmer profiles (e.g., age, education), IT skill levels, and farming systems. Taking farmer profiles into consideration is indeed important to ensure more inclusive and targeted engagement with farmers, as well as increased adoption of digital tools (Adereti et al., 2023). Participants considered it would be useful to integrate virtual fencing into demonstration farms, and organising farm walks, and knowledge exchange groups, all of which are important elements which can help farmers in their decisions to adopt, or not, digital livestock technologies (Kopler et al., 2023). As virtual fencing represents a significant investment, providing more research on cost-effectiveness and financial support through grants and funding (e.g., through the Targeted Agriculture Modernisation Scheme in Ireland) to help farmers acquire this type of technology was considered important by study participants, especially in a context where farmers have to face many environmental and societal challenges. These types of devices can be costly; thus attention must be paid not the reinforce the already existing gap between smaller and larger enterprises. One stakeholder also suggested the possibility of combining financial support with the delivery of animal welfare or environmental benefits, which would constitute a suitable strategy in reaching sustainability goals on the island of Ireland. Finally, providing clarity on data ownership and use was also considered a priority by participants, as the data collected with digital agricultural tools are often considered business or trade data as opposed to personal data (Rotz et al., 2019; van der Burg, Bogaardt and Wolfert, 2022). There is currently a lack of transparency around these questions due to a lack of legislation and regulatory framework specifically aimed at agricultural data; therefore, it is not clear who is benefitting from the data, who owns it, and how it is used (Wiseman et al., 2019).

Supporting animal welfare

As highlighted by stakeholders in the study, minimising impacts on animal welfare is key for virtual fencing to be acceptable on farm. To this aim, it was considered important to provide suitable training in consideration of animal breed, sex, age, and temperament. There is significant individual variation in the rate at which animals learn (Campbell et al., 2018; Verdon et al., 2020; Eftang et al., 2022), thus having an appropriate training plan in terms of length, design, and timing is crucial. This requires more research on these aspects, and impacts on animal welfare are still an active research area that remain to be fully investigated. Participants emphasised that clear guidance should also be provided on collar sizes and intensity of electric pulses, which should be carefully tailored to individual animals. To facilitate learning, participants suggested adopting gradual fencing strategies (e.g., starting with one virtual fence). Familiarising animals with moving from one virtual pasture to the other would be beneficial as some were concerned if animals would get used to the virtual boundary location and not be willing to cross it when moved. As discussed with participants, animal movement to new virtual boundaries may be facilitated with the use of incentives (e.g., food). Virtual pastures must be carefully designed and more information on adequate paddock size should be provided, although it was clear from the discussions that there is no *one-size-fits-all*. Participants suggested avoiding tight corridors and corners due to issues of drift and potential confusion for the animal if boundaries are too close together. Whilst some farmers did not consider VF efficient for small pastures, some studies have demonstrated the ability of this technology to contain beef cattle within small paddocks, highlighting the need for more research to provide farmers with adequate guidance (Holohan et al., 2023). Virtual boundaries must also be planned carefully, allowing sufficient access to water and shelter if required and considering potential discrepancies with GPS drift and network signal. When moving paddocks, stakeholders suggested leaving a gap between the old and the new paddock, as animals may want to return to the original site and cross the common boundary if these are adjacent. Where possible, boundaries can be harmonised with the landscape to reduce ambiguity (e.g., using naturally occurring ditches). As some animals appear to learn faster than others, a strategy to select those animals and their offspring may be necessary, as well as promptly removing those animals who do not learn. One stakeholder suggested considering the use of positive training to replace aversive methods, such as rewarding animals for turning back when they hear the audio cue. Overall, a crucial element emphasised by participants was that virtual fencing systems should not become a replacement for farmers but a supplement to animal husbandry.

Supporting the industry

Participants in the study highlighted that the use of virtual fencing technology may raise some concerns from the public about animal welfare. Whilst the data collected with digital tools could be used as evidence (e.g., for farm assurance schemes or during inspections) (Schillings, Bennett, and Rose, 2023) and give farmers legibility, they also mentioned potential cyber-security risks around access to data. They emphasised that efforts should be made to increase public awareness, such as using appropriate signage (e.g., keeping dogs on leads near places where livestock are virtually fenced). Overall, a need for more research was identified on the use of virtual fencing (e.g., possibilities to use collars on a certain percentage of the flock), conservation management specific to the island of Ireland and long-term animal welfare impacts. Indeed, one farmer suggested that despite the quality of support provided by their technology supplier, they had concerns about most of the research being performed in the country where it was developed:

'One little point that I would make is that most of the research is (country of origin)-based. We are totally different in terms of the nature of our fragmented farm. So just for the history of Irish agriculture, we have a lot more fragmented farms, we have a lot of commonage. I have talked to them (the company) on different issues and they're really, really helpful. But you discover that a lot of their research is based on conservation management in large woodlands in (country of origin), and I don't know if that can be applied in Ireland or if there is peer-reviewed, published literature that's applicable to something that we have in Ireland with our fragmented farms, commonage and so on.' (Farmer 6).

Participants have emphasised that agricultural research institutes and governmental bodies should be more involved in research around virtual fencing, considering its potential to address important challenges relating to sustainability, biodiversity, and animal welfare. Where possible, future research and policy should also encourage participatory approaches, involving animal representatives, citizens, and NGOs, among others, to promote the uptake of digital tools such as virtual fencing technology (Eastwood et al., 2012).

Limitations of the study

This study involved participants from the island of Ireland; thus, we acknowledge that discussions with study participants applied to a specific context. However, the main topics discussed are in accordance with the main topics found in other studies (e.g., Brier et al., 2020), thus it is possible that the benefits and challenges encountered with virtual fencing mentioned in this study can apply to wider livestock grazing contexts. In addition, we acknowledge the limited sample size due to a currently low level of adoption of this technology in Ireland, which may have limited opportunities to explore wider topics which have not been discussed by study participants. Whilst we were not able to recruit enough participants to conduct more focus groups, we conducted personal, in-depth interviews to gain a deeper understanding of the topics discussed. Furthermore, contact details of technology users were provided by the virtual fencing technology company, which introduces a possible bias regarding the attitudes of participants towards the technology. However, we suggest that this bias was minimal, as those participants also reported challenges they encountered and concerns about the technology. Finally, it would have been interesting to conduct focus groups with farmers who are not using virtual fencing (and/or who are not aware of the technology), to gain further insights. Similarly, whilst this was not the focus of our study, research on public perception of virtual fencing would be relevant for future studies, especially considering the ethical aspects of the technology.

Conclusion

The use of the ESR framework has highlighted, for the first time in this context, the important potential of virtual fencing technology to help farmers monitor and manage livestock grazing more efficiently, particularly in high nature value areas, therefore increasing environmental sustainability and safeguarding the provision of ecosystem services. These areas can be difficult to manage, due to their often vast and remote nature. Through more efficient use of resources and monitoring, as well as removing the need for physical fences thereby reducing workload, resource use and potential danger to wildlife, virtual fencing can help farmers in redesigning livestock grazing farming towards more sustainable systems. Using virtual fencing technology, farmers can indeed improve their livestock grazing and conservation strategies, reduce the costs and labour associated with setting up physical fences, and monitor their animals remotely. However, there are still challenges related to the use of virtual fencing which must be considered and addressed to achieve successful redesign of livestock grazing systems, including among others, concerns around reliability, cost-effectiveness, animal welfare impacts, and public perception. It is important that more research is undertaken to clarify uncertainties around efficacy and ethical implications, as well as adequate support provided to farmers in relation to cost, training, and data handling. Efficient collaboration between stakeholders, including the public, is needed to ensure a robust and holistic evaluation of virtual fencing technology and its ability to promote sustainable grazing management.

Ethics approval

Ethical approval for this study was granted by the University College Dublin Human Research Ethics Committee. Reference number of committee approval: LS-LR-23-21-Schillings-Russell.

Data and model availability statement

None of the data were deposited in an official repository. The data that support the study findings are confidential to maintain anonymity of the participants.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

Author ORCIDs

Juliette Schillings: https://orcid.org/0000-0001-7190-6553.
Conor Holohan: https://orcid.org/0000-0001-5752-3986.
Francis Lively: https://orcid.org/0000-0003-0706-5045.
Gareth Arnott: https://orcid.org/0000-0003-1525-3708.
Tomas Russell: https://orcid.org/0000-0003-0799-360X.

CRediT authorship contribution statement

J. Schillings: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **C. Holohan:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **F. Lively:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **G. Arnott:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **T. Russell:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of interest

There is no conflict of interest or competing interest.

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