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Front cover, small photographs from top row:

A deep water fly trap anemone *Phelliactis* sp., Yvonne Leahy; **Common Newt** *Lissotriton vulgaris,* Brian Nelson; **Limestone pavement**, Bricklieve Mountains, Co. Sligo, Andy Bleasdale; **Garden Tiger** *Arctia caja,* Brian Nelson; **Violet Crystalwort** *Riccia huebeneriana*, Robert Thompson; **Coastal heath**, Howth Head, Co. Dublin, Maurice Eakin; **Meadow Saffron** *Colchicum autumnale*, Lorcan Scott

Bottom photograph: **Dexter cattle** delivering conservation grazing as part of a National Parks & Wildlife Service Farm Plan, Barry O'Donoghue

Disclaimer: This is an independent review and reflection, of a national pilot using Precision Livestock Management, in the form of 'Virtual Fencing', using devices manufactured and supplied by Nofence. The relevant Nofence user guidance and manual, available on the Nofence website should be referred to for all use of Nofence collars. Any queries on the technology, whether hardware or software, should be directed to Nofence support.

Pioneering Precision Livestock Management (Virtual Fencing) in Ireland. A review of a 3-year pilot with focus on the environment, the livestock and the farmers.

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Executive Summary

Various ways to manage livestock grazing have developed over the years, from human supervision, to wood, stone, wire and electric fences. Now, the virtual fence is an option. The concept involves remote mapping, Global Positioning System (GPS) sensors and wireless technologies, to keep animals in certain areas, and out of others. The animals have a GPS-enabled collar fitted and the perimeter of the grazing area is defined by geo-coordinates, which can be drawn on a smart device screen using an associated application (app.). As an animal approaches the virtual perimeter, the GPS collar emits an audio cue. As the animal progresses, the audio warning will increase, and if they persist, the animal will receive an electrical pulse as they cross the perimeter fence coordinates. The 'learning'/training process is the key factor, *i.e*. to associate the link of the audible cue(s) to the electric pulse, such that once the animal hears the audible cue, they would be deterred from continuing to/through the perimeter, ultimately without the need for any electrical pulse. The development and uptake of this technology has been slow up to recent times, but there is now significant interest in virtual fencing systems, for controlling grazing management and animal movement, including here in Ireland.

From Summer 2020 to Winter 2022, a team comprising the author and fifteen farmers progressed Ireland's first virtual fencing studies, with a total of 101 cattle collars and 71 sheep collars deployed for use across various terrains and habitats in Counties Donegal, Leitrim, Sligo, Galway, Wexford and Tipperary. One of the primary objectives of the team was to provide a feasibility study, to break new ground for other parties who may be interested in adopting this cutting-edge approach to land management. The trials were undertaken with a view to managing important habitats and safeguarding sensitive soils, which in turn are important for carbon, water and biodiversity. How we manage our land, particularly in a country like Ireland, where approximately two-thirds of the terrestrial area is farmland, is of immense importance in addressing the enormous challenges relating to the biodiversity and climate crises. The coordinated team aspect of the pilot offered a support network and knowledge transfer platform across the farms and farmers, as well as central collation of results and experiences from across a variety of landscapes, habitats, animals and farming systems, so that a solid foundation could be built for prospective future users.

It was absolutely necessary that assurances could be given that the technology used in this pilot was consistent with animal welfare regulations, principles and codes of practice, so extensive background investigations and training sessions were undertaken prior to using the technology in the field. Rigorous, real time animal behaviour monitoring took place over the period of the pilot, which ran from May 2020 to December 2022.

In summary, the virtual fencing concept was pioneered by this research group in Ireland over three grazing seasons with a view to evaluating:

- effectiveness in maintaining cattle and sheep location as desired
- applicability in delivering quality environmental goods, including biodiversity, water, and soils
- how it works for the animals
- how it works for the farmers/livestock managers.

This pilot has provided real life scenario testing in an Irish context that can be used to inform an approach for future possible roll-out. Apart from environmental management, identified benefits of remote Precision Livestock Management included improved lifestyle of livestock managers due to a reduced requirement for manual labour and capital costs (*e.g*. time, effort and expenditure in erecting permanent fences and moving temporary fences) and knowing

where animals were via the mobile app. These are key advantages in uplands habitats and difficult terrain, and on offshore islands, and are considered to add to the security and safety of the animals. There is however, no substitute for the direct inspection of animals at least once daily. There are also a number of caveats and conditions that need to be considered for any livestock manager contemplating whether virtual fencing is a suitable venture for them, their animals and the land they are managing. It may not be suitable in all contexts, and should not be undertaken without adequate training, know-how and back-up support.

The potential for a new era in the relationship between Irish farmers and livestock has been explored, along with opportunities for a new era in the management of lands for environmental interests. These initial steps have been vital to inform the strengths, weaknesses, opportunities and threats of Precision Livestock Management using virtual fencing in an Irish farming context. The technology has the potential to be a ‘game-changer’, but should only be considered for any given use or site, following very careful and detailed planning, and a full understanding of the weaknesses and limitations that may pertain to the technology for any given use or site. Training and mentorship, and the provision of national standards in the use of the technology are also deemed necessary.

Acknowledgements

This pilot could not have been undertaken without the participating farmers and their families. The care and understanding that they had for their animals and land was exemplary, as was the proactive way in which they engaged with the virtual fence technology. Their ongoing feedback and engagement throughout the programme, as well as their end of project reviews formed the basis for the conclusions of this report. A huge thank you to Eileen, Joe, James, Liam, Chris, Jack, Enda, Linda, Shaunie, Sean, Brendan, Mary, Colm, Eoin and Paul.

Nofence, particularly Synne and Ingrid, were of very valuable assistance throughout the programme.

Various individuals and groups were consulted and engaged in the lead up to and throughout the programme, including the Scientific Animal Protection section of the Health Products Registration Authority, Bernadette O’Brien (Teagasc), Dolores Byrne (Atlantic Technological University), Tony Waterhouse (Scottish Rural Upland College), John Carey (Corncrake/Traonach LIFE), David McCormick and Michael Martyn (Michael Martyn Agri-Envrironmental Consultants), James Owens (Oran Ecology) and John Gallogly (Philip Farrelly & Associates).

1 Introduction

1.1 Overview

Many ecosystems, habitats and species are dependent on the grazing effects of herbivores (Baggio *et al.*, 2021; Silveira, 2021; WallisDeVries *et al.*, 1998). Grazing, whether by wild or feral herbivores or domestic livestock, is a dominant influence on Ireland's natural and semi-natural habitats and is particularly influential in the context of semi-natural grasslands, wetlands and heathlands of conservation interest (NPWS, 2019). The relationship between grazing and nature in Ireland presents a classic 'Goldilocks' situation; too hot (intensive) or too cold (extensive or absent) and a particular habitat or species may suffer. What is 'just right', in terms of grazing, will tend to differ depending on the ecological interest or target, and will also depend on various factors, not least of which is the present extent and condition of the ecological interest or target. For example, a habitat may be presently 'overgrazed' or 'undergrazed' relative to the niche or requirements of a particular ecological interest or target. Factors including climate, weather, exposure, elevation, management prior to and after grazing, grazing species and breed, stocking rate and the timing, intensity and duration of grazing, will all have a bearing on the influence of grazing on a habitat or species. In many areas, particularly at a medium to large scale, there will be variation in terms of habitat types and conditions. For example, a typical upland commonage in the West of Ireland will have a combination of wet and dry heaths along with blanket bog or other habitats, often occurring as a mosaic. So while appropriate grazing levels are essential to maintaining and restoring habitats of conservation interest and the biodiversity that they support, grazing with nature conservation in mind (or conservation grazing) cannot be a simple consideration of just stock type and numbers (as often tends to be the case). The advent of results-based agri-environmental schemes (see O'Rourke & Finn, 2020) has provided both opportunities and challenges to land managers, ecologists, advisers and policy makers in terms of how optimum conditions can be provided by grazing. It is thus important that various supports and tools, that can assist land managers in delivering quality results, are identified and considered.

In 2019, the author began to research the concept of Precision Livestock Management technology, specifically virtual fencing, with a view to managing stock in a way that benefits the natural environment. The term 'virtual fencing' encapsulates the maintenance of animals within or outside of specified areas, through the use of GPS locational devices (*e.g*. collars), as opposed to using physical fencing. Appendix 1 includes some of the salient points that were noted during this background research, including those from peer-reviewed literature, and communications with suppliers and practitioners. After researching the technology and exploring the market, Nofence technology was chosen as part of this national pilot project, given their products had been used by farmers across Europe in the previous years. This NPWS pilot was the first time the technology was used in Ireland and also one of the first uses in North West Europe. The objectives of the pilot extended beyond environmental interests alone, and included consideration of how the technology worked for the animals and the farmers in an Irish context. In doing so, it is envisaged that this pioneering project has provided a foundation ahead of any future possible application of virtual fence technology across Ireland.

1.2 Hardware, software and technology

Nofence, a company originating in Norway, developed what it calls "the world's first virtual fence". The specifications of the cattle and sheep collars are presented in Appendix 2. Collars and a dedicated Nofence app (Figure 1) combine to provide a package that allows animals to be maintained within or out of particular areas. Using the app, the livestock manager can zone the areas (known as ‘pastures’) that they want the animals to be kept into or out of.

Nofence virtual fencing systems consist of a collar device, which starts to play an audio sound when the animal crosses a virtual border. The warning sound consists of a tone scale, starting on the lowest tone. The warning sound can never skip a tone, and thus the electric shock always instantly follows the tone with the highest pitch. The warning sound never lasts for shorter than five seconds, and never for longer than 20 seconds. The duration of the sound depends on the animal’s speed across the virtual border.

When the animal responds to the warning sound by turning around, the tone scale plays downward until the animal is back inside the virtual fence, upon which the sound stops playing. If the animal does not turn as a response to the warning sound, it will get an electric pulse in the neck region. The electrical pulse from the Nofence collar (Energy = 0.2 Joule per pulse; Voltage = 3 kV) is less powerful than that from a regular wire electric fence (6 Joule and 6-9 kV). This was physically confirmed by some of those involved in this pilot holding the collar and walking beyond the pasture perimeter. The actual duration of discomfort *i.e.* while receiving electric pulse is one second.

Should the animal continue to walk in the same direction (out of the virtual fence), despite receiving the initial warning sound and a following electric pulse, it walks into the second warning zone, where the pattern from warning zone 1 is repeated. The system consists of a maximum of three such warning zones (Figure 2). If the animal crosses all three warning zones, it is reported as escaped and the owner receives a push notification through the mobile phone app. Collars cannot emit any more than three pulses before the animal is registered as escaped. When it escapes, it has to be registered inside the pasture again for the collar to be able to give any new warnings or pulses. The audio signals are turned off and the electric shock is deactivated, and the collar goes into trace mode. If the animal returns to the grazing area of its own, the system is reactivated, and the owner is notified.

The purpose of the collar devices is thus to alert the animal (by audio signal) as to when they are approaching the pasture perimeter, which they should then not breach, following an initial training period (see Section 1.3, Animal Welfare and Training). Both collar types (Figure 1) are manufactured with a durable, hard casing and held loosely ahead of the animal’s shoulders and behind their head with a flexible strap, to which the device is connected with metal chains (Figures 3 and 4). The batteries are charged by solar panels on either side of the collar. A motion sensor registers acceleration along three axes and provides information about the animal's movements. Satellite signals from American and Russian GLONASS determine the position of the collar (and by proxy, the animal that is wearing the collar). Nofence uses the 2G and 4G network in order to communicate with the app. In order to receive notifications and updates from the collars to the apps, there must be mobile phone coverage in the pasture.

Figure 1 Cattle Collar (left) and Sheep Collar (right) with Nofence App on mobile device.

Nofence also has associated ‘shelter beacons’ to avoid ‘positional drift’ when animals may be in the ‘shade’ of building, for example, when communication between the collar and satellites may be obscured by a roof or wall, leading to the collar registering an inaccurate location and potentially emitting audio cues or electrical pulses. The Nofence shelter beacon is a Bluetooth unit, which disabled the operating mode when the collar is within 10 m range.

During the pilot, detailed data was automatically recorded at 15 minute intervals by the Nofence technology, including locational data, application of audio cues, and application of electric pulses. This detailed data shall be made available as part of further research analysis.

1.3 Animal welfare and training

Prior to purchasing the technology, extensive research and advance communications were undertaken, including consideration of literature on the subject, available suppliers, experience of suppliers, support from suppliers and so on (see again Appendix 1 for some insight). Nofence was the longest established supplier available to the Irish market and had over 40,000 collars utilised across more than 200 million hours of usage by more than 3000 customers internationally. Peer reviewed evaluation of Nofence collars had recently been undertaken and published (Eftang & Bøe, 2019). Following this, it was considered that the use of Nofence would not have any negative impact on the animals over the duration of the project. Furthermore, it was considered that the fact that animals could, via the app, be located across extensive terrain and be kept out of dangerous locations (*e.g.* bog pools, craggy areas, beach fronts, *etc.*) the technology would assist in their safety and welfare.

Advance engagement took place with the farmers that were involved in the study. This was important, as the pilot project was dependent on the farmers, for undertaking physical visits and monitoring of the animals over the duration of the project. Their commitment to good husbandry and appreciation of animal well-being was obvious from discussions with them and visits to their holdings. They were competent in animal care and forage management, with necessary skills and many years of experience. The animals were individually known to the farmers, and the farmers had the ability to sense varied temperaments and behavioural patterns. So too, the lands and habitats therein were known by the farmers. Each farmer had a vet that they could call on, although veterinary assistance was not required at any point throughout the pilot.

During the initial training phase, it was a fundamental requirement for participating farmers to observe the collared animals closely for sustained periods at frequent intervals, to discern how they habituated to the virtual fence collars and technology. When trained and initially released (in the grazing area), this requirement remained in place for the first week, and thereafter it was a fundamental requirement that the animals would be physically inspected on a daily basis. The animals had access at all times to ample forage and water, and where extreme weather conditions presented, the animals were to be closely observed, cared for or moved elsewhere. Essentially, the regular good husbandry requirements of farmers on a day-to-day basis was not to change by virtue of having the virtual fencing in place; in fact the animals were physically observed more than would normally have been the case, in addition to regular checking on the app throughout the day (including hours of darkness).

The farmers/livestock managers were asked to closely observe and record:

- reactions of animals to being collared for the first time
- adaption to the audio cues/electrical pulses in the training period
- adaption to the audio cues/electrical pulses in the grazing period
- influence on and influence of flocking/herding behaviour (including whether the application of the collars influenced non-collared followers including lambs and calves)
- communication of data to the app

The Nofence manual outlines numerous steps and considerations towards optimal animal experience with the product, for example in relation to pasture design and obstacles in the environment. Information videos and further details on the technology can be found at www.nofence.no.

Prior to fitting the collars, the farmers became acquainted with the hardware, software and technology by doing some ‘dummy runs’; looking at the functionality of drawing pastures, changing the perimeters, walking towards the perimeter with the collar, monitoring the locational data on the app and so on.

The collars were fitted to the animals in standard livestock handling facilities that ensured their safety and the safety of the handler. The collars were checked to ensure a good fit, which was deemed to be a space of 6-9 cm, equivalent to enough room to place an adult fist between the collar and the animal’s neck. Once they were fitted, the last pre-release task was to ensure the strap length was good in relation to their necks and the battery/solar packs, and that they could move their head up and down freely, mimicking grazing behaviour. Once this was checked, the animals were released into a field/paddock that had physical boundaries, where they could be observed as part of the initial training phase. It was important that the virtual boundary (the virtual line surrounding the virtual pasture) existed only in one part of the field/paddock in which the animals were being trained. If one were to consider a field/paddock with four sides and a virtual pasture with four sides, just one side of the virtual pasture would fall within the field/paddock, such that the animals would meet the physical fence/hedgerow on three sides, rather than the virtual line surrounding the virtual pasture. This helped the animals realise that when they turned around from the side where the virtual line (and associated audio cues) existed, they would not receive an electrical pulse.

The ear tag numbers of the animals were noted and linked to the individual ID numbers on the app. This proved useful when notifications were received from the app, in matching the event to the cows' individual personality.

A training period of 3-5 days was applied in all cases prior to taking the animals to the target grazing area. This training was in all cases, undertaken in a controlled pasture area of 0.3 – 0.5 ha, with physical boundaries. Cows and sheep were allowed to graze and behave as normal within the area. The controlled pasture area then had a virtual fence drawn with an associated control device (typically a smartphone or tablet) via the dedicated Nofence app, with one side of the perimeter splitting the controlled pasture area (Figure 2).

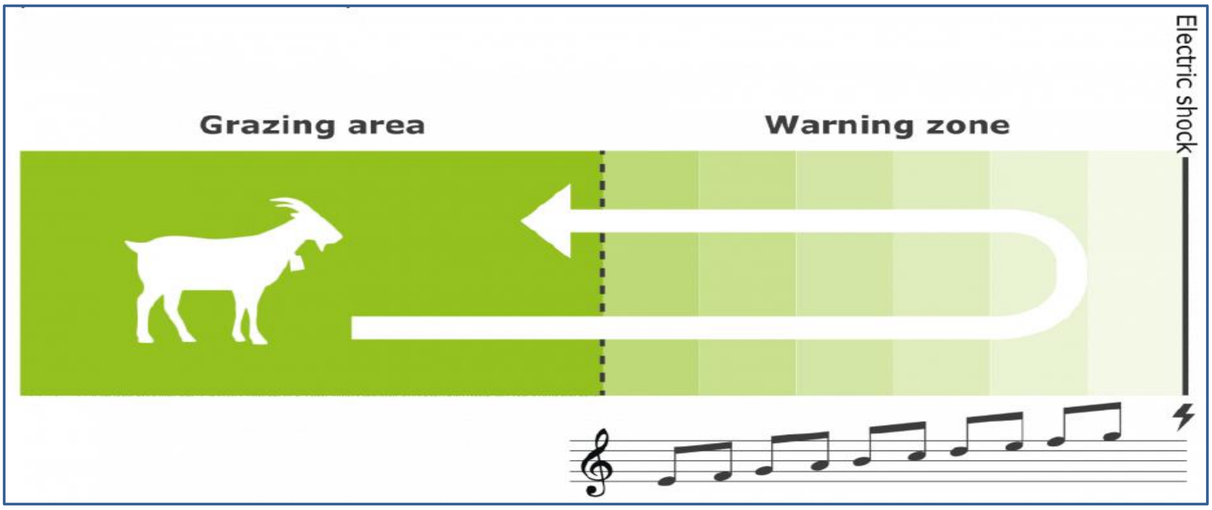

Figure 2 The virtual fence line and operation of the collar as the animal approaches the line.

The purpose of the training period was to habituate the animal to associating the audio signal from the collar device with an impending electrical pulse, should the animal continue towards the virtual boundary, as signalled by an increasing sound level. Concurrently, the purpose of the training period was to observe the behaviour of the animals during this time. The farmers had the facility to shut off the virtual boundary at any time, should adverse reactions be noted. In summary, the training period was intensely supervised to ensure (a) that animal welfare standards were maintained and (b) that 'learning' was occurring.

Figure 3 Galloway heifers wearing Nofence collars in a paddock during the training phase. Photograph: Shaunie Boyle.

Once the cattle/sheep were considered to be trained, they were transferred to the grazing areas, which were deemed from an ecological and environmental perspective, to be in need of regulated grazing. During transfer (*e.g.* by walking, trailer or boat), the collars/pastures were deactivated. Practical considerations in laying out the pasture design were crucial, for example to ensure there was always access to water and ample suitable forage and to avoid dangerous areas. So too, the size, shape and design of the pasture was taken into account so that there is no potential for animals to be confused, *e.g.*, by tight angles, excessively narrow corridors or too many small exclusion zones in close proximity. Illustrations of good pasture design were available in the Nofence manual.

Behavioural observations by the livestock managers continued across the grazing period, including observations of grazing, ruminating, lying, resting and social activities as well as matching what was observed in the field, in terms of location, to what was recorded via the app. Should cattle/sheep have exited the pasture perimeter, an automatic notification was issued to the farmer via the app. The animal's location was transmitted every 15 minutes, even if they were outside the virtual pasture. At the end of the grazing trials, the collars were removed and the equipment cleaned and stored securely and the animals were either moved to other sites or housed as normal.

2 Study area, livestock and participants

This project was undertaken across 12 sites, with a total of 7,184 ha available for grazing. A summary of the sites, the number and type of animals and the farmers/project participants is provided in Appendix 3. All but three sites were under the sole management of the participants in this project (those three sites were commonage with third party shareholders). A variety of geographical locations were included, from the far North West of the country to the South East, and a variety of landscape types from an offshore island to uplands reaching over 600 m above sea level. So too, a variety of environmental interests including peatlands, grasslands, birds, waterbodies, *etc*. were represented. Eleven of the 12 sites were designated under the European Nature Directives (n=6) or close to (<2 km) designated sites (n=5). Some of the sites were among the most remote and difficult to access farm holdings in Ireland, where various issues presented, including logistics and costs of physical fencing, specific nature conservation considerations, access and water infrastructure, monitoring of livestock, *etc*.

A total of 15 individual herd owners were supplied with a combined total of 101 cattle collars and 71 sheep collars across the 12 sites. Each farmer participating in the project had a farming system that has been specifically adapted to their land, often following from how previous generations farmed (*e.g*. summer booleying, winter foggage, spring calving/lambing, *etc*.). The farmers (11 males and four females) ranged in age and perspectives and there was also an inter-generational aspect to the project, with three generations involved at a number of the sites, which is worth reflecting on in the context of how age-old traditions of management might now be taken forward into the future.

Each farmer/livestock manager had an in-depth understanding of their land, and in consultation with NPWS, considered the ability of different parts of the land to sustain grazing in a manner that is balanced and complementary to delivering conservation objectives. Different combinations of grazing pattern were required, each unique to the site-specific circumstances presented and the overall habitat delivery objective. A number of the farmers were participants in the NPWS Farm Plan Scheme (NPWS, 2020), with specific actions identified for habitat management.

The farmers received dedicated introductory and training sessions on the use of the Nofence technology, including online webinars with Nofence specifically for this group, reference to online material, site visits and support from the network involved in this project. Furthermore, the author maintained regular contact with each farmer in relation to providing data and feedback on the use of Nofence collars on their individual holdings. This allowed a coherent picture to emerge from across the various sites and practices, in terms of how this modern technology has worked for the lands, the animals and the farmers.

Figure 4 Dexters wearing virtual fence collars on one of the project sites. Photograph: James Gilmartin.

A combination of the following breeds were involved in the pilot project: Connemara Mayo Blackface (sheep), Dexters (cattle), Kerry (cattle), Galloway (cattle), Hereford (cattle), Angus (cattle) and Charolais (cattle). Different ages of animals were used across the different sites, but animals less than 12 months were not fitted with collars). The farmers did not have very large herds and knew the individual animals and their behavioural characteristics well.

Figure 5 Galloways at one of the project sites, grazing an upland area of blanket bog with virtual fence collars. Photograph: Eileen Condon.

3 Operation of the technology

3.1 Registering users

Each individual farmer partaking in the pilot was set up with a Nofence user account, to allow full functionality and control of the apps and access to data, by logging on with their username and password.

3.2 Registering collars

Each collar to be used by each farmer had to be registered with the Nofence app and then assigned to a virtual pasture. Bluetooth technology was used to link and add collars to the user account. Each collar was given a name (typically the animal ID *e.g.* cow name or tag number) in order to recognize which collar related to which individual animal.

3.3 Pasture design and implementation

Pasture boundaries were established using the Nofence app, by digitising on the screen of a smart device. The app operated with orthoimagery, so that one could identify the points (vertices) where one wanted to place 'fence posts' for the outline of the pasture. Each site (and farm set-up) had specific requirements in terms of pasture design, but by and large each site was sub-divided into sub-management units, to appropriately target grazing and grazing intensity (including stocking rate and how much time animals could spend in a sub-management unit according to available forage), habitats, existing habitat condition and so on. Some sites had habitats that were sensitive to or not tolerant of grazing (*e.g*. areas of wet heath or habitats deemed in need of a break from grazing) and these were excluded from grazing entirely, or for certain periods. Other sites had habitats that were in need of more grazing (*e.g.* sites that had become dominated by one vegetation species at the expense of others, or sites where vegetation structure was poor for associated wildlife). Some sites had public roads or beaches, or neighbouring lands with livestock, whereby physical fencing was already present and the virtual boundaries were set back from these physical fences. Some sites had dangerous areas such as cliffs or wet/swampy areas, with exclusion zones factored into the virtual pasture design. When the pasture was created and saved, with an identifier label (typically relating to names given to parts of the farm by the farming family), the collars were assigned to the pasture, so that the collars would function in line with the pasture boundaries. Each individual pasture could be edited to adjust the boundaries *e.g*. to open a new area to grazing or to close off an area that was previously part of the pasture, but since grazed to an intended level. Pastures that were created and saved could be stored and used for future *e.g*. should animals/collars be moved to a different pasture for an interim period.

3.4 Shelter beacon

Where animals had access to a barn or shed within a pasture, shelter beacons were employed to ensure that the roof or walls did not interfere with the collar's ability to receive accurate GPS signals. Without these, 'positional drift' may have occurred, and if the drifted position was registered outside of the Nofence boundary, the collar may have emitted audio warnings and electric pulses. The Nofence shelter beacon was a Bluetooth unit, which disabled the operating mode when the collar came within a 10 m range. Whenever the animal moved out of the shelter beacon's range, the operating mode would come back on.

4 Results and observations

4.1 Animals

4.1.1 Reactions of animals to being collared for the first time

On their release into the training area, reported behaviours mostly consisted of cattle tossing heads and trotting, and sheep running together and stopping to look around. These were similar to normal behaviours that would be expected in any case, following release from handling facilities. No adverse or unusual reactions were observed and the animals seemed rather accepting of the collars and devices.

Figure 6 Connemara Mayo Blackface immediately after being fitted with Nofence sheep/goat collars. Photograph: Brendan Joyce.

4.1.2 Adaption to the audio cues/electrical pulses in the training period

When a cow or sheep moved towards the perimeter fence, the animal would hear an audio signal at a point of approximately 3 m distance from it. As the animal approached closer, the audio warning would increase (to a maximum of 78 dB), and if s/she persisted, s/he received an electrical pulse as s/he crossed the perimeter fence coordinates. When animals received an electrical pulse, the general reaction was to reverse away from the point at which 'contact' was made with the virtual fence. The frequency of pulses for individual animals ranged from 0 to 10 in a day. In the majority of cases, the number of pulses had decreased to 0 in a day by Day 4 of training, by which stage it was deemed the animal had successfully habituated to the technology, realising that the virtual perimeter (as far as they should approach) was close by when the audio cue was emitted. This was recorded by observation, as animals slowing or pausing further movement in the direction of the virtual fence, when the audio signal was heard. Of all animals that were part of the pilot, none was deemed to have failed the training period, albeit one animal was removed from the pilot following an issue with the collar (see Section 4.5).

4.1.3 Adaption to the audio cues/electrical pulses in the grazing period

When in the virtual pasture, it was noted that there were far fewer pulses per day than was the case during the training phase. In terms of individual and collective animal training/'learning', the trend observed was that, within 48 hours, the animals had largely become accustomed to the audio signal identified to them, and that if they proceeded in a particular direction they were liable to receive an electrical pulse and thus would not proceed in that direction. Thereafter, both audio warnings and electrical pulses declined significantly, in line with what Eftang & Bøe (2019) reported. However, pulses still occurred, and certain individual animals were more frequently associated with pulses than others, even months after initial introduction to the technology.

There are a number of reasons why an animal may have received pulses after the training phase, including individual variation (*e.g*. in characteristics or adaptation), bonds with other individuals, herd/flock instinct, environmental factors and technical/device issues (see Section 4.5). Pulses during the grazing period were also associated with movements of the virtual pasture boundaries.

4.1.4 Influence on and influence of flocking/herding behaviour

The collars were not noted to unnaturally influence flocking or herding behaviour, beyond what would have been expected under ordinary circumstances. For cattle where there was no existing herd bond, collared cattle largely remained within their virtual pasture boundary and did not follow or go to the non-collared cattle. For cattle where there was an existing bond, issues were noted, whereby collared cattle looked to move to or with the uncollared cattle. For mothers that had calves, they largely were happy to allow their uncollared calves to 'creep' outside the virtual boundary and return in their own time, as would be noted in a physical fencing scenario. When weaning was undertaken, mixed results were recorded, depending on the methods employed in weaning. When cows were in heat, the virtual fence was not sufficient to keep them from escaping. Sheep displayed very strong flocking characteristics and where uncollared sheep were present or within view, the virtual fence was of limited value in keeping the collared sheep within the virtual pasture boundaries. For any ewes with lambs, no issues were recorded, but it should be noted that in the cases of this pilot, the lambs would have had to have travelled a significant distance from their mothers if they were to go to the other side of the virtual boundary.

4.1.5 Animal safety and welfare

The collars allowed for dangerous areas to be made inaccessible to animals. Due to logistics and practicalities, physical fencing may never have been an option or possibility in such cases. Examples included steep, rocky slopes and crags, and multiple bog pools. It should be noted (as per Section 4.5) that the technology (as with physical fencing) should not be considered infallible and should not be taken as a guarantee that animals will be kept away from hazards, but it certainly provides for an improvement beyond where fencing could not be undertaken.

Furthermore, the ability to know where an animal was at regular intervals throughout the day, added to the safety and welfare of the animals and allowed appropriate responses to be activated earlier than might otherwise have been the case. For example, a calf was rescued at one of the sites by virtue of the signal received from the collar his mother was wearing. On a remote and extensive mountain area, the app was showing the mother to be apart from the rest of the herd. The farmer subsequently investigated this on the ground and found she was with her calf, who had become stuck in a quagmire.

One of the earlier considerations prior to using the collars, was that of weight. Intuitively, there were concerns among the group that the entire equipment loading (including the collar device, battery and neck strap) might potentially present a burden to the livestock, particularly sheep (adult ewes weighing approximately 60 kg) and the indigenous Dexter cow (adults weighing 300-350 kg). The cattle collars weighing approximately 1.5 kg and the sheep collars weighing approximately 0.5 kg, were 0.5% and 0.8% of Dexter and adult ewe body weights respectively. It should be noted that other cattle breeds on the pilot project were heavier and stronger. In attaching tracking devices to birds, a figure of no more than 3% is generally applied and in school children, a figure of no more than 10% is taken to be appropriate for school bag weight. Despite the low percentage of body weight that the collars accounted for, the fact the collars were to be placed around the animals' necks still led to the consensus that the reaction of the animals to the collars, not just immediately upon placement, but for some days after, should be carefully scrutinised, to ensure that they were not impeding normal activity or burdening the animals. None of the project farmers recorded any such issues. One of the farmers noticed that when cattle fed at a trough, the collar clanging against the metal appeared to bother some of the animals. A potential consideration highlighted by one of the farmers was that there could be a risk of a cow scratching on a fence post and becoming stuck by virtue of the collar chain/strap surrounding the post. This was not observed, but nonetheless is an important consideration for those looking to use virtual fence collars.

4.2 Environment

4.2.1 Management of habitats

The collars allowed for defined and adaptive management of habitats. Certain areas were deemed in need of greater grazing, for example to return rank vegetation on a coastal grassland or dry heath to a more species-rich condition. Other areas were deemed in need of a lighter touch; for example, wet heath habitat or very wet sites, where animals might only be usefully deployed for a limited period, at a particular time of year or in particular conditions. Other areas were deemed off-limits, for example where nesting or roosting birds of conservation concern were present or where waterbodies needed to be protected from animals entering and potentially causing damage. The collars then are potentially usable in various site-specific scenarios (including what was undertaken in this pilot) for conservation grazing (or exclusion or limitation of grazing).

To use a term often repeated by the farmers involved in this pilot, the virtual fencing has the potential to be a 'game changer' in various respects. Habitat management is certainly one of those. As Ireland progresses with result-based agri-environmental schemes and nature restoration, virtual fencing could play an important role in targeting grazing in a sensitive and appropriate manner, to deliver the results required, whether in terms of biodiversity, soil, water or climate.

The GPS functionality of the technology allows for review and discerning of clear patterns in relation to habitat use and selection. This is powerful information at a site level and also at an overall landscape or project level, with multiple data that can be utilised for research purposes, to further inform applied conservation action, including management of habitats.

4.2.2 Habitat use

As mentioned, the technology allows for detailed, forensic investigation of habitat use, thanks to the GPS tracking of the collar, which shows spatial and temporal patterns of grazing for the individual animal. This can be extrapolated to include all collared animals. This is valuable in understanding how livestock, including different species, different breeds and indeed different individuals interact with and utilise areas of land, habitat and vegetation. It also allows for clear display of where animals tended to favour, in the form of a heat map (Figure 7). This can be viewed in real time, as well as an entire overview of movements since the beginning, and is very useful in identifying any vegetation/habitat selection or avoidance. It allows for associated management (either on the ground or remotely) to ensure a particular area or a particular habitat is grazed at an appropriate level, according to the conservation objectives for the site. The advent of result-based agri-environmental programmes, where scorecards and associated guidance and interaction between farmers and ecologists give a clearer understanding of what is 'just right' by way of habitat condition, aligns well with the usefulness of virtual fencing and the GPS tracking of grazing livestock. Without too much trouble, it should be possible to assign a stocking/grazing regime to a particular area of habitat for a period of time, using virtual fencing technology. Where mosaics of habitat occur, it would be possible to assign less grazing pressure to certain areas or habitats than others, in line with the conservation/ecological requirements. For example, a typical mountain area in the West of Ireland will have wet and dry heaths and blanket bog occurring in mosaic. The condition of the habitat at the outset is also of course a central consideration, whereby a habitat of the same type may require different intensities and duration of grazing, depending on its original condition (sometimes habitats are colloquially referred to as 'overgrazed' or 'undergrazed'). It is intended that habitat use and other data arising from this project will be analysed comprehensively, but it was interesting to note that the virtual fence allowed for detailed management, including concentrating grazing in areas that would otherwise not have been selected, and keeping grazing away from areas that may otherwise have been over-selected. Animals always had access to water and it was interesting to note the importance of this resource and the significant amount of time spent close to standing or moving water, particularly during high temperatures. So too, the utilisation and association with access tracks was noted, and the virtual fence was able to keep animals from concentrating unduly along such tracks.

Figure 7 A heat map generated by the Nofence app, based on GPS data from the collar.

4.2.3 Impact on habitat condition

A primary aim of this project was to examine how virtual fencing could be used in delivering greater environmental outcomes than the management approaches that had been undertaken up to this point. Thanks to the engagement between NPWS, farm planners and the farmers in question, by and large virtual fencing was shown to be a useful tool in this regard, when used as part of an overall package including stock type, timing, ecological considerations and much more.

- Sensitive soils, including peat soils, and wet grassland received less poaching where the animals were kept away from areas prone to poaching
- Coastal grasslands were grazed systematically during winter to clear out rank vegetation and allow floral species to thrive during the summer and autumn
- Wet grasslands were grazed in a measured way, allowing for control in grazing levels and timing
- Large expanses of upland habitats were grazed extensively, with adjustments made to ensure animals were not spending too long in areas that could otherwise have been overgrazed (*e.g*. wet heaths or areas close to access tracks), while grazing was introduced to areas that were of reduced habitat quality due to, for example, the encroachment of bracken or proliferation of *Molinia*

The concept of grazing and nature can often spark debate in relation to what is most appropriate, with polar views sometimes arising. Some would say grazing should be prohibited and that ‘nature’ should take its course. Removing grazing may or may not result in a desired or natural result, depending on what has happened with the land heretofore (*e.g*. invasive species may proliferate). Others would say that the maintenance of a particular habitat or species in favourable conservation status, or the keeping of invasive species in check requires a particular grazing regime. Others might simply consider agricultural output as a sole function of livestock grazing/farming.

From the biodiversity perspective, maintenance or restoration of favourable status for habitats or species of conservation concern, or promotion of species richness, should in most circumstances be the guiding objective. Context is key. For example, bracken can be a valuable habitat in particular contexts and circumstances, but a threat or pressure to natural and semi-natural habitats in other contexts and circumstances. The management objectives of this project were a combination of ecological and agronomical, whereby the ecological objective was to have as much biodiversity and as many habitats in good condition as possible. Using the app and technology, certain areas were targeted for grazing, while others were kept free of grazing. Overall, improvements were noted in terms of habitat condition and biodiversity value.

4.3 Farmers

4.3.1 Farmer time, finances and incorporation into working day

Technology should ultimately exist to make life easier. The farmers involved in the project all felt that the virtual fencing technology helped in this regard. If the virtual fence line needed to be moved, it did not entail a significant amount of time or labour. Something that might previously have taken hours, a day or even days, could now be done in a couple of minutes by adjusting the pasture boundary on the screen of a smart device. This was of particular importance to farmers who had jobs away from the farm and who would have had limited time availability at certain times of the week, particularly in winter when daylight was short.

The overall costs of the system are not cheap, and the overall longevity of the collars and batteries in Ireland remains to be seen, but given the significant rise in costs of fencing materials and manual labour, it does offer an interesting and viable alternative, particularly for areas where a significant amount of fencing may be required. Physical fences can entail a large upfront financial and time investment in construction, but so too in terms of upkeep, especially in remote and mountainous terrain. In certain circumstances, planning permission may be required for physical fencing, costing significant money to get through the planning process. In certain circumstances, it may not be desirable from a nature perspective, to have physical fences erected. The virtual fence negates the need for these issues, providing potential for win-wins for nature and the farmer.

4.3.2 Communication of data to the app

As referenced previously, the devices were set to record and transmit data to the app every 15 minutes. By and large, this worked well and detailed information was provided directly to the app and was also registered and stored on the user's account, so that all data collected during the service of the device could be viewed (the app displayed data/analytics for up to 7 days only). The farmers felt the app gave them 'peace of mind' in relation to knowing where their animals were at regular (15 minute) intervals, 24 hours a day. Clear examples of this included extensive upland areas, which given their remote and difficult nature, would allow for no more than one visit a day, and the offshore island site, where the farmer would need to take a 120 minute round journey (including a ferry), which might not have been possible in adverse weather conditions.

However, in 'blackspots', where mobile network reception was poor, data transmission was intermittent or even non-existent. This did not mean the devices were not functional (the satellites would still know where the devices were and the pre-designed virtual boundary would still be active) but it did result in reduced functionality and user-experience. Another downside in 'blackspots', was that if the pasture was not previously designed (when the app and collars were within mobile reception), it proved very difficult or impossible to design a pasture boundary onsite.

The automated production of heat maps was deemed to be one of the most useful facilities of the Nofence app. This allowed a real time review of where animals had been concentrating and accordingly, allowed adaptive management to ensure certain areas were not over-grazed and that less utilised areas received some level of grazing, where appropriate. This, along with knowledge of the habitats and conditions onsite, will be of significant benefit when used in an informed and adaptive manner as part of efforts to restore environmental conditions on various sites.

4.3.3 Battery life

One of the key considerations in advance of deploying collars, was that of battery life. This is vitally important, as by and large, the sites being grazed were not close to handling facilities, which would allow for the removal of a depleted collar/battery and replacing a new one. In researching the precision livestock management hardware on the market, it was noted that Nofence collars had a solar charging capacity, with two solar panels either side of the device. For summer grazing, solar charging extended battery life to the point that replacements were not required. Generally, solar charging during summer maintained the batteries at an average of 90%. For winter grazing, from fully charged batteries at the outset, the charge was at approximately 50% after a grazing period of six weeks and replacements were required after approximately 8 weeks, before the batteries would reach 25% charge. Batteries were replaced on rotation, asynchronously, by a subset of 'spare' batteries. Batteries that were removed were then recharged and available for replacement on the next set of collars that needed charged batteries. A longer period would be required to determine how efficiently the batteries hold their charge after several years.

4.4 Interesting observations

Through this pilot, it was observed that individual animals, with individual personalities adapted to the virtual fence technology in different ways. Some individuals challenged the virtual fence more than others. Some were not as quick to adapt or 'learn' as others. This is a key consideration; not all animals should be considered the same and virtual fencing may not be appropriate for certain individuals. Lee & Campbell (2021) also highlighted this important point. The word 'learn' has been placed in inverted commas throughout this report, for some animals may well have grasped the concept that an electrical pulse would follow the audio cues, but still not want to yield to that concept, at least in particular situations.

During heatwaves in the summer of 2022, the importance of water, including streams and rivers, lake and water troughs was noted by virtue of GPS heat maps, showing areas where animals frequented. On one of the upland sites, cattle were recorded to visit and stay at the shore of a small lake during daily temperatures of >30°C. The collars were observed to be submerged when the animals lay in the water. This did not interfere with the functionality of the collars. In wet vegetation, and when raining, the collars functioned as they normally would. When asked about operating in such conditions, Nofence stated that pulses are released at a somewhat lower voltage in wet conditions compared to dry conditions, due to resistance.

The ability of animals to sense oncoming bad weather was noted, whereby the day before storms, animals in upland locations all moved down to a lower elevations which were more sheltered. When and where biting midges were prevalent, it was observed that animals frequented parts of the landscape, which were breezier. These observations highlight the importance of providing various environmental features for animals within the grazing pasture, beyond the obvious requirements of food and water.

An individual cow broke into a neighbouring vegetable garden one evening just before dark. The farmer was not in a position to attend, but was able to alert his neighbour to this by virtue of seeing the location on the app and the neighbour was able to remove the cow from the garden.

4.5 Issues

Technical or device issues were encountered with a total of eleven collars. No animal welfare issues resulted from these technical problems, although the potential for animal welfare issues did present in one case and was immediately addressed by the farmer (see below). A common issue arose with six collars. The devices were functioning as virtual fences, but the locational data was not being transmitted to the app. An additional collar both stopped communicating to the app and stopped emitting audio cues. Having removed the collar (when it was apparent the collar stopped communicating with the app), the farmer noticed the audio cue issue before the animal that had been wearing the collar came close to the virtual fence line. With a further two cattle collars, a glitch in connectivity with the telecommunication company that had oversight of the collar software occurred. The same issue had affected hospitals and other institutions in Norway, as well as Nofence. This had the effect of 'non-reporting' collars and the inability to register collars to a new virtual pasture. Following the wider telecommunications glitch, the two collars continued to experience problems and investigations by Nofence engineers determined that the collars needed to be replaced. The animals that had those two collars re-joined the main herd in the meantime and had to be retrained when the replacement collars were fitted. With another two collars, there appeared to have been 'locational drift', but no definite conclusion was drawn as to the specific cause of why the collar was emitting electric pulses, despite the collars (on two different study sites) being inside the pasture boundary and the other collars at the same location not experiencing any such issues. While on one site, the electrical pulses were infrequent, on another site, the pulses were numerous (four to five pulses) within a short space of time (three minutes). As the farmer was onsite and observing, the collar was immediately removed from the animal and not used again. A possible reason for the issue in the latter case may have been that the pasture was re-designed but that the collar had not, at the time, registered the new pasture boundary, due to network coverage.

Where the collars were not communicating locational information to the app, the farmers were unable to determine, using the app, where the individual animals wearing these collars were. The app was either showing that the collar/animal was stationary, providing an erroneous locational point or area where the collar/animal was not providing ‘unknown state’ or ‘missing report’ messages. The collars were not damaged in any way and on investigation, Nofence confirmed that there appeared to be technical issues and replaced the collars.

Where the collar was not emitting an audio cue, this was deemed to be a significant issue because the animal could have come in contact with the virtual fence line and received an electrical pulse, thereby confusing the animal and upsetting what had been ‘learned’ by way of associating the audio cue with the perimeter of the grazing zone.

Where the collars did not allow registration to a new pasture, the animals were effectively free to travel anywhere. They joined with the rest of the original herd from which they were selected. Theoretically, such issues could result in animals accessing unsafe areas, damaging a sensitive habitat, disturbing sensitive species, damaging a valuable crop, accessing roads, and so on.

As any experienced farmer will attest, even physical fences are not infallible, with various factors potentially impacting on them, whether power failure, someone forgetting to close a circuit, shorting, physical breaks, low battery voltage or other issues. There will always be a need to maintain physical inspections of animals under care and there will always be a need to regularly monitor the hardware and technology at use, whether physical or virtual fencing. A possible benefit of the virtual fencing is that errors may become apparent even when the farmer is not onsite, but this is not always the case.

Four other types of issues were recorded, resulting in animals escaping through the virtual fence boundary. In summary, these were:

- collar fit (or fleece/hair thickness)
- collared animals encountering non-collared animals
- bond between animals
- specific circumstances

On four farms, a subset of cattle and sheep were able to move past the virtual fence boundary without apparently receiving any electrical pulse, due to collar fit, whereby there was not sufficient contact between the collar and the animal. Each of the three sheep flocks that were part of the pilot experienced issues, with the sheep being able to move past the virtual fence boundary without apparently receiving any electrical pulse. This was deemed to be due to thick fleeces insulating the animals from any electrical pulse. Even after shearing, there were still some individual sheep that from observations, did not appear to be receiving any electrical pulse as they exited the virtual pasture.

Where collared sheep were on a site where they could mix with non-collared sheep, more than half of the collared sheep would continually escape the virtual fence boundary, to roam with the non-collared sheep. When the non-collared sheep were not present, the collared sheep did not escape the virtual pasture.

A cow that was in oestrus broke through the virtual fence boundary to a bull outside of the pasture. This observation is somewhat contrary to the observation of Lee *et al.* (2008), who reported that bulls could be trained to stay away from cows in oestrus by using electrical stimuli.

Weaning of collared cows and their calves was undertaken on three farms over the period of the project. In two cases, the virtual fence boundary was tested, with electric pulses registered. In one herd, a very protective mother, who would have traditionally broken through physical electric fencing at the time of weaning, breached the virtual fence boundary, while her comrades did not. In another herd, the same was noted, with one mother breaching the boundary and others staying within the boundary. In another herd, the mothers were left in a field for one night afterwards and then moved back to the hill (and virtual fence pasture) with no breakouts.

On one occasion, when collared cattle were transferred from enclosed land to a commonage, the animals were excited by the open range and they galloped through the Nofence boundary, which had inadvertently been placed in a downhill position. This position didn't help, as the running animals gathered downhill momentum, and went through the boundary. This situation was corrected by immediately placing the virtual fence boundary outside the group of cattle. With the exception of one further escape by a single animal, that was the extent of the escapes for the grazing season.

4.6 Farmer reviews and reflections

Three case studies are presented below, submitted by three of the farmers that led on the pilot project.

4.6.1 Case study 1: Upland heath, Co. Tipperary

Our hill farm is located in the Knockmealdown Mountains in South Tipperary. We own a herd of Galloway cattle. This breed is suitable for our extensive grazing system, and the beef produced is marketed as a premium product to the final consumer. We were interested in the use of virtual fencing to enable cattle to graze specific areas of upland commonage hitherto not possible, due to the impracticality of physical fencing in these areas. Our experience of virtual fencing has exceeded our expectations, and has proved to be a game-changer for us as farmers of cattle on upland areas.

In the absence of adequate grazing in certain areas, some vegetative species can have a competitive edge and dominate to the detriment of other species and vegetative biodiversity. Purple moor-grass (*Molinea caerulea*), bracken (*Pteridium aquillinum*), soft rush (*Juncus effusus*), and European gorse (*Ulex europaeus*) are examples of species that can dominate in the absence of targeted grazing.

After determining that areas of leggy, mature heather on our uplands were not of importance for species of conservation concern (*e.g.* roosting/nesting birds), a key objective for a particular area of our uplands was to rejuvenate the dry heath habitat diversity via grazing. NPWS mapped the areas to be grazed and later re-assessed the impact of precision grazing using virtual fencing on these mapped areas. The results after three grazing seasons were very positive, with habitat quality improvements noted across the target plots. The cattle grazed and browsed the area of mature heather and in doing so also trampled the heather, providing a more varied height, structure and density of vegetation as well as more openness required for floral diversity.

Virtual fencing enabled the animals to avail of grazing that was plentiful. A key requirement as part of this pilot was for us, as farmers, to monitor the health and welfare of the cattle. The herd involved in the precision grazing was in good condition and their calves were born within the virtual pasture without any problems. The access to upland grazing not formerly available to these animals enabled them to remain in the pasture for the full grazing season, which would be more natural than housing. Virtual fencing allowed us to move the animals without stressing them, as there was minimal disturbance to their pastures, due to the technological aspect of the fence. The condition of cattle was assessed at regular intervals using the Irish Cattle Breeding Federation (ICBF) scorecard and we were very happy with their condition.

The use of virtual fencing on our cattle grazing our uplands enabled us to utilise forage that was previously not practically accessible. The opportunity to access this natural forage delivered an economic benefit to our direct sales business. The ability to change a fence post on an App on our mobile phone was labour-saving and increased our appreciation of how technology can benefit farming, especially on open mountain, where conventional fencing is not an option. This makes the virtual fence system a game-changer. We would view the use of virtual fencing as positive from a habitats, agricultural ecosystems, and economic perspective, whilst also contributing to European Union (EU) food security. We did experience some teething problems with virtual fencing, but these were outweighed by the benefits, a snapshot of which were mentioned here.

4.6.2 Case study 2: Upland heath and semi-natural grasslands, Co. Leitrim

I am an Agricultural Science teacher and part time cattle and sheep farmer based outside Manorhamilton in North Leitrim in conjunction with my family. The farm is predominantly based on heavy, poorly drained soils which have been semi-improved in part. Much of the farm would be described as having HNV grasslands. Alongside this, the farm also has shares on Benbo commonage which would be mainly wet heath with blanket bog on the upper regions. The farm is organic and is certified by the Organic Trust. The farm is managed extensively, with great emphasis being placed on farming in harmony with the environment and the landscape. Holistic context design is used on the farm to develop strategies of the farming model which aims to make sure that decisions are made with the head, the heart and the pocket all in mind. The main production on the farm comes from weanling calf sales from the continental cross suckler herd and store lambs from the midseason lambing ewe flock. The impact of the wet climate, cow choice and land type leads to an extremely short grazing season, which in turn has a negative effects on profitability and time management. Steps are currently being taken to reduce cow size with an emphasis on introducing Shorthorn, Angus and Speckled Park genetics into the herd with a view to lengthening the time spent on grass.

Alongside these breeds, we also run a small Dexter herd on the farm. Dexters are a native Irish cow approximately 350 kg fully grown, which would be half the size of a continental cow. They are a dual-purpose breed and are excellent grazers from a conservation perspective. It was with these traits in mind that I approached the NPWS with a view to trialling GPS collars on the commonage. I have always felt that the commonage was an underused resource on the farm. Cattle have not been on the mountain in living memory. Reasons for this include access to animal type and return on time invested. The greatest barrier was lack of appropriate fencing. The commonage is approximately 150 ha and animals were free to roam when and where they wished in search of pasture. It was felt GPS collars had the potential ability to overcome this obstacle. Overgrazing with sheep has seen a proliferation of heathers such as ling heather and bell heather on the commonage. I felt that introduction of bovines into such a habitat would check heather growth through both trampling and grazing, improve biodiversity of plants and wildlife allowing other plants to grow due to reduced competition from the heather while also improving production and reducing housing period from a farm profitability standpoint. Over the period of the trial, many positive benefits were noted, along with some notes of caution.

First and foremost, having instant access to identifying where your animals are gives great confidence to the farmer. Alongside this, if the animals do leave their allotted area, you get notified immediately and can react appropriately. Heat maps are generated on a daily basis and these can be used in conjunction with on the ground analysis to determine the effect of grazing on what is an extremely sensitive habitat. To date, all environmental effects have been positive. These effects have been independently assessed by an ecologist as part of the trial. Areas of sphagnum moss have not been damaged while the dominance of heather and *Molinia* have begun to be addressed. The Dexters spend six weeks in June and July on the commonage and come off the mountain in good condition and appear well suited to his habitat at that time of year. I would add a word of caution that it has not all been plain sailing. The age and sex of the animal have shown a marked difference in how they respond to the collars. Coupled with this, and taking into account the size of your herd, I would advise using as large areas as possible when designing your pastures as I would not feel confident in the collars working correctly in small areas. Herd instinct will likely supersede any virtual boundaries provided by the collar. Also, certain animals are by their nature more suitable to adapting or 'learning' than others. To conclude from my own learnings to date, I would feel that through proper training for both farmer and cow, alongside more in-depth research, GPS collars can play an extremely beneficial role in conservation grazing in an Irish context.

4.6.3 Case study 3: Semi-natural grasslands on an off-shore island, Co. Donegal

Toraigh (Tory Island), Co. Donegal is an inhabited offshore island approximately 12 km off-shore. Agricultural activity has largely ceased on the island and cattle grazing had not occurred on Toraigh for approximately 25 years. I introduced five Galloway heifers to selected plots on the island as part of a targeted conservation grazing strategy to improve habitat for the Annex 1 bird species Corncrake (*Crex crex*).

Nofence collars were utilised to help with the remote monitoring of the animals (I do not reside on the island), focus targeted grazing to certain areas (*e.g*. rank grassland) and away from other areas (*e.g*. neighbouring gardens).

In the absence of previous grazing, the grassland were blanketed with a thick mat of dead vegetation, which ultimately limited spring growth and reduced habitat availability for Corncrakes. The combination of cattle breed, engagement with ecologists and the virtual fencing made for an excellent combination for the restoration of grassland habitats on Toraigh.

A marked improvement in the grazed plots was noted, with heavy thatch grazed down, animal hooves having open up fresh ground for plant species, and animal dung provided much-needed nutrient recycling. Several plots were in a stage of regrowth within weeks of the animals having ceased grazing and moved on to new plots.

The animals had already been well introduced to the collars prior to their grazing on the island and no issues were noted during the training phase. It was noted that one of the animals tested the Nofence system significantly more than the other four animals.

The ability to remotely monitor the animals was a considerable help, given I was not resident on the island. It provided insight into animal behaviour within the plots and was of particular use in helping direct grazing to particular areas and away from other areas. I can see use for the collars in different areas of my lands at different times of year (*i.e*. there can be multiple uses beyond the island grazing).

4.6.4 Ratings of the technology by farmers involved in the pilot

The evaluation of the Nofence technology by farmers participating in this pilot are represented here according to average ratings (1-5) and comments including overarching points, positive experiences and negative experiences.

Table 1 Ratings assigned by project farmers in relation to various aspects of their experience using Nofence during the project period (2020-2022). 1 = poor, unsatisfactory; 2 = fair, not very satisfactory; 3 = moderate; 4 = good, satisfactory; 5 = very good, very satisfactory.

Aspect	Average Rating
Reliability of the technology	3.7
Interaction of the animals with the technology	4.4
Usefulness of the technology in managing for environmental outputs	4.3
Usefulness of the technology in managing for agricultural outputs	4.3
Usefulness in managing animals and grazing effort	4.6
Usefulness in knowing where animals were	4.7
Usefulness of information available through the app (*e.g*. notifications re audio, pulses, escapes, *etc*.)	3.9
User-friendly nature (or otherwise) of the technology	4.6

Table 2 Ratings assigned by project farmers in relation to their likelihood of using or recommending Nofence. 1 = very unlikely; 2 = unlikely; 3 = moderate; 4 = likely; 5 = very likely.

Aspect	Average Rating
Continue using the technology	4.6
Seek to get more collars	3.9
Purchase the collars if they were not grant supported	3.0
Purchase the collars if they were grant supported	4.1
Recommend the collars to other liv+estock managers	4.3
Recommend the need for appropriate training and support in relation to the use of the collars and technology	5.0

4.6.5 Individual farmer reflections

While participating farmers kept in regular communication throughout the pilot, some provided summaries as to their experience when completing the ratings above. These are reproduced here to provide further insight for the reader or potential future users.

Farmer 1: “I have been involved in many trials over the years but for me this has the most potential on my farm. Where all cattle in the group have collars, this worked really well and for me is a game-changer in management, from both agricultural and environmental perspectives. The cattle showed no negative effects and after the first hour appeared very content and behaved as if they always had them. The technical device problems experienced with a few of the collars was disappointing, especially when considering the cost. Another point to note was that there can sometimes be slight variations in where you think the perimeter is on the screen versus where it is in reality. On an extensive hill this is not a big issue but it would be important if you were close to a road way for example, it would be important to verify by walking with a collar, as to exactly where the boundary is set."

Farmer 2: "When collared sheep mixed with non-collared sheep then the results were poor, although at least you could identify where the sheep were, which was positive. If you were introducing sheep onto a mountain with no other sheep then I would be very confident of this system working well. If like me you were managing a number of sheep where there are other sheep possibly belonging to other shareholders then it has a limited value."

Farmer 3: "In general all the animals became familiar with the collars fairly quickly. I did have a situation where they opened the latch on the gate and escaped out onto the road but by being alerted through the app, I was able to track their location and go straight to them to return them to the paddock."

Farmer 4: "As a long-term commonage grazier, the technology far exceeded all expectations. The utilisation of undergrazed areas was of huge benefit to us. A positive aspect was that it enabled keeping a herd in an area not traditionally utilised. A negative aspect was the teething problems (device technical problems) associated with a novel technology."

Farmer 5: "Year one (using cows without calves) was very successful in managing the hill. Year two, when using bullocks, it was not as successful as they were much more adventurous. Perhaps the shock may not have been enough to deter crossing the threshold, with the hairy coat of the Dexters. A positive aspect was being able to locate animals on the hills; this gave great confidence in putting them up there in the first place. A negative aspect was the difficulty in using the virtual fencing in small paddocks, where the animals would traditionally have moved between paddocks. I felt I needed to include all paddocks as one pasture, rather than dividing them, so as not to risk any confusion with animals not being able to move as they always would have. Furthermore, I only became aware after using the collars, that the app has an adjustable threshold setting for the number of pulses that must be received by an animal before it registers as a push notification on the app. In effect, on reviewing the data export (containing all information relating to the collars I used), some animals had received more pulses than was originally apparent from the app. I would recommend there needs to be more information and guidance from the supplier and connection with those that have previously used the technology".

Farmer 6: "It worked really well when the collared sheep were isolated in training and for a short period when the group of sheep were on their own on the mountain. Once they encountered other sheep without collars, the collared sheep would break out consistently. A positive aspect was how easy it was to train the sheep and I would predict from my initial experience that where 100% of the sheep in an area had collars then it would be a success from a land management point of view. You always knew where the sheep were which is positive. The fact that when sheep mixed with others on the commonage, we lost the controlling element of the fence for at least 50% of them on a consistent basis. A negative aspect was the when a collar was giving a 'missing' report."

Farmer 7: "Very happy with them, can be a huge addition to land management in an upland situation where targeted grazing is required. Easy to use, great feedback from the data gathered. Peace of mind when you could see where the stock grazed, especially as the cattle I had were 9 miles offshore on an island. I have nothing negative to report on the technology".

Farmer 8: "Very useful technology especially in areas where you cannot easily see animals. Didn't take long for animals to be trained. A positive aspect was being able to locate animals and keep them fenced off from certain areas. A negative aspect was when one collar didn't work/update and gave incorrect messages to an animal. I was disappointed with the manufacturer's support response in relation to this."

Farmer 9: “It's a fantastic stock management tool. Ideal for part-time farming. Fantastic way of managing unfenced extensive grazing sites in an environmentally-friendly way. A positive aspect was knowing where animals were at all times and how they were utilising the grassland. The most difficult aspect was putting on the collar and training the animals, but after that there were no issues.”

5 Discussion

5.1 Strengths, weaknesses, opportunities and threats

The results and observations of the pilot programme have provided very useful insights on the use of Precision Livestock Management using virtual fencing, from the perspective of the animal, the environment, and the farmer/livestock manager. Tables 3, 4 and 5 summarise what have been noted as the strengths, weaknesses, opportunities and threats (SWOT), in relation to these three core considerations. These should be considered primarily in the context in which the pilot programme operated; relatively low stocking, conservation grazing oriented systems on various terrains and habitats in different parts of Ireland.

Table 3 SWOT analysis arising from observations with regard to livestock

Strengths	**Weaknesses**
• For the majority that adapt and 'learn', clear understanding in relation to where they can and cannot access. • Livestock manager can react to any issues more readily than might otherwise be possible without remote knowledge of animal location. • Animals can be kept away from dangerous locations. • The electrical pulse an animal may receive is less than that which may be received from a physical fence.	• Studies have shown virtual fencing technology is not 100% effective at keeping animals within defined boundaries • Any technology is fallible – GPS drift, failure of collars, non-communication with app and unexplained occurrences were all encountered during this pilot. • Disorder may arise where not all animals are collared, particularly where there is an existing bond between collared and uncollared animals of the same flock or herd. The proportion of a flock or herd that will need to carry collars in order to maintain herd/flock integrity and unity is unknown and may vary, but is expected to be high. • Some animals may not adjust to the technology.
Opportunities	**Threats**
• Ability for multiple users to monitor animals • Data and experience provides opportunities to adjust grazing regime to suit animals • Animals 'born into' a system using virtual fencing may adjust more readily to the technology • Experience gained in Ireland and elsewhere can add to training and protocols to ensure animal welfare is to the fore of all considerations	• Livestock managers using the technology without appropriate training. • Livestock managers feeling the technology is a substitute for good stock keeping. • Livestock managers considering all animals have the same characteristics/abilities/personalities. • Collars active on mothers at weaning time • Inappropriately designed virtual pastures. • Technological failure. • Improper care of collars. • Failure to check technology and correlate what the app is showing with what is happening on the ground. • Considering virtual fencing for external boundaries, roads or public areas.

Table 4 SWOT analysis arising from observations with regard to the environment

Strengths	Weaknesses
• Negates the need for physical infrastructure (for the most part, physical fencing was still required at outer boundaries and roads, *etc*.). Physical fencing of posts and wire could impact negatively on habitats by dividing areas in a manner that is not in line with habitat or grazing requirements. They can also lead to increased trafficking (livestock walking) along the inside of the fence or pinch-points, where animals may congregate *e.g*. between 'paddocks', by gates or by water troughs. They can also pose a threat to birds, which may collide with fences or fragment or alter the territories of other animals such as mammals. They can also alter the physical or aesthetic appearance of an area which has traditionally remained open and undivided. Physical fencing can also be very costly and in particular cases, may require planning permission and associated environmental assessments. • The ability to keep animals out of sensitive areas (habitats, waterbodies, nesting areas, *etc*.) and the ability to ensure appropriate grazing in areas that might otherwise have been avoided or over selected. • The ability to adjust grazing in real time, to suit the habitat and the ground conditions or prevailing weather. • The ability to review and correlate grazing patterns with habitat quality, to inform approaches to grazing in future seasons to improve habitat quality.	• Studies have shown virtual fencing technology is not 100% effective at keeping animals within defined boundaries. • Any technology is fallible – GPS drift, failure of collars, non-communication with app and unexplained occurrences were all encountered during this pilot. • Where internet reception is poor, user capabilities will be diminished. • The ecological results of the grazing managed by virtual fencing is as good or as weak as the ecological understanding of the person managing the virtual fencing and the grazing effort.
Opportunities	**Threats**
• Integration of the technology to agri-environmental management plans and schemes (with an accredited training course focussing on appropriate use of the technology and its applications in conservation grazing). • Ready adaption to various environmental challenges; from safeguarding ground-nesting birds to appropriate grazing levels, to safeguarding soils and waterbodies. • A greater understanding of how animals use various sites and the reaction of the receiving environment to that use. • Data collation. • Landscape approaches, including commonage management.	• Livestock managers using the technology without appropriate training or sufficient understanding of environmental objectives. • Livestock managers feeling the technology is a substitute for good stock keeping. • Inappropriately designed virtual pastures. • Technological failure. • Failure to respond to real time changes (*e.g*. ground conditions becoming saturated, shifts in weather, location of nests, *etc*.)

Table 5 SWOT analysis arising from observations with regard to farmers/livestock managers

Strengths	Weaknesses
• Reduction of labour hours and expense in erecting, moving and maintaining fences, often in difficult terrain. • The ability to keep animals away from dangerous areas (*e.g*. bog pools, steep crags, cliffs, *etc.*). It should be noted that virtual fencing should not be treated as an absolute in this regard. • The ability to know the location of animals (at 15 minute intervals), wherever the farmer is. • A safety system (to a degree) where walkers might leave gates open. • The closer consideration and analysis of how the animals use the lands which they have access to. • The ability to direct animals to graze in areas that they may not otherwise have grazed, leading to an increase in the forage area available. Animal welfare should at all times remain a priority and at no time were animals directed to an area where they did not have sufficient quantity and quality of forage. • The ability to improve habitat quality and consequently payments, where active in result-based agri-environmental schemes.	• Studies have shown virtual fencing technology is not 100% effective at keeping animals within defined boundaries. • Any technology is fallible – GPS drift, failure of collars, non-communication with app and unexplained occurrences were all encountered during this pilot. • Where internet reception is poor, user capabilities will be diminished. • The proportion of a flock or herd that will need to carry collars in order to maintain herd/flock integrity and unity is unknown and may vary, but is expected to be high. • Cost of procuring collars and paying for subscription. • Animal locations are recorded every 15 minutes and should not be taken as equivalent to real time.
Opportunities	**Threats**
• A grant scheme to support the wider uptake of this technology. • An accredited training course focussing on appropriate use of the technology and its applications in conservation grazing • Data collation. • Landscape approaches, including commonage management. • Experience and knowledge exchange between those utilising the technology.	• Livestock managers using the technology without appropriate training. • Livestock managers feeling the technology is a substitute for good stock keeping. • Livestock managers considering all animals have the same characteristics/abilities/personalities. • Inappropriately designed virtual pastures. • Technological failure. • Improper care of collars. • Failure to check technology and correlate what the app is showing with what is happening on the ground. • Considering virtual fencing for external boundaries, roads or public areas.

5.2 Recommendations and other considerations

As with any new tool or technology or method, training is an integral part of understanding how best to utilise and get maximum benefit from the new approach and in this case, to ensure animal welfare and environmental obligations are to the fore in the use of Precision Livestock Management. Online training workshops were provided to the farmers partaking in this pilot project. These were informative and useful in terms of understanding the concept and the functionality of the collars and the technology. The support network provided by the collective project team proved invaluable in terms of the real-life application of the collars and technology. The experience gained by the first two farmers was immensely important in helping the remaining farmers fit the collars, train their animals, set up pastures, and troubleshoot any issues. Mentoring and advice in the form of physical meetings, farm visits and phone calls from the first two and more experienced farmers could not have been more highly valued, in terms of smoothly upscaling the roll out of the project across various farms. It should also be considered that not everybody is tech savvy and assistance in this regard is required in a subset of cases.

Should the technology be rolled out nationally as part of any future grant scheme(s), it is strongly recommended that applicant farmers are approved for such funding only if they:

- Attend and pass an accredited training course, which covers all relevant aspects of the collars and their application in the field
- Have an identified and approved mentor, who is able to provide effective advice in an efficient manner
- Agree to supply data arising from the collars to the funding body

It is also recommended that the concept and practice of virtual fencing be integrated into relevant farming discussion groups/Knowledge Exchange Groups.

Understanding of the technology is one element. Understanding of the animals is another fundamental element. The matters of herd bond and flock bond and social/family structures are important considerations in planning an approach to each individual use case. If non-collared animals have access to the same area where the virtual pasture is, as well as its surrounds, it appears to be necessary to break the herd bond (for a prolonged period, perhaps months) to reduce the incidence of collared cows or sheep wanting to join the non-collared animals, particularly where non-collared animals outnumber collared animals. Essentially, this would involve treating a herd as two herds, collared and non-collared, where the herds will ‘run’ separately. Even then, there is no guarantee that the natural instinct to herd or flock together will not override the ‘learnings’ of the individuals or group in relation to the virtual fence line and its audio cues. Individual/family/sex/age group bonds are all to be considered, as well as the land and topography and natural or physical barriers/fences that may exist to augment the virtual fence line. Individual farmers would know which animals would be most suited to combine as part of a single social unit (together in the collared herd or the non-collared herd). A separate question arises, where a farmer may have one bull or one ram but more than one social unit. Again, the solution will need to be considered and delivered by the individual farmer to suit their needs and the needs of the animals.

There is likely a threshold of percent of herd collared, which may be different for each use case, below which the system may not function entirely. The scenario factors may include terrain, size of pasture, forage quality and quantity available, temperament of animals, bond between individuals (*e.g*. mother and calf), *etc*. The required ratio of collared to non-collared animals (and other associated factors) merits further research, to provide greater clarity for farmers ahead of purchasing and using virtual fence collars.

Weaning of calves from mothers can be a stressful time for the animals. It is recommended that appropriate steps are taken at this time in any case, but that virtual fence collars should not be active on the animals involved.

Some of the farmers noted that removing the battery from the collar device was relatively difficult. The spring-loaded battery latch needs to be squeezed with the thumb and forefinger with pressure. One of the project farmers innovated a tool to provide extra leverage to do this, making battery removal easier.

A potential consideration highlighted by one of the farmers was that there could be a risk of a cow scratching on a paling post and becoming stuck by virtue of the collar chain/strap surrounding the post. This was not observed, but nonetheless is an important consideration for those looking to use virtual fence collars. There would be merit in considering a collar design that would allow for drop off, should the collar become snagged.

It is imperative that those with the responsibility of caring for the animals keep close observations on the animals in any case, but particularly when they are wearing collars that can deliver an electrical pulse. Such observations should be undertaken visually (in person), via the app and via the account data export function on the Nofence web portal to ensure the animal is in good condition and to ensure what is observed in person is aligned with what is registered by the app and by the data download.

Where new animals are entered into the herd and intended to be fitted with virtual fence collars, they need to be trained in the same way as the others, rather than introducing them without any training and assurance that they have adapted well to the technology.

6 Conclusion

This pilot, the first of its kind in Ireland and one of the very first in North Western Europe, has proven successful in exploring the strengths, weaknesses, opportunities and threats of virtual fencing in the contexts of (i) animal experience (ii) environmental management and (iii) farmer experience. There is no doubt that when used correctly and working correctly, it can be a valuable tool for conservation grazing, it can support farmers in various ways and add to the safety and welfare of animals. The opportunities are as vast as the combined knowledge of farmers who have farmed their lands for generations and ecologists who can identify where on the road to 'ideal' a habitat or landscape is. For example, considering Ireland's uplands, which have been the subject of considerable change in terms of society and nature, there are opportunities to re-imagine the management of these precious lands, which hold over 40% of the Special Area of Conservation network and 14 Annex I habitat types, provide the source for our waterways and are home to some of Ireland's richest cultural heritage. Where sheep have recently dominated, there are opportunities to re-introduce cattle for more holistic management and this technology can offer more comfort and security for those interested in doing so. Where grazing has been lost, it can be re-introduced and where grazing pressure should be reduced or excluded, this can be facilitated by the technology.

However, the technology is not without risk. It should be considered as an additional tool, only to be used in the correct circumstances and in the correct way. As with various tools and technologies, training is deemed necessary. Any technology can be prone to technical issues, either one-off issues, periodic issues or issues leading to redundancy. While virtual fencing allows livestock to be checked more regularly and remotely, it is not a substitute for checking animals up close to see how they are.

It is recommended, following this national pilot on virtual fencing that the technology is worth advocating and supporting in the context of conservation grazing with low stocking rates. It is also advised that any livestock manager looking to utilise the technology should have to undertake an accredited training course, to ensure appropriate understanding, management and care of the technology, particularly as it relates to animal welfare. Should grant funding be provided for this fencing technology, as is presently the case for physical fencing, it would be very beneficial to have a data sharing agreement as part of the grant funding. The data arising from the technology at a large scale would be immensely valuable in understanding and improving the grazing impact on various environmental receptors including habitats, wildlife, water and soil. Indeed, it may be necessary from an animal welfare point of view, to enable oversight on whether any issues are arising for individual or collective animals. A pilot offered the opportunity to intimately engage with participating farmers, but if scaled up to hundreds or thousands of farmers, the risks of poor practice or individual technical difficulties could be significant. It would also be worth facilitating Knowledge Exchange Groups focussing on conservation grazing, including the use of virtual fencing, to discuss the various applications and objectives as well as the associated strengths, weaknesses, opportunities and threats.

Precision Livestock Management, including virtual fencing, is only ever likely to be part of a wider equation that considers the environment, the animals and the farmers. For any conservation efforts, a holistic approach must always be considered, and this will include matters beyond grazing (or exclusion of grazing). If Precision Livestock Management is to be part of this, it needs to be a comfortable fit with other efforts (including various conservation management techniques), the wider workings of the farm or estate available to the grazing animals and the timing of grazing. Paradoxically, the ultimate in the delivery of conservation grazing using Precision Livestock Management may in fact be to achieve a balance that is as close to nature as possible, whereby the animals can replicate what they might do in nature without human influence. There are obviously a large number of considerations for this to be achievable, if even on a handful of farms or estates.

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Appendix 1 Salient points noted from a scoping review undertaken prior to the initiation of this pilot in relation to the availability, efficacy and animal welfare of Virtual Fencing

The concept of virtual fencing for animals appears to have originated with Peck (1973), who patented a system for dogs and cats. This, along with various adaptations since, including for livestock, have been based on a perimeter wire in or on the ground (Fay *et al.*, 1989; Brose, 1990; Aine, 1992: Rose 1994 and 1996; Quigley, 1995). Marsh (1999) patented the first wireless system based on GPS-technology. In reviewing current technologies, NPWS identified four commercially available Virtual Fence collar systems; these systems operate in conjunction with beef cattle in Australia/New Zealand (eShepard of Agersens) and in the USA (Vence), while the 'Halter NZ' system is used with dairy cows and the Nofence system (Norway) was used with goats initially, and now with cattle as well. The Nofence system was chosen for this pilot.

Virtual fencing has been identified as a potential game changer in relation to livestock (cattle and sheep) farming (Umstatter *et al.*, 2011; Anderson *et al.*, 2014) for various agronomic interests, but so too environmental interests (Campbell *et al.*, 2019a,b; Campbell *et al.*, 2020; Jachowski *et al.*, 2014).

Campbell *et al.* (2020) showed virtual fencing to be 99.8% effective (highlighting that it was not 100% effective) at preventing cattle accessing a sapling regeneration area. Campbell *et al.* (2017) dealing with cattle and Marini *et al.* (2018) dealing with sheep, reported that when the virtual fence location was moved, both cattle and sheep entered the new pasture area within hours, demonstrating that they 'learn' to respond to the audio cue and not the location that cues are given.

Schalke *et al.* (2007) indicated that animals which were able to clearly associate an electric stimulus with their action, and consequently able to predict and control the stressor, did not show considerable or persistent stress indicators. Lee *et al.* (2008a, b): indicated that low-level electric pulses resulted in stress response of cattle being minimal. Umstatter (2011) and Rutter (2014) outlined the animal welfare benefits of systems *e.g*. virtual fences for livestock, *etc*. McSweeney *et al.* (2020) observed some negative behavioural changes (reduced grazing and ruminating times) with dairy cows in an intensive grazing scenario, whereas Umstatter *et al.* (2015) at a less intensive stocking rate found no changes in general activity or lying behavior associated with virtual fencing and found that the animals had 'learned' or adapted to the virtual fencing. Brunberg *et al.* (2017) worked with Virtual Fences on sheep in Norway and showed the importance of the system working properly to enable the animal to 'learn' the system properly. Campbell *et al.* (2019) concluded that with virtual fencing technology most animal interactions occur on the first day, that there were no extreme reactions during the training phase and that individual animals experienced an average of 2.5 (range 1–6) audio cue/electrical pulse combinations while 'learning' the system. VRM *et al.* (2017) who undertook a review on behalf of the Norwegian government, was instrumental in enabling Nofence (from Norway) to sell their products (goat collars initially, and then cattle collars) within Norway and subsequently internationally. Eftang & Bøe (2019), in a study specific to the Nofence devices concluded that the devices worked well, without any obvious effects on the animals, who adapted relatively quickly to the warning signals.

Personal Communications with Dr. Tony Waterhouse of Scottish Rural Upland College identified that "some stress indicators are observed on pairings of sound and pulse initially, but then a significant shift is observed after a day or so, to the use of the audio cue only".

The ability of each individual to 'learn' the system is an important factor to reduce stress. Lee *et al.* (2009) looked at cattle's associative 'learning ability' to virtual fences when hearing a neutral audio cue before the aversive electric stimuli. They found a higher percentage of correct avoiding behaviours (turning, backing up or stopping), as a response to the audio cue the more session's animals took part in, suggesting the ability to adapt or 'learn'.

Appendix 2 Technical specifications of the Cattle and Sheep/Goat Collars

Cattle Collar

Electrical Specification
Input voltage: 3.4 V – 4.2 V
Power consumption: 500 uA to 1.5 A
Audio warning level: 82 dB @1 m
Solar charging max peak power: 2291 mW

Communication interface
Bluetooth
LTE Cat-M1 and 2G
GNSS Receiver - Glonass and GPS

Environmental
Ingress Protection: IP67 (@ 0.25 m depth in 0.5 hrs)
Temperature range: -25 to +65℃ (Operating and storage)

Physical
Dimension (box): 153.5 x 145.4 x 54.2 mm
Weight collar unit 858 g
Weight battery 450 g
Weight neck strap 138 g
Total weight, carried by animal: 1446 g

Sheep and Goat Collar

Electrical Specification
Input voltage: 3.4 V – 4.2 V
Power consumption: 500 uA to 1.5 A
Audio warning level: 82 dB @1 m
Solar charging max peak power: 1385.3 mW

Communication interface
Bluetooth
LTE Cat-M1 and 2G
GNSS Receiver - Glonass and GPS

Environmental
Ingress Protection: IP67 (@ 0.25 m depth in 0.5 hrs)
Temperature range: -25 to +65℃ (Operating and storage)

Physical
Dimension (box): 84.8 x 90.5 x 109.0 mm
Weight collar unit 292 g
Weight battery 192 g
Weight neck strap 21 g
Total weight, carried by animal: 505 g

Appendix 3 Description of sites where the pilot was undertaken

Site	Location	County	Habitat	Terrain	Designated Site(s)	Nature Interests	Commonage	Private Land	Project Participants (Individual Herd Numbers)	Area (Ha)	Cattle	Sheep
1	Knockmealdown Mountains	Waterford	Upland Peats	Undulating, 200 m-486 m	c. 2 km from Lower River Suir SAC (002137)	Peatlands, Invertebrates, Birds, Water	Yes	Yes	1	945.92	5	0
2	Benbo Mountain	Leitrim	Upland Peats	NE Slope, 150 m-300 m	<1 km from Lough Gill SAC (001976)	Peatlands, Invertebrates, Birds, Water	Yes	Yes	3	39	15	0
3	Aroo Mountain	Leitrim	Upland Peats	NE Slope, 150 m-300 m	Aroo Mountain SAC (001403)	Peatlands, Invertebrates, Birds, Water	No	Yes	1	51.16	5	0
4	Kilmuckridge	Wexford	Coastal Grasslands	Coastal, Low Lying, sandhills and slacks	Kilmuckridge-Tinnaberna Sandhills SAC (001741)	Fixed Dunes, Invertebrates, Birds	No	Yes	1	21	6	0
5	Kilmichael	Wexford	Coastal Grasslands, Wet Grassland	Coastal, Low Lying, sandhills and slacks	Kilpatrick Sandhills SAC (001742)	Fixed Dunes, Species Rich Grassland, Invertebrates, Birds	No	Yes	1	32	6	0

6	Tory Island	Donegal	Semi-natural grassland	Coastal, Low Lying	Tory Island SPA (004073)	Corncrake, Grassland	No	Yes	1	8.95	5	0
7	Connemara	Galway	Upland Peats	Undulating, 60 m-360 m	Connemara Bog Complex SPA (004181) and SAC (002043)	Peatlands, Invertebrates, Birds, Water	Yes	No	1	960	10	40
8	Connemara	Galway	Upland Peats	Undulating, 60 m-360 m	Connemara Bog Complex SPA (004181) and SAC (002043)	Peatlands, Invertebrates, Birds, Water	Yes	No	1	2482	6	0
9	Ox Mountains	Sligo	Upland Peats	Undulating, 200 m-380 m	Lough Hoe Bog SAC (000633)	Peatlands, Invertebrates, Birds, Water	Yes	No	2	240	16	31
10	Bluestack Mountains	Donegal	Upland Peats	Undulating, 200 m-570 m	c. 1 km from Owendoo And Cloghervaddy Bogs SAC (2046) and Lough Eske and Ardnamona Wood SAC (000163)	Peatlands, Invertebrates, Birds, Water	Yes	No	2	2307.31	15	0
11	Bluestack Mountains	Donegal	Upland Peats	Undulating, 200 m-640 m	c. 1 km from Lough Nillan Bog (Carrickatlieve) SAC (000165) and River Finn SAC (002301) and Meenaguse Scragh SAC (001880). C. 3 km from Lough Nillan	Peatlands, Invertebrates, Birds, Water	No	Yes	1	23	12	0

12	Killarga	Leitrim	Wet Grassland	Undulating 80 m-100 m	N/A	Grassland, Invertebrates, Birds, Water	No	Yes	1	23	6	0

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