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An Economic and Environmental Analysis of Virtual Fencing for Precision Grazing

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ABSTRACT

The UK grazing livestock sector is challenged by declining farm profitability and stringent environmental policy. Innovative technologies such as virtual fencing could enable a balanced economic and environmental performance of beef production. Virtual fencing is a livestock management tool relying on invisible boundaries perceived as auditory, electrical, or vibrational cues emitted by devices worn by grazing animals. This analysis compares virtual and conventional fencing from an economic and environmental perspective using a multi-objective linear programming model. Optimal livestock management scenarios are identified for two typical UK cattle grazing systems. In intensive lowland beef finishing, virtual fencing achieves the lowest economic performance and a beef carbon emission intensity comparable to electric fencing. In an extensive upland suckler cow system, virtual fencing enables ecological conservation and reduces beef carbon emission intensity but increases labour input compared to set stocking. This *ex-ante* assessment illustrates how precision grazing technologies can be simultaneously evaluated against economic and environmental objectives. The results indicate that, under current cost structures, virtual fencing is unlikely to be competitive with electric fencing in intensive lowland beef finishing systems, where it delivers similar environmental outcomes at higher cost. In contrast, in upland suckler cow systems, virtual fencing can support habitat protection and reduce beef carbon emission intensity but remains constrained by capital and labour costs. These findings suggest that virtual fencing is unlikely to be widely adopted on purely commercial grounds but could play a targeted role in the delivery of publicly subsidised conservation programmes such as the UK's Environmental Land Management schemes.

JEL Classification: C6, Q16, Q56

1 | Introduction

The beef sector in developed economies is locked into a context of declining farm profitability and stricter environmental compliance requirements. These challenges are exacerbated by increasing input prices (Jackson 2025), coupled with greater consumer attention to animal welfare and a growing preference for grass-fed beef (Behrendt and Weeks 2019). While cattle grazing has a positive influence on the nutritional profile of beef (Golinski et al. 2023) and promotes animals' health and welfare (Musinska et al. 2025), it may also have a negative impact on

grassland ecosystems due to land use change, overgrazing and climate-related risks (Harland et al. 2025). Consequently, complex trade-offs among economic and environmental outcomes in grass-fed beef production and how these are affected by technological innovations such as virtual fencing (VF) are becoming an important research topic.

Traditionally, grazing farms have been managed through set stocking (SS) practices whereby livestock have continuous and uncontrolled access to a specific unit of land (Allen et al. 2011). On the other hand, different forms of rotational

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stocking alternating grazing and rest periods among three or more paddocks can be employed with the aid of movable fences to achieve greater control over animal distribution in time and space (Allen et al. 2011). Compared to rotational stocking, SS involves lower infrastructure and labour input, minor investment risk and reduced management complexity (Gillespie et al. 2008; Whitt and Wallander 2022). However, the persistence of grazing animals on the same area may result in suppressed plant growth, overgrazing, soil compaction, sediment and nutrient loss as well as livestock productivity decline (Department for Environment, Food, and Rural Affairs (Defra) 2022; Vandermark 2023). Conversely, rotational stocking requires additional labour and infrastructure but allows for higher grazing efficiency. The latter may bring about benefits such as improved forage and soil quality, higher pasture biomass and ground cover, reduced supplementary feeding, lower enteric methane emissions and greater livestock productivity (Fajardo et al. 2025; Higgins et al. 2019; Golinski et al. 2023; Marchegiani et al. 2025; Musinska et al. 2025).

The adoption of innovative fencing technology could enable graziers to tap into the benefits of rotational stocking while avoiding its economic drawbacks. Originated in the US in the 1980s, VF is a livestock management tool relying on invisible boundary zones perceived as auditory, electrical or vibrational cues emitted by devices worn by grazing animals (Golinski et al. 2023; Hoag, Reuter, et al. 2024). The current virtual fence technology is digitally created on a mobile application in real-time using Global Navigation Satellite Systems (GNSS) (Figure 1). After initial training, animals learn to respond to the cues emitted by VF devices and stay within the designated grazing area (Harland et al. 2025; O'Donoghue 2022). Animal distribution during grazing and interactions with the virtual fences are recorded to aid farmers' decision-making for precise pasture management and improved animal traceability and welfare (Harland et al. 2025). O'Donoghue (2022) estimated that at least 40,000 VF devices are in use globally on more than 3000 farms. Established VF manufacturers include Agrifence, Corral Technologies, Gallagher, Halter, Monil, Nofence and Vence (Golinski et al. 2023; Harland et al. 2025; Musinska et al. 2025).

The experience of early users of VF technology has been increasingly documented in the scientific literature, highlighting a range

of potential drivers and barriers to its adoption (Table 1). Among its advantages, VF technology has been frequently described as reducing labour time and costs associated with installation and maintenance of physical fences as well as being particularly useful for excluding animals from environmentally sensitive or risky areas (Campbell et al. 2020; Hoag, Reuter, et al. 2024; Hoag, Vorster, et al. 2024; Schillings et al. 2024; Silber et al. 2025). On the other hand, animal training requirements, high technology costs, frequent animal escapes and GNSS connectivity issues are significant obstacles for its adoption (de Avila et al. 2025; Hoag, Vorster, et al. 2024; Kiefer et al. 2025). Despite some optimism arising from early use of this technology, trade-offs between drivers and barriers of VF adoption make it difficult to evaluate its net economic and environmental impacts on grass-fed beef production. Therefore, this study provides an example of how the multiple impacts of technology choice in precision livestock grazing can be evaluated under current agricultural policy in the absence of comprehensive primary data.

Although several studies have suggested that VF may reduce the trade-offs between economic and environmental objectives of livestock production (e.g., Hoag, Reuter, et al. 2024; Hoag, Vorster, et al. 2024; Schillings et al. 2024; Silber et al. 2025), such trade-offs have not been previously analysed through rigorous multidisciplinary approaches. Building on the outcomes of previous research, this study hypothesises that use of current VF technology reduces the trade-off between economic and environmental goals in two typical UK beef systems. The two UK beef systems considered are a lowland intensive beef finishing (LBF) enterprise located in the UK West Midlands and an upland extensive suckler cow (USC) enterprise adapted to Welsh conditions. The economic and environmental performance of VF is used to simulate farmer decision-making when choosing between conventional or innovative fencing strategies. Rotational stocking managed with VF (RS-VF) is compared with SS on both farms and with rotational stocking managed with electric fencing (RS-EF) on the LBF farm. The set of environmental goals analysed includes beef carbon emission intensity (CEI) and pasture biomass as a proxy for grassland health. Additionally, the USC system is assumed to enable ecological conservation by excluding grazing cattle from sensitive areas with the aid of VF. These indicators are selected because they are easily quantifiable, but they are not exhaustive.

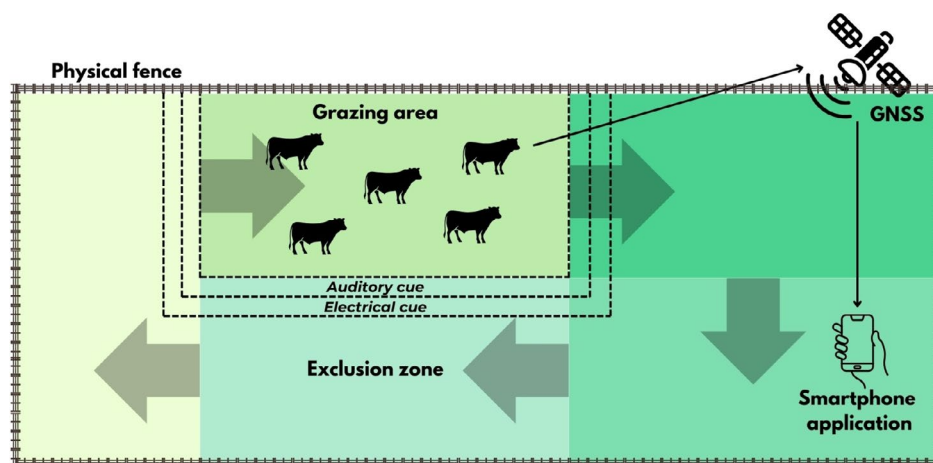


FIGURE 1 | A visual representation of a typical virtual fencing system. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

TABLE 1 | Drivers and barriers of virtual fencing adoption.

Drivers	Barriers
Lower labour costs associated with animal rotations and fence maintenance ^{a,b,c,d}	High technology costs ^{g,l}
Lower infrastructure and fence maintenance costs ^{a,b,c,d,e}	Issues related to GNSS connection (e.g., interference in woodland or GNSS drift in remote areas), collar damage and collar loss in the environment ^{t,b,c,g,h,m,o}
Promotion of rotational stocking practices on leased land by removing the need to install fencing infrastructure ^f	Animal escapes make it impossible to use virtual fencing for ownership boundaries. Therefore, physical fences are often still required ^{b,g}
Simplified grazing of cover crops, crop residue or failed crops on mixed farms ^g	Fitting virtual fencing devices correctly can be cumbersome and time-consuming ^b
Opportunities for participating in ecosystem service markets ^a	Young animals cannot wear virtual fencing devices. This stresses mothers when young animals walk through virtual fences ^b
Natural landscape not disrupted and movement of wildlife species unaffected ^{a,b,g,h,i}	Public acceptance issues (e.g., biosecurity issues if passers-by not separated from livestock) ^{c,d,h}
Exclusion of animals from environmentally sensitive areas where installing physical fences is difficult, not feasible or forbidden ^{a,b,d,g,h,j,k,l,m,n}	Animals managed remotely may become unfamiliar with humans and stressed when handled for reasons requiring human contact ^c
More labour flexibility and convenience, particularly in montane areas ^{a,b,c}	Virtual fencing does not prevent animals belonging to other farmers from entering pasture ^p
Exclusion of animals from areas of cultural heritage importance (e.g., archaeological sites) ^h	Requires learning by farmers and training of animals ^{g,p}
Exclusion of animals from risky areas (e.g., high parasite burden, areas with poisonous plants, areas near bodies of water, cliffs) where installing physical fences is difficult, not feasible or forbidden ^{c,g,h,j}	Electrical cues may be ineffective on sheep in full wool or very hairy cattle ^h
Easy identification of escaped animals or animals requiring visual inspection ^{g,h}	Some individual animals may never learn to adapt to virtual fences (e.g., animal temperament or deaf animals) ^{g,h}

Source: ^aHoag, Reuter, et al. (2024); ^bHoag, Vorster, et al. (2024); ^cSchillings et al. (2024); ^dWatzold et al. (2024); ^eHarland et al. (2025); ^fEhlert (2023); ^gde Avila et al. (2025); ^hDefra (2022); ⁱGolinski et al. (2023); ^jMarchegiani et al. (2025); ^kMusinska et al. (2025); ^lKiefer et al. (2025); ^mSilber et al. (2025); ⁿOuzman et al. (2026); ^oO'Donoghue (2022); ^pNijhuis (2023).

The UK is chosen as a case study for two main reasons. Firstly, it represents a unique example of a livestock grazing sector afflicted by declining farm profitability and increasingly environmentally orientated agricultural policy frameworks. Mean farm business income for UK livestock grazing farms is currently negative and in decline (Defra 2025). Consequently, these farms have increasingly been supported by public funding and diversification activities (Defra 2025). However, with the introduction of the Environmental Land Management schemes (ELMS) (Defra 2024), farmers are now expected to reduce their environmental footprint and accelerate delivery of ecosystem services to maintain access to public funding. Secondly, UK upland extensive grazing systems provide an example where VF might be an economically feasible option to introduce or continue cattle grazing on unenclosed land. Indeed, these systems are often subject to common land regulation restricting the installation of physical fences to preserve free movement of wildlife and the rural public (UK Government 2006). This shared resource regime allows holders of grazing rights to introduce animals in the common for a certain part of the year. Commoners are also exempt from the requirement to construct fences along the outer border of the common by Section 155 of the Highways Act 1980,

which makes it an offence if livestock enter public roads, but not when public roads pass over a common or otherwise unenclosed ground (UK Government 1980). The absence of physical fences on common land makes it difficult to achieve the required precision to promote ecological conservation through lower stocking rates and/or protection of marginal areas from grazing animals, which are currently encouraged by ELMS such as the Countryside Stewardship scheme (CS) and the Sustainable Farming Incentive (SFI) (Defra 2020). Therefore, VF could constitute an opportunity to enable publicly subsidised conservation grazing in the UK uplands.

2 | Materials and Methods

2.1 | Modelling Procedure

The methodology employed in this study consists of a three-phase procedure (Figure 2). Firstly, initial data were collected from peer-reviewed and grey literature. Secondly, an animal and grassland biology model and an online platform were used to estimate livestock productivity, grassland performance and beef

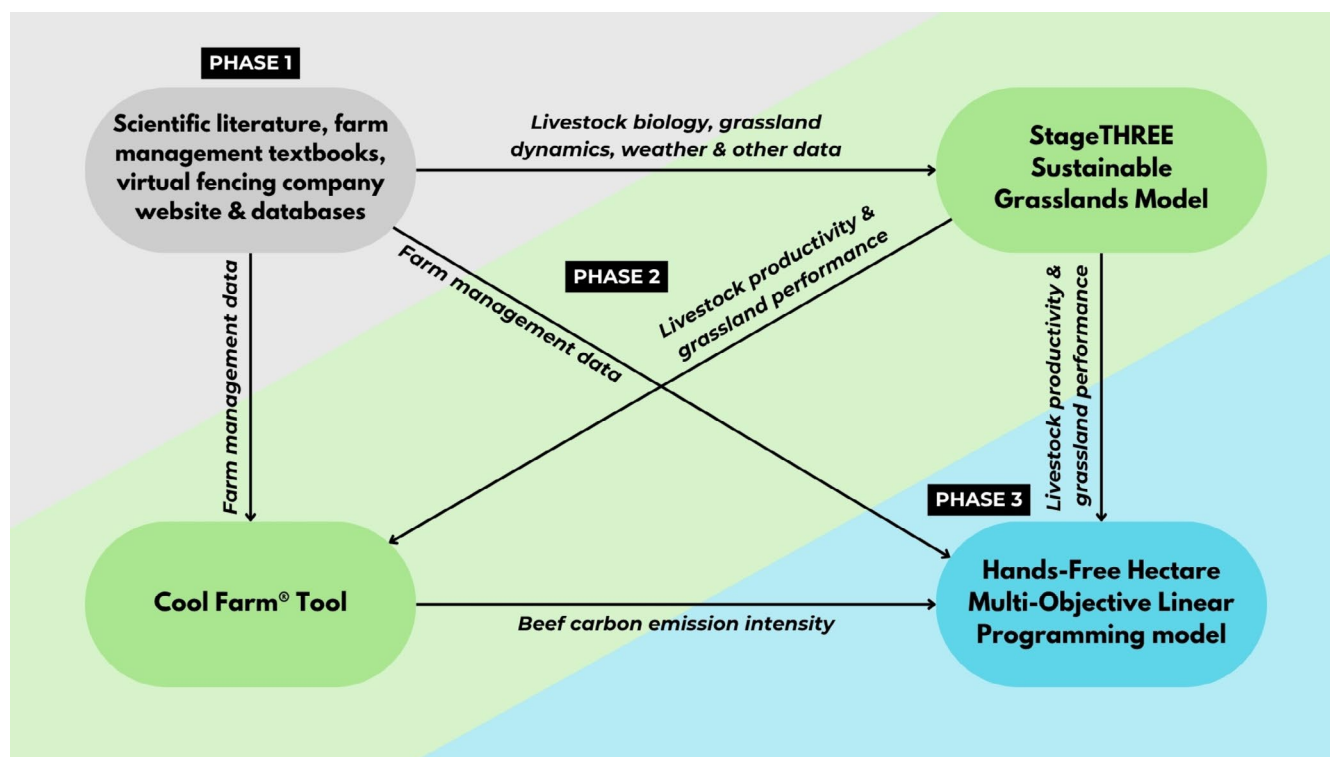


FIGURE 2 | A conceptual outline of the three-phase modelling procedure used in this study. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

TABLE 2 | Costs and lifespan of virtual, woven-wire and electric fences.

Fence type (component)	Cost	Lifespan
Virtual fence (collar)	£ 295 each	6year
Virtual fence (collar subscription)	£ 28 year ⁻¹ each	—
Virtual fence (replacement battery)	£ 80 each	6year
Virtual fence (battery charger)	£ 80 each	6year
Woven-wire permanent fence	£ 6.75 m ⁻¹ (Agro Business Consultants (ABC) 2023)	30year (Turner et al. 2011)
Electric fence	£ 6.75 m ⁻¹ (ABC 2023)	20year (Windh et al. 2019)

CEI. Lastly, a multi-objective decision-making tool incorporating data collected and generated during the first two phases quantified the economic and environmental performance of VF in comparison with conventional fencing. These outputs were used to simulate farmer decision-making when prioritising different goals while choosing among the tested fencing strategies. This methodological approach provides a robust basis for holistic *ex-ante* technology adoption assessments in the absence of publicly available commercial data. The employed multi-objective model was able to identify optimal whole-farm plans while incorporating realistic animal and plant biology parameters. Unlike partial budgeting or most process-based simulation models, these whole-farm plans were also able to optimise for resource competition (e.g., labour) among multiple field operations. Moreover, simulating farmer decision-making through multi-criteria analysis provides an early indication of farmers' willingness to adopt and adapt to technology innovations and their capability to accept new environmental policies before

farmers have enough experience with the technology to credibly respond to surveys (e.g., Behrendt, Takahashi, et al. 2020; Pham-Kieu et al. 2024).

2.2 | Initial Data Collection

The VF system modelled in this analysis is commercialised under the brand Nofence (Nofence 2025). This specific VF product was selected because Nofence is the major VF provider in the UK. Data related to the Nofence technology, including functionalities, costs, operational practice and real-world performance data, were collected through the company's website (Nofence 2025) and personal communication with the Nofence technical and sales teams. Costs and lifespan for VF system components and conventional fencing types are shown in Table 2. The VF device used in the Nofence system is a collar worn by the animal and linked to a mobile application requiring the payment

of an annual subscription. Physical fences are not applicable to the USC farm due to common land regulation restricting the installation of physical fences (UK Government 2006). Besides, electric fences on upland farms may be impractical due to frequent maintenance and inspection requirements as well as electric flow interference from tall vegetation (de Avila et al. 2025). Farm fixed costs and expenses related to livestock, labour, reseeded lowland grassland operations and energy consumption are provided in Table S1. The assumed grassland areas are 43 ha for the LBF farm and 96 ha for the USC farm. These areas respectively coincide with the mean farm size of lowland and less favoured area grazing livestock farms in England (Defra 2025). Beef sale prices are £2.40 kg liveweight⁻¹ on the LBF farm and £2.45 kg liveweight⁻¹ on the USC farm (Redman 2023).

The intensive LBF system is a spring-autumn trading enterprise, while the extensive USC system is a self-replacing herd producing weaners for autumn sale. On the LBF farm, the stocking period spans from March 1st to between November 11th and December 1st depending on how quickly animals reach their target sale weight. On the USC farm, the stocking period spans from April 1st to October 31st based on a fixed calendar. Livestock are housed in a barn from November 1st to March 31st on the USC farm while no winter housing is practiced on the LBF farm. The USC farm assumes a shorter stocking period due to less favourable weather conditions in the UK uplands and to ensure a sufficiently long winter closure period to receive the 'CUP12: Shepherding livestock on moorland (remove stock for a minimum of 4 months)' (£ 43 ha⁻¹) and the 'CUP3: General moorland management' (£ 55 ha⁻¹) subsidies under the CS scheme (UK Government 2015a, 2015b). A third payment received by the USC farm is the 'CIGL1: Take grassland field corners or blocks out of management' SFI option (£ 333 ha⁻¹) (UK Government 2015c). The first two subsidies are paid for the entire land on the USC farm, while the latter only applies to land taken out of grazing in the USC-RS-VF scenario. The land excluded from grazing in the USC-RS-VF scenario is assumed to be 5% of the available land. This was considered a reasonable baseline value because the CIGL1 SFI option is a limited area action involving several small, protected areas distributed as evenly as possible across the land to provide wildlife shelters (UK Government 2015c). Increasing this value would result in greater management complexity and more frequent animal interaction with the virtual boundary zones, which may lead to lower VF system effectiveness and additional collar battery recharges. To explore the influence of this assumption on model results, the effect of excluding larger areas from cattle grazing is explored via sensitivity testing.

Livestock operations are assumed to be managed by a farm operator supported by casual labour during peak times. The imputed cost of farm operator labour is pro-rated at £ 76,866 year⁻¹, including 20% additional compensation for marketing and management (Lowenberg-DeBoer et al. 2021; Redman 2023). Casual labour costs £ 98 day⁻¹ including pension and insurance (Redman 2023). The farm operator is assumed to be employed full-time on the LBF farm and part-time on the USC farm. Pasture access by farm workers is assumed to be constrained by the number of days per month on which the probability of favourable weather is at least 80% based on historic data from Agro Business Consultants (ABC) (2023). This approach has

been used in previous research to model farm management risk (e.g., Lowenberg-DeBoer et al. 2021; Maritan et al. 2025). Pasture on the LBF farm is reseeded in August every 4 years (Maritan et al. 2024). Pasture management operations are assumed to be custom hired because of their low frequency. On the USC farm, no pasture operation is required because animals feed on wild plant species (i.e., rough grazing). Additional labour operation and time assumptions are provided in Table S2.

2.3 | StageTHREE Sustainable Grasslands Model

Livestock productivity and effects on grassland dynamics are estimated with the StageTHREE Sustainable Grasslands Model (SGM) developed by Behrendt, Liu, et al. (2020) and run in Matlab (The Mathworks Inc 2024). Among other functions, the SGM simulates the interactions between livestock management and grassland resource conditions subject to predefined climate risk scenarios (Behrendt, Liu, et al. 2020). The SGM has been used in previous studies to quantify grazing livestock productivity under different grassland sustainability regimes and environmental payment schemes (e.g., Behrendt, Takahashi, et al. 2020; Behrendt et al. 2022; Brown et al. 2020).

On the LBF farm, the grassland resource is assumed to be composed of 90% ryegrass (*Lolium perenne* L.) and 10% legume mixed sward (*Trifolium* spp.). Grass growth data from the Forage for Knowledge database maintained by the Agriculture and Horticulture Development Board (AHDB) (2025) were used to calibrate the SGM simulations for the LBF system (Figure S1). The target biomass residual on the LBF farm is 2000 kg dry matter (DM) ha⁻¹ following AHDB (2018) recommendations for intensive grazing systems. Optimal stocking rates for each grazing system are derived by iteratively running the SGM until modelled pasture biomass is in equilibrium in the 10th year of the simulation and coincides with the target biomass residual. A 10-year simulation horizon was chosen to allow for system stabilisation under a deterministic climate.

The same approach is used for the USC farm, but assuming a different pasture botanical composition and a higher target biomass residual (i.e., 2500 kg DM ha⁻¹) to preserve ground cover and pasture health. The upland pasture is assumed to be composed of 75% fescue/bentgrass (*Festuca/Agrostis* spp.) and 25% heather (*Calluna vulgaris* L.). The daily grass growth function is adjusted for the assumed species mix, and it is obtained from the hill grazing management model documented in English Nature (1994).

Historical weather data for both farm locations were extracted from an online database (Raspisaniye Pogodi 2025). The weather stations selected for data extraction are Shrewsbury (England) for the LBF farm and Bala (Wales) for the USC farm. Temperature and rainfall averages for the two modelled farms are shown in Figures S2 and S3. Other key data used in the SGM are provided in Table S3.

After running each scenario in the SGM, animal biology outputs were transferred to the multi-objective linear programming

model described below. Key differences among scenarios included herd size, mortality rates, amount of supplementary feeding, sale weight and duration of the grazing period. These factors depended on pasture botanical composition and biomass. Therefore, animal biology parameters were affected by grazing strategy (i.e., set or rotational stocking) rather than by fencing type (i.e., conventional fencing or VF).

2.4 | Cool Farm Tool

A subset of SGM outputs was uploaded to the online Cool Farm Tool (CFT) (Cool Farm Alliance 2025a) to estimate beef CEI. The CFT relies on Tier-1 and Tier-2 United Nations Intergovernmental Panel on Climate Change methodologies documented by the Cool Farm Alliance (2025b). The beef CEI indicator focuses on the stage of the beef lifecycle that occurs on-farm, reflecting that this is where livestock farmers have direct decision-making power. Therefore, for the LBF farm, the focus of the beef CEI indicator is on kg of meat added during finishing. Greenhouse gas emissions before this phase (i.e., calf rearing and feed and fertiliser transport emissions) are excluded from the calculations. Emissions beyond the farm gate such as ex-farm transport and processing at the slaughterhouse are also excluded. The beef CEI on the USC farm follows the same approach and includes calf rearing emissions for animals born on farm. On this farm type, beef CEI also accounts for emissions during winter housing such as solid storage manure management and bedding use emissions. CFT inputs for the two modelled farms are shown in Table S4.

2.5 | Hands-Free Hectare Multi-Objective Linear Programming Model

The last phase of the modelling procedure consisted of simulating livestock grazing operations and quantifying decision-maker utility across farm management strategies with the Hands-Free Hectare Multi-Objective Linear Programming (HFH-MOLP) model in the GAMS software (GAMS Development Corporation 2024). The HFH-MOLP model is an expansion of the Hands-Free Hectare Linear Programming model developed by Lowenberg-DeBoer et al. (2021) and based on the well-tested Purdue Crop/Livestock Linear Program (Dobbins et al. 1994). The HFH-MOLP model was calibrated during a farmer workshop held at Harper Adams University on 13th October 2023 where preliminary results of this analysis were presented and underlying assumptions discussed with 13 participants having real-world experience with the Nofence system (Digitalisation for Agroecology (D4AgEcol) 2026). The model is a decision-support tool that estimates the best compromise among economic and environmental farm-level goals for a range of management scenarios based on pre-defined objective function weights. The resolution and smallest decision unit of the HFH-MOLP model is 0.01 ha (i.e., sub-parcel level). It relies on the goal programming approach described in Hazell and Norton (1986, 72) to minimise or maximise the deviation from goals without violating labour and land resource constraints.

The farm-level goals considered in this study are to maximise return on operator labour, management and risk taking (ROLMRT), to minimise beef CEI and to maintain optimal pasture biomass

throughout the year. ROLMRT is an economic indicator which accounts for farm returns on variable and fixed costs assuming that the farm operator is compensated out of profit rather than wages. Beef CEI is treated as an environmental indicator and is expressed as kgCO₂eq per kg of bone-free meat (BFM) assuming 48.5% BFM per kg liveweight (Clune et al. 2017). Lastly, optimal pasture biomass is modelled using a time-based score quantifying the percentage of days in a year during which pasture biomass is below a target biomass residual (i.e., a score of 100% indicates that the target pasture biomass residual is always achieved during the stocking period). Evidence from long-term grazing systems research shows that pasture biomass management is fundamental to regulating sward composition, controlling the ingress of undesirable species, mitigating soil erosion and runoff, supporting biodiversity and water quality and maintaining ground cover (e.g., McDonald et al. 2023). Therefore, the time-based pasture biomass score is treated as a proxy environmental indicator for grassland health. The impact of VF on animal welfare is not included in this analysis because it is difficult to quantify and because it has been extensively studied elsewhere (e.g., Campbell et al. 2019; Hamidi et al. 2022). The HFH-MOLP model code is available in the Appendix S1 attached to the online version of this article.

Tested livestock management scenarios consist of a combination of fencing strategies, stocking rates and cattle rotation intensities (Table 3). Baseline stocking rates, expressed in livestock units (LU) per ha, correspond to the stocking rates estimated with the SGM while ensuring that biomass residual matches the user-defined target value. Additional livestock management options include stocking rates at $\pm 10\%$ from baseline on the LBF farm and $\pm 25\%$ from baseline on the USC farm. These additional options are included to represent a wider range of stocking rates and to allow for greater decision-maker flexibility. The variability on the USC farm is larger than on the LBF farm because of lower baseline stocking rates. On the LBF farm, one LU corresponds to one castrated store, while on the USC farm one LU corresponds to either one breeding bull or a cow-calf pair. Scenarios managed with electric fencing or VF assume that the farmer implements rotational stocking across 5, 10 or 15 rectangular paddocks of equal size and via an adaptive multi-paddock approach. The latter is a combination of biomass- and time-based grazing rules whereby livestock are rotated as soon as a grazing area reaches a predefined target biomass residual or a maximum number of days grazing, whichever occurs first. The farmer has the option to rotate livestock up to every 2, 5 or 10 days on the LBF farm and up to every 3, 7 or 14 days on the USC farm. These rotational frequencies follow typical UK practice for intensive and extensive grazing systems, respectively. The resulting livestock management options are three for the two SS scenarios and 27 for the three rotational stocking scenarios.

For each scenario, the HFH-MOLP model estimates decision-maker utility depending on the achievement of the tested farm-level goals and the importance placed on the goals by the farmer typology under investigation. The HFH-MOLP model objective function is as follows:

$$\min G = w_1 \left(\frac{G_1^-}{G_{opt1}} \right) + w_2 \left(1 - \frac{G_2^-}{G_{wrtst}} \right) + w_3 \left(\frac{G_3^-}{G_{opt2}} \right) \quad (1)$$

TABLE 3 | Analysis scenarios and grazing management options included in the HFH-MOLP model. LBF-SS and USC-SS are the reference scenarios in the analysis.

Scenario description	Scenario identifier	Number of paddocks	Stocking rates	Rotation frequency
Lowland beef finishing farm, set stocking, woven-wire fences	LBF-SS	1	Baseline or baseline $\pm 10\%$	—
Lowland beef finishing farm, rotational stocking, woven-wire fences + electric fences	LBF-RS-EF	5, 10 or 15	Baseline or baseline $\pm 10\%$	2, 5 or 10 days
Lowland beef finishing farm, rotational stocking, woven-wire fences + virtual fences	LBF-RS-VF	5, 10 or 15	Baseline or baseline $\pm 10\%$	2, 5 or 10 days
Upland suckler cow farm, set stocking, no physical fences	USC-SS	1	Baseline or baseline $\pm 25\%$	—
Upland suckler cow farm, rotational stocking, virtual fences	USC-RS-VF	5, 10 or 15	Baseline or baseline $\pm 25\%$	3, 7 or 14 days

where G represents farmer utility loss as a result of suboptimal goal achievement, which the model aims to minimise; w_1 , w_2 and w_3 are objective function weights assigned to each farm-level goal such that their sum equals 100%; G^-_1 is the negative deviation from maximum ROLMRT expressed in £ year^{-1} (G_{opt1}); G^-_2 is the positive deviation from maximum beef CEI expressed in $\text{kgCO}_2\text{eq kg BFM}^{-1}$ (G_{wrtst}); and G^-_3 is the negative percentage deviation from the maximum pasture biomass score (G_{opt2}).

Maximum ROLMRT is estimated with a single-objective version of the HFH-MOLP model using the following objective function:

$$\text{Max } \prod = \sum_{j=1}^n c_j X_j \quad (2)$$

subject to:

$$\sum_{j=1}^n a_{ij} X_j \leq b_i \text{ for } i = 1 \dots m \quad (3)$$

$$X_j \geq 0 \text{ for } j = 1 \dots n \quad (4)$$

where \prod is total farm ROLMRT; c_j is the per unit economic return to fixed resources (b_i 's) for the j th activity; X_j is the level of the j th production process or activity; a_{ij} is the amount of i th resource required per unit of the j th activity; and b_i is the amount of the i th resource available.

Maximum beef CEI is equivalent to the highest beef CEI estimated with the CFT across livestock management options and scenarios. Maximum beef CEI is 20.31 $\text{kgCO}_2\text{eq kg BFM}^{-1}$ on the LBF farm and 82.25 $\text{kgCO}_2\text{eq kg BFM}^{-1}$ on the USC farm. Lastly, the maximum pasture biomass score is 100%, indicating that a specific livestock management option allows for the target biomass residual to be always maintained throughout the year.

Additional economic indicators were estimated as follows:

$$\text{Net return} = \text{ROLMRT} - \text{Farm operator labour compensation} \quad (5)$$

$$\text{Farm operator labour compensation} = \text{Days worked} * \text{£76,886} \quad (6)$$

$$\text{Beef production cost} = \frac{\text{Total costs per ha}}{\text{Beef produced per ha}} \quad (7)$$

where total costs per ha include farm operator labour compensation, variable costs (e.g., casual labour and supplementary feeding) and fixed costs (e.g., conventional fencing infrastructure).

The simulated decision-maker typologies are characterised by different objective function weight values (Table 4). Environmentally orientated farmers are assumed to place between 60% and 90% of importance on the economic goal and between 10% and 40% on the two environmental goals combined. The assumption to limit the weight on the environmental goals to a maximum of 40% follows farmer behaviour literature highlighting farm business viability as a key prerequisite for prioritising non-economic functions of agriculture such as environmental impacts (Lampkin et al. 2015; Reidsma et al. 2023). In other words, it is assumed that UK farmers are not motivated by environmental benefits in the absence of sufficient income justifying the continuation of their agricultural business. Because farmers may not simultaneously prioritise the minimisation of beef CEI and the optimisation of pasture biomass, the environmentally orientated farmer typologies modelled include farmers simultaneously placing equal importance on beef CEI and pasture biomass (Environmentally orientated (A)), as well as farmers only focusing on one of these two environmental indicators (Environmentally orientated (B) and (C)). For simplification, farmer utility results are estimated in 5% weight steps for the environmentally orientated (A) decision-maker and in 10% weight steps for the other two environmentally orientated decision-makers.

2.6 | Sensitivity Analyses

The current VF technology is continuously evolving. Thus, the analysis was integrated with testing the sensitivity of two factors

TABLE 4 | Objective function weight combinations defining the importance placed on tested goals for the four modelled decision-maker typologies.

Decision-maker typology	Economic goal		Environmental goals	
	Maximise ROLMRT (w_1)	Minimise beef CEI (w_2)	Optimise pasture biomass (w_3)	
Production-orientated	100%	0%	0%	
Environmentally orientated (A)	60%–90%	5%–20%	5%–20%	
Environmentally orientated (B)	60%–90%	10%–40%	0%	
Environmentally orientated (C)	60%–90%	0%	10%–40%	

TABLE 5 | Economic performance by scenario.

Scenario	ROLMRT (£ ha ⁻¹ year ⁻¹)	Farm operator labour compensation (£ year ⁻¹)	Net return (£ ha ⁻¹ year ⁻¹)	Beef production cost (£ kg liveweight ⁻¹)
LBF-SS	1681	17,201	1281	1.86
LBF-RS-EF	1955	21,949	1445	1.86
LBF-RS-VF	1563	18,623	1130	1.98
USC-SS	-73	2579	-100	3.89
USC-RS-VF	-72	5937	-134	4.27

that may change with future technological upgrade. These include the cost of the VF technology, which depends on its useful life and acquisition cost as well as on the possibility to only place collars on part of the herd, and labour input requirements. Economic results were also tested for their sensitivity to a range of important assumptions that were required to run the HFH-MOLP model, but which may have masked important economic insights. These include: (i) beef premium prices paid for potential environmental benefits of beef produced with VF; (ii) the effect of farm size to identify the minimum area required for the VF system to breakeven with alternative fencing strategies; and (iii) the impact of excluding grazing cattle from a larger area on the USC farm to increase the annual CIGL1 payment rate.

3 | Results

3.1 | Economic Performance

On the LBF farm, the HFH-MOLP model selected livestock management options with increased stocking rates in all three LBF scenarios to maximise farm profitability regardless of the value placed on the environmental weight. In the rotational stocking scenarios, the optimal strategy was to rotate cattle up to every 10 days among 10 paddocks. Maximum ROLMRT was achieved in the LBF-RS-EF scenario, while the poorest economic performance was estimated in the LBF-RS-VF scenario. In terms of beef production costs, the LBF-RS-EF scenario had an economic performance comparable to SS (i.e., the LBF-SS scenario). VF showed the least desirable economic outcome regardless of how this was expressed (Table 5).

The economic performance of the USC farm substantially differed from that of the LBF farm. Because producing beef on this farm type is unprofitable at the assumed beef prices, the

HFH-MOLP model minimised economic losses by selecting livestock management options with reduced stocking rates. In the USC-RS-VF scenario, optimal livestock management involved rotating animals up to every 7 days across 15 paddocks. ROLMRT values in the USC-SS and USC-RS-VF scenarios were comparable. However, due to a substantial increase in labour time when handling livestock in a rotational stocking system, net return in VF was 33% lower than in the USC-SS scenario despite total ELMS payments being 17% higher when cattle were excluded from ecologically sensitive areas. VF had the least desirable economic outcome in terms of beef production cost.

On the intensive LBF farm, total ROLMRT was estimated at £ 72,275 year⁻¹ in the LBF-SS scenario, £ 84,080 year⁻¹ in the LBF-RS-EF scenario, and £ 67,197 year⁻¹ in the LBF-RS-VF scenario. Rotational stocking increased beef productivity per ha but also incurred higher variable costs. Beef productivity was 2.39 t ha⁻¹ in the LBF-SS scenario and 2.68 t ha⁻¹ in the two rotational stocking scenarios. In the latter scenarios, the increase in revenue thanks to a higher beef productivity exceeded the additional variable costs needed to manage a larger herd, but the cost of the VF technology negated this economic benefit. Annual fencing cost in the LBF-SS scenario was £ 1844. Adopting electric fences slightly increased this figure to £ 2274 year⁻¹, whereas VF led to a substantial rise in fencing cost to £ 13,548 year⁻¹. Furthermore, the VF system increased variable costs by £ 5578 required for annual subscription of the cattle collars. One of the economic benefits identified in the VF scenario in the LBF system was a reduction in farm operator labour time compared to electric fencing. SS required 53 person-day year⁻¹ (1 person-day = 8 h). This value increased to 68 person-day year⁻¹ in the LBF-RS-EF scenario, but to only 58 person-day year⁻¹ in the LBF-RS-VF scenario. Casual labour was required in March in all three LBF scenarios. 20 person-day year⁻¹ of casual labour were needed in the LBF-SS scenario, while the two rotational stocking

scenarios required 37 person-day year⁻¹ each. Total net return was £ 55,074 year⁻¹ in the LBF-SS scenario, £ 62,131 year⁻¹ in the LBF-RS-EF scenario and £ 48,574 year⁻¹ in the LBF-RS-VF scenario. Annual farm budgets for the LBF farm are provided in Table S5.

On the extensive USC farm, total ROLMRT was negative £7048 year⁻¹ in the USC-SS scenario and negative £6879 year⁻¹ in the USC-RS-VF scenario. Rotational stocking led to a marginal increase in beef productivity and a higher amount of beef sold despite 5% of the available land being taken out of production for ecological conservation purposes. Beef productivity was 0.14 t ha⁻¹ in the USC-SS scenario and 0.15 t ha⁻¹ in the USC-RS-VF scenario. The rotational stocking scenario had a stocking rate lower than SS. Thus, the increase in total beef sold was due to higher animal selling weights. This aspect led to per-animal cost savings in the USC-RS-VF scenario which partly compensated for VF adoption costs and additional labour time required. VF costs were estimated at £3547 year⁻¹ as capital expense plus £1690 year⁻¹ for collar subscription. Protecting 5% of the available pasture from grazing animals generated some fixed cost savings and increased the amount of ELMS payments. However, labour requirements in the USC-RS-VF scenario were more than double those in the SS scenario, which led to net return losses. The USC-SS scenario absorbed eight person-days year⁻¹, while VF required 18 person-days year⁻¹. No casual labour was hired in either scenario on the USC farm. Total net return including ELMS payments was negative £9627 year⁻¹ and negative £12,816 year⁻¹ in the USC-SS and USC-RS-VF scenarios, respectively. Annual farm budgets for the USC farm are shown in Table S6.

Livestock productivity parameters are shown in Table 6. In the LBF system, rotational stocking resulted in higher stocking rates and marginally lower animal sale weights compared to SS. The implementation of rotational stocking enabled greater pasture consumption, as highlighted by a 12% increase in total beef sold.

This is also reflected in the dietary intake parameters shown in Table S7. Herd forage intake was more than 709 t year⁻¹ in rotational stocking as compared to 663 t year⁻¹ in SS. Furthermore, rotational stocking enabled the intake of a higher proportion of the more nutritious leguminous species. Annual total mixed ration (TMR) consumption per animal in rotational stocking was higher than SS, making it possible for animals to reach their target sale weight earlier. This justifies why the stocking period in the LBF-RS-EF and LBF-RS-VF scenarios was 15 days shorter.

For the USC system, the herd sizes shown in Table 6 represent the number of on-farm animals immediately after calves are born on March 15th. Total stocking rates were 0.67 LU ha⁻¹ in the USC-SS scenario and 0.64 LU ha⁻¹ in the USC-RS-VF scenario. Animal selling weights were substantially higher in the USC-RS-VF scenario, where total beef sold was 13.99 t year⁻¹ compared to the 13.25 t year⁻¹ produced with SS. As shown in Table S7, livestock forage intake was almost equivalent in the two upland farm scenarios despite the USC-RS-VF scenario having a smaller available pasture area throughout the year. In the VF scenario, animals could consume a higher proportion of the more desirable fescue/bentgrass species, which partly explains their higher selling weights.

3.2 | Environmental Performance

The environmental performance in terms of ensuring optimal pasture biomass during the stocking period was comparable across tested scenarios on both farms (Table 7). The expected positive effects of rotational stocking on pasture biomass residual associated with lower risks of overgrazing were not seen in these results. On the LBF farm, the HFH-MOLP model prioritised higher beef productivity at the expense of suboptimal pasture biomass during 5% of the year. On the other hand, pasture biomass on the USC farm was maintained above the 2500 kg DM

TABLE 6 | Livestock productivity parameters by scenario.

Scenario	Livestock type	Initial herd size (hd year ⁻¹)	Stocking rate (LU ha ⁻¹)	Animals sold (hd year ⁻¹)	Sale weight (kg)	Total beef sold (tonne year ⁻¹)
LBF-SS	Stores	177	4.12	172	596.62	102.62
LBF-RS-EF	Stores	198	4.60	193	596.28	115.08
LBF-RS-VF	Stores	198	4.60	193	596.28	115.08
USC-SS	Suckler cows	63	0.66	11	554.97	6.10
	Bulls	1	0.01	1	737.73	0.74
	Heifers	21	—	11	174.75	1.92
	Bull calves	2	—	21	213.60	4.49
USC-RS-VF	Suckler cows	60	0.63	11	591.91	6.51
	Bulls	1	0.01	1	750.19	0.75
	Heifers	20	—	10	188.55	1.89
	Bull calves	21	—	21	230.33	4.84

Note: The differences between initial herd size and animals sold depend on animal mortality rates when the livestock/grassland system is at equilibrium. These mortality rates are estimated by the SGM and consider factors affecting animal body condition. On the USC farm, the difference in animals sold and initial herd size also accounts for herd replacement rules required to maintain a stable herd size at SGM model equilibrium.

TABLE 7 | Grassland performance by scenario.

Scenario	Minimum pasture biomass (kg DM ha ⁻¹)	Maximum pasture biomass (kg DM ha ⁻¹)	Pasture grazing residual (kg DM ha ⁻¹)	Days below target biomass residual	Pasture biomass score (%)
LBF-SS	1858	3153	2307	17	95
LBF-RS-EF	1830	3084	2514	18	95
LBF-RS-VF	1830	3084	2514	18	95
USC-SS	2943	3968	3303	0	100
USC-RS-VF	2939	3971	3304	0	100

TABLE 8 | Beef carbon emission intensity by scenario (kgCO₂e/kg BFM⁻¹).

Scenario	Grazing	Grass fertiliser	Feed production	Enteric fermentation	Manure	Energy	Sum
LBF-SS	0.8	3.9	2.9	12.4	0.0	0.1	20.1
LBF-RS-EF	0.7	3.5	3.0	11.5	0.0	0.1	18.7
LBF-RS-VF	0.7	3.5	3.0	11.5	0.0	0.1	18.7
USC-SS	4.9	0.0	21.7	39.3	7.2	0.0	73.1
USC-RS-VF	4.4	0.0	19.7	35.5	6.5	0.0	66.1

ha⁻¹ target during the entire year because of the reduced stocking rates to minimise economic losses.

Beef CEI estimates are provided in Table 8. The main contributors to beef CEI in the LBF system were enteric fermentation (61%–62%), grassland fertilisation (19%) and feed production (14%–16%). Enteric fermentation and grassland fertilisation emission intensities were lower in rotational stocking because of a higher beef productivity, while feed production emissions were higher due to a greater annual TMR intake. The LBF farm did not generate manure management emissions because no winter housing was performed. Overall, the rotational stocking scenarios generated a beef CEI that was 7% lower than in SS in the intensive LBF system. On the USC farm, because the stocking period lasted 214 days in both scenarios, the reduction in grazing emissions was only due to an increased beef productivity per ha. The main contributors to beef CEI in the USC system were enteric fermentation (54%) and feed production (30%). Manure management during winter housing was also an important factor. Total beef CEI was 10% lower in the USC-RS-VF scenario compared to SS.

3.3 | Farmer Utilities

The achievement of the tested economic and environmental goals was multiplied by their respective weights and summed together to estimate total farmer utility by scenario and decision-maker typology (Equation 1). Because the ranking of scenarios was not sensitive to the environmental weights, Figures 3 and 4 include mean farmer utility along tested ranges rather than utility for individual environmental weight values. On the LBF farm, the highest farmer utility was obtained in the LBF-RS-EF scenario regardless of decision-maker

typology. The second-best choice was SS. On the USC farm, farmer utilities were higher in the USC-RS-VF scenario, but the utility gain compared to the USC-SS reference scenario was close to negligible.

3.4 | Sensitivity Analysis Results

Sensitivity analyses explored economic factors that could be prioritised by manufacturers to improve the economic performance of current VF technology. On the LBF farm, it was estimated that, at the assumed 6-year collar lifespan, VF would generate a net return higher than SS if individual collar price was reduced by 60%. This reduction requirement would diminish to 40% if the lifespan of the collars was extended to 9 years. However, no solution was found to achieve profitability comparable to electric fencing. On the USC farm, VF would generate a higher net return than SS with a 90% price reduction and a useful life of 9 years.

Another option to reduce VF costs is collaring only part of the herd (Musinska et al. 2025; Schillings et al. 2024). At the current initial investment and with a 6-year lifespan, it was estimated that VF would be as profitable as SS on the LBF farm if only 62% of the herd was collared, with this figure reducing to 39% on the USC farm. Outperforming electric fencing would require collaring only 22% of the herd on the LBF farm, which might make VF ineffective.

Technology advancement may improve economic outcomes by abating labour time requirements. It was estimated that a 30% reduction in labour time in the LBF-RS-VF scenario and 40% in the USC-RS-VF scenario would make VF more economically competitive than SS, while a decrease of 70% would be needed to match net return in the electric fencing scenario on the LBF farm.

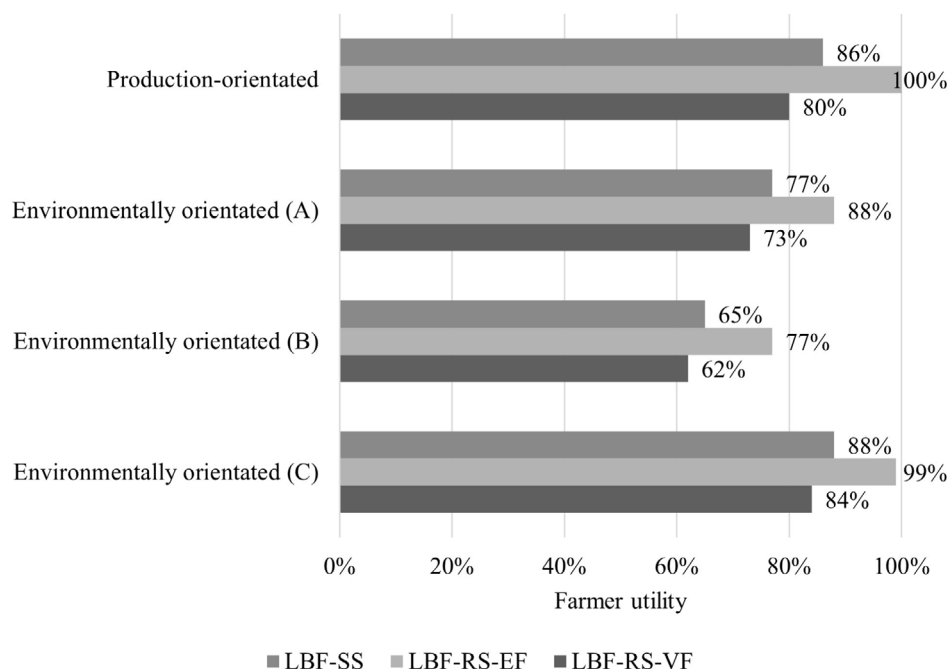


FIGURE 3 | Mean farmer utility by scenario and decision-maker typology on the lowland beef finishing farm. The environmentally orientated (A) farmer places 5% to 20% of importance each on minimisation of beef CEI and optimisation of pasture biomass. The environmentally orientated (B) farmer places 10% to 40% of importance on minimisation of beef CEI and 0% on optimisation of pasture biomass. The environmentally orientated (C) farmer places 0% of importance on minimisation of beef CEI and 10% to 40% on optimisation of pasture biomass.

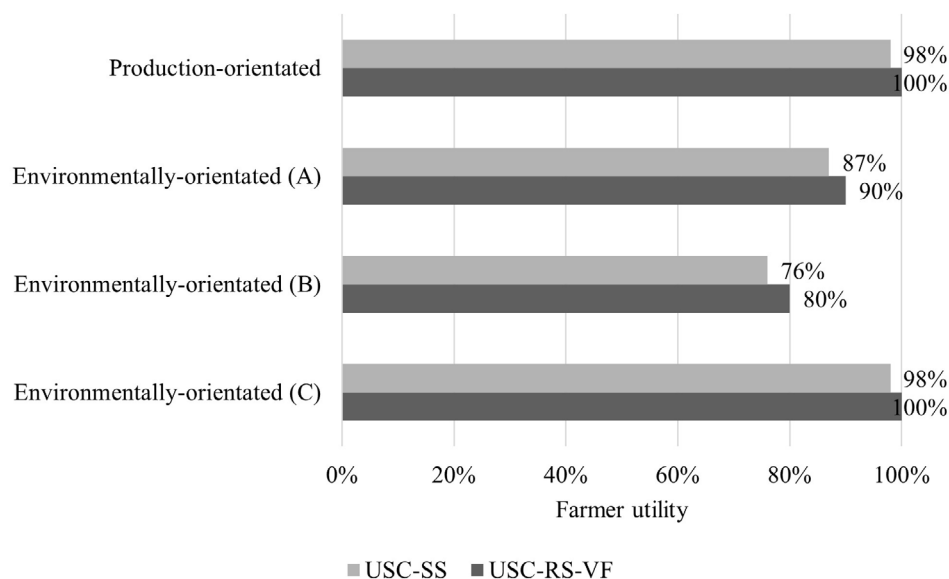


FIGURE 4 | Mean farmer utility by scenario and decision-maker typology on the upland suckler cow farm. The environmentally orientated (A) farmer places 5% to 20% of importance each on minimisation of beef CEI and optimisation of pasture biomass. The environmentally orientated (B) farmer places 10% to 40% of importance on minimisation of beef CEI and 0% on optimisation of pasture biomass. The environmentally orientated (C) farmer places 0% of importance on minimisation of beef CEI and 10% to 40% on optimisation of pasture biomass.

Beef premium prices that could be fetched for the environmental benefits enabled by VF were also tested. On the LBF farm, because VF produced comparable environmental outcomes to electric fencing, a beef premium was only assumed in comparison to the LBF-SS scenario. It was estimated that a 3% beef premium in the LBF-RS-VF scenario would result in a net return higher than the LBF-SS scenario, which could be justified by the lower CEI of beef produced with the use of VF. On the USC farm,

the beef premium required to outperform the USC-SS scenario was 10%. This beef premium could be justified by the lower beef CEI as well as the enablement of ecological conservation on 5% of the grassland area.

The results of the sensitivity analysis testing breakeven points of VF at larger farm sizes produced no feasible solution. This is because the initial investment and recurring costs for the VF

technology are linearly dependent on herd size, that is, a larger herd requires a larger number of collars and collar subscriptions. In other words, the VF technology commercialised by Nofence does not possess economies of scale.

A final approach to compensate for VF costs for upland graziers could be to expand the amount of area protected from grazing. Indeed, an increase from 5% (4.8 ha) to 12% (11.5 ha) would result in the VF scenario generating a net return higher than SS, though this economic indicator would still be negative. The amount of area protected would need to be as high as 31% (29.8 ha) to achieve a net income of £0 in the USC-RS-VF scenario. This value is infeasible because it exceeds the 25% maximum allowance imposed by the CIGL1 payment rules.

4 | Discussion

This study hypothesised that current VF technology could reduce the trade-off between economic and environmental goals in the two modelled livestock systems. The tested indicators showed that trade-offs changed to different extents depending on livestock system type, but they were not reduced. Therefore, the study hypothesis is rejected. Indeed, in a more intensive beef finishing system, the cost of the VF technology negated the productivity benefits achieved with rotational stocking thereby increasing the trade-off between beef productivity and a lower beef CEI. On the other hand, no environmentally beneficial effect was encountered in terms of pasture biomass as a proxy for grassland health, which is in line with results from Ouzman et al. (2026). On the USC farm, VF adoption enabled habitat protection combined with a reduction in beef CEI in comparison to SS. However, these environmental benefits had a high cost due to the initial investment required to purchase the VF system and higher labour input resulting in a farm net return lower than SS. Like on the LBF farm, VF did not reduce the risk of overgrazing within the grazing area. These results are reflected in the estimated farmer utility values indicating that rotational stocking managed with current VF technology is not the optimal fencing strategy for neither the LBF nor the USC farm. On the latter, farmer utilities achieved with VF are comparable to SS. Thus, the optimal fencing strategy in UK USC systems may change even with minor modifications of the available conservation grazing subsidies.

Overall, model solutions indicate that the achievement of the identified environmental benefits will largely depend on future reduction of economic barriers to VF adoption. Previous VF literature shows contrasting views on the socio-economic effects of this technology. Several studies reported lower labour time and fencing costs when adopting VF. However, most of this research only considered qualitative data and farmers' perceptions (e.g., Hoag, Vorster, et al. 2024; Schillings et al. 2024; Watzold et al. 2024). Quantitative socio-economic analyses of VF are rare, do not focus on whole-farm resource planning, overlook important animal biology impacts, and assess substantially different farm business models. For example, the partial budgeting analysis by Hoag, Reuter, et al. (2024) investigated VF adoption on US cattle farms through a lease business model. The authors found that VF became more profitable than physical fences at very large

farm sizes (Hoag, Reuter, et al. 2024). Conversely, the sensitivity analysis of farm size in the present assessment showed that the studied VF product does not possess economies of scale and consequently its economic performance does not improve at larger farm sizes. Kiefer et al. (2025) conducted a partial budgeting analysis of VF adoption on dairy farms in Germany. Their economic findings generally align with the results of the present analysis. However, the authors assumed fixed stocking rates across scenarios, a constant number of cattle rotations per year, and did not model cattle biology and pasture biomass. Consequently, their results could not capture the finer interactions between herd management and grassland dynamics necessary to optimise livestock management and estimate environmental outcomes.

The results of the sensitivity analyses indicate that VF would economically outcompete the reference SS scenarios on the LBF farm if its initial investment was reduced, the useful life of the collars was extended or a combination of both. However, electric fencing on the LBF farm and SS on the USC farm remained the most profitable scenarios even when VF had acquisition costs close to zero. Part collaring could be another option to make VF competitive, but its impacts on VF effectiveness are still unknown. Reduction in labour time is another potential area of interest to improve the economic performance of VF, though competing with electric fencing would require substantial labour input reduction on farms where electric fencing is a feasible alternative. Key functions that could be targeted by VF providers include the enablement of remote management of herd moves between paddocks during the entire stocking period and improved system effectiveness to reduce animal escapes in extensive grazing systems. Indeed, these were the two VF operations that absorbed the highest amount of labour time per hectare. A reduction in current labour requirements coupled with the higher quality of time spent using VF compared to managing electric fences in the fields would increase the perceived value of this technology (Hoag, Vorster, et al. 2024). Combining qualitative labour implications with quantitative labour estimates via mixed method approaches is an area of further investigation.

The analysis also estimated that reasonable beef premium prices could help reduce economic and environmental trade-offs in comparison to SS on both farms. The 3% premium needed on the LBF farm could be justified by the lower CEI of beef produced in the LBF-RS-VF scenario, while the 10% required on the USC farm could be additionally justified by the enablement of ecological conservation on part of the grazing area. However, fetching a premium in lowland beef finishing systems remains difficult due to electric fencing producing comparable beef CEI outcomes. Because the studied VF product does not possess economies of scale, these insights are valid beyond averaged-sized LBF and USC systems in the UK.

A final sensitivity analysis identified 12% as the amount of protected area required for VF to generate a net return higher than SS on the USC farm. However, to generate a positive net return, at least 31% of the area would need to be protected and receive the CIGL1 SFI payment. This value is higher than the maximum of 25% allowed under this scheme option. Despite the negative net return, excluding 25% of the area from cattle grazing would reduce the economic and environmental trade-offs of VF on the

USC farm compared to SS. Such an approach would be in line with the goal of the UK Government to take marginal and less productive land out of farming to help meet climate and environmental objectives (Defra 2024). VF could facilitate this transition without forcing farmers to completely discontinue beef production in the UK uplands, thereby maintaining a traditional part of the local economy and supporting the generation of ecosystem services associated with these habitats. Nevertheless, VF capital costs would remain challenging for less intensive and part-time farmers in these regions and would likely need to be subsidised.

The results of this study are for LBF and USC farms in the UK. Additional analysis is required to generalise the identified economic and environmental trade-offs of VF adoption for different countries and livestock systems (e.g., dairy). Further research opportunities also include: (i) testing lower or higher target biomass residual values, potentially differentiated depending on stocking method; (ii) analysis of VF products commercialised by brands other than Nofence, such as those adopted through leasing contracts (e.g., Vence) and products requiring the installation of a LoRaWAN radio base station (e.g., Vence, Halter); (iii) testing the performance of VF against additional environmental indicators such as grassland species richness; (iv) assessment of VF use in remote areas where grazing animals could only be reintroduced if remote livestock management was enabled by technology (e.g., O'Donoghue 2022); and (v) the impacts of VF on labour quality and competition between livestock and crop enterprises in mixed farming, where this technology could reduce herbicide use and create economies of scope (de Avila et al. 2025; Mosnier et al. 2021; Ouzman et al. 2026).

5 | Conclusion

Using the example of VF in UK beef cattle grazing, this study explored the effects on economic and environmental trade-offs of precision grazing technology adoption in a context of declining farm profitability and growing environmental compliance. It was found that VF may be more profitable or less profitable than SS depending on livestock system type and that economic and environmental trade-offs of beef production are not reduced. In an intensive beef finishing grazing system, VF was less profitable than electric fencing while resulting in comparable environmental outcomes, thereby increasing the trade-offs between the tested economic and environmental indicators. Overall, VF adoption in the UK grass-fed beef sector is expected to face challenges related to reduced profitability, higher production costs and competition from conventional fencing strategies in rotational stocking.

Farmer utility implications for the different fencing options were estimated using a multi-criteria decision-support tool. On a lowland beef finishing farm, the best performing fencing strategy was electric fencing regardless of the goals considered and the assumed degree of farmer environmental orientation. Electric fencing was followed by SS. Conversely, results for SS and rotational stocking managed with VF on an upland suckler cow farm indicated comparable farmer utility regardless of decision-maker typology. The utility values were so similar that

minor changes in agricultural subsidy payments may affect the relative ranking of the modelled scenarios.

Sensitivity testing analysed several factors that could be prioritised by farmers and VF providers to mitigate adoption barriers of VF. Results indicated that reducing technology ownership costs or marginally extending the lifespan of the VF collars, collaring only part of the herd, or reducing labour input might be feasible but challenging options to make VF the most profitable scenario. Beef premium prices ranging from 3% to 10% rewarding the identified environmental benefits would result in VF becoming more profitable than SS. It was also shown that the identified economic barriers are not influenced by farm size. Lastly, on the upland suckler cow farm, the economic and environmental trade-offs of beef production could be reduced by excluding grazing cattle from a relatively large portion of the farm to receive habitat conservation payments thanks to VF use.

Because of the increased trade-offs between economic and environmental outcomes when adopting VF, rotational stocking managed with electric fencing is likely to remain the most desirable livestock management option in UK intensive grazing systems. For extensive upland grazing systems, VF could generate some environmental benefits, but these come at a high cost requiring agricultural subsidy compensation. These results are for lowland beef finishing and upland suckler cow systems following UK industrial practice. Further research is required to assess the economic and environmental impacts of VF adoption in other countries and livestock systems (e.g., dairy and mixed farms) while considering additional environmental indicators and possibly modifying key underlying assumptions made in this assessment.

Author Contributions

Elias Maritan: conceptualization, data curation, formal analysis, methodology, writing – original draft, writing – review and editing. **Karl Behrendt:** funding acquisition, conceptualization, formal analysis, methodology, supervision, writing – review and editing. **Sarah Morgan:** conceptualization, writing – review and editing. **Steven Mark Rutter:** conceptualization, writing – review and editing. **James Lowenberg-DeBoer:** conceptualization, methodology, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the [Supporting Information](#) of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Predicted versus observed grass biomass for the modelled LBF system. The system used grass growth data extracted from the Forage for Knowledge database (Agriculture and Horticulture Development Board (AHDB), 2025) for SGM calibration. **Figure S2:** Historic rainfall and temperature data from 2006 to 2024 at Shrewsbury (England) used for SGM simulations of the LBF farm (Pogodi, 2025). **Figure S3:** Historic rainfall and temperature data from 2011 to 2024 at Bala (Wales) used for SGM simulations of the USC farm (Pogodi, 2025). **Table S1:** Farm fixed costs and variable costs related to livestock, labour, reseeded lowland grassland operations and energy consumption. Data sources and additional information are provided at the bottom of the table. **Table S2:** Labour time by livestock operation

and scenario. Data sources and key assumptions are provided at the bottom of the table. **Table S3:** SGM parameter sets used to model livestock productivity and grassland performance. See Behrendt, Liu, et al. (2020) for a detailed explanation of soil and grassland parameters and their impacts on modelled grassland dynamics. Data sources are provided at the bottom of the table. Livestock are assumed to be of British breed. DOY=day of year (1 to 365). **Table S4:** CFT inputs used to estimate beef carbon emission intensity. Values provided in ranges depend on stocking rates, number of paddocks, herd rotation frequencies and/or scenario. The inputs whose sources are not specified were estimated via the SGM. **Table S5:** Annual farm budget by scenario on the lowland beef finishing farm. **Table S6:** Annual farm budget by scenario on the upland suckler cow farm. **Table S7:** Livestock dietary intake parameters by scenario under steady-state conditions.