A multi-objective optimisation analysis of virtual fencing in precision grazing

Elias Maritan[1], Karl Behrendt[1], James Lowenberg-DeBoer[1], Sarah Morgan[2], S. Mark Rutter[3]

[1] Food, Land and Agribusiness Management Department, Harper Adams University, Newport, United Kingdom

[2] Agriculture and Environment Department, Harper Adams University, Newport, United Kingdom

[3] Animal Health, Behaviour and Welfare Department, Harper Adams University, Newport, United Kingdom

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Abstract.

Virtual fencing is a precision livestock farming tool consisting of invisible boundaries created via Global Navigation Satellite Systems (GNSS) and managed remotely and in real time by app-based technology. Grazing livestock are equipped with battery-powered collars capable of delivering audio or vibration cues and possibly electric shocks when approaching or crossing an invisible boundary. Virtual fencing makes precision grazing possible without the need for physical fences. This technology originated in the US in the 1980s. To-date, virtual fencing products such as eShepherd®, Halter®, Nofence® and Vence® are available worldwide. There are more than 3,000 virtual fencing adopters globally, with this figure expected to grow in forthcoming years. Despite its growing adoption rate, economic and environmental implications of virtual fencing are largely undocumented in public research.

The present study is a multi-objective optimisation analysis of virtual fencing in UK beef cattle precision grazing systems. It uses the Hands Free Hectare Multi-Objective Linear Programming model (HFH-MOLP) developed at Harper Adams University, Newport, UK. The HFH-MOLP model is a decision-making support tool suited for whole-farm resource planning in situations of conflicting farmer priorities. This analysis simulated two grazing farms producing beef either via set or rotational stocking and using different fencing types, including woven wire, electric, and virtual fencing. The first farm was assumed to be a lowland mixed farm with an intensive beef finishing enterprise located in the UK West Midlands. The second farm consisted of an extensive

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suckler cow grazing farm situated in the Welsh uplands. On each farm type, the economic and environmental performances of different stocking methods were compared to quantify trade-offs between monetary returns and greenhouse gas (GHG) emissions across fencing strategies.

Results showed that, regardless of the ecological orientation of the decision-maker, the preferred scenarios were rotational stocking managed with electric fencing on the lowland mixed farm, and set stocking on the upland extensive grazing farm. The electric fencing scenario generated an annual return of £ 97,685 compared to £ 85,907 in the virtual fencing counterpart, with both systems emitting 222 MgCO_2eq. On the extensive grazing upland farm, set stocking achieved an annual return of £ 5,310 compared to £ 1,614 in the virtual fencing scenario, though the latter produced slightly lower GHG emissions and prevented animals from grazing an ecologically sensitive area.

Despite its lower economic competitiveness, virtual fencing provides some advantages in terms of increased work flexibility, improved ecology conservation in remote habitats, and simplified animal welfare standards compliance. Further technical improvements related to data collection may transform virtual fencing into a multi-purpose technology. For example, additional economic value could be generated if the technology enabled farmers to detect certain diseases quicker than conventional methods. Recommendations for virtual fencing providers include a reduction in collar and mobile application subscription costs, the extension of the useful life of the collars, and the potential of having virtual fencing subsidised by Government schemes such as the UK Farm Investment Fund. The study concludes with methodological improvements to be addressed in future research.

Keywords.
Virtual fencing, Precision grazing, Beef production, Digitalisation, Agroecology

1. Introduction

Virtual fencing is a precision livestock farming tool used to manage grazing livestock without the need for physical fences (Maritan *et al.*, 2024). It consists of an invisible boundary relying on Global Navigation Satellite Systems (GNSS) and managed remotely and in real time by app-based technology (DEFRA, 2022; Golinsky *et al.*, 2023; Maritan *et al.*, 2024). The animals wear battery-powered collars capable of delivering auditory or vibrational cues and possibly electric shocks when the virtual boundaries are approached or crossed (DEFRA, 2022; Maritan *et al.*, 2024). Over a relatively short span of time, animals tend to respond to less invasive auditory or vibrational cues and learn to avoid crossing over the invisible boundaries (Maritan *et al*., 2024). A visual representation of a typical virtual fencing system is shown in **Figure 1**.

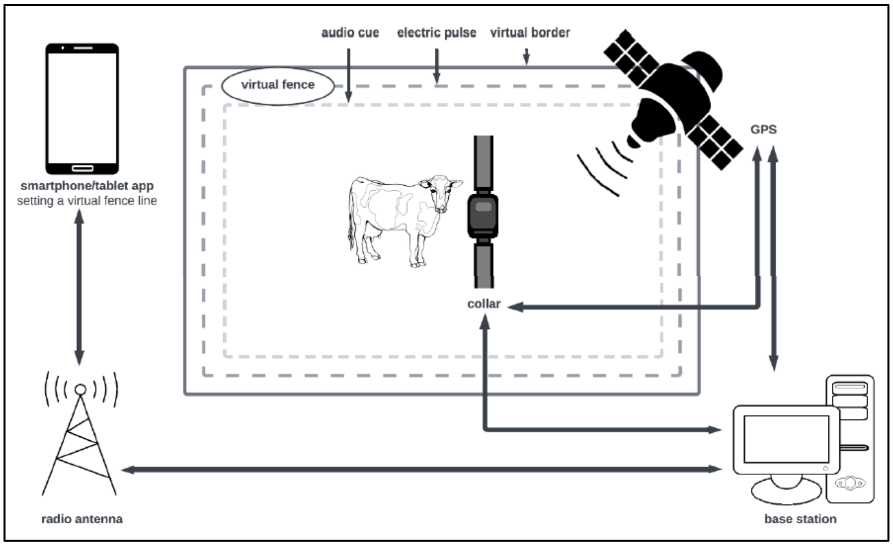

Figure 1. A typical virtual fencing system (Golinski *et al.*, 2023).

This technology originated in the US in the 1980s for companion animals and was soon adapted to cattle and small ruminants (Golinski *et al.*, 2023). To-date, virtual fencing products for domesticated livestock such as eShepherd®, Halter®, Nofence® and Vence® are available worldwide (Golinski *et al.*, 2023). There are currently more than 3,000 virtual fencing adopters globally (O'Donoghue, 2022), with this figure expected to grow in forthcoming years, especially on conservation grazing farms (ADAS, 2023; DEFRA, 2022). Despite its growing adoption rate, economic and environmental implications of virtual fencing are largely undocumented in public research.

Grazing operations traditionally rely on set stocking practices, whereby livestock are allowed to access a pasture area for a relatively long period of time without interruption (Allen *et al.*, 2011; DEFRA, 2022). Set stocking may lead to problems such as biodiversity loss due to patch grazing of more palatable grass species, overgrazing in areas of prolonged livestock presence, and increased risks of infections and injuries as a result of soil compaction (DEFRA, 2022). Although set stocking requires lower labour inputs, the absence of resting periods reduces pasture supply both in the short and in the long term. This in turn negatively affects livestock productivity, or leads to higher supplementary feed requirements to maintain economic viability. Besides, set stocking also makes it impossible to prevent animals from grazing ecologically sensitive areas.

The alternative to set stocking is rotational stocking, which may be termed in several other ways depending on pasture layout and rotation intensities (e.g., strip, mob, and cell grazing). Rotational stocking involves recurring periods of grazing and rest among three or more paddocks by exploiting movable or fixed physical fences, thus allowing for increased efficiency and more precise management of forage consumption (Allen *et al.*, 2011). However, this practice requires higher farm infrastructure and labour requirements as well as a greater investment risk (Gillespie *et al.*, 2008; Meat & Livestock Australia, 2023). Virtual fencing may help mitigate these aspects while preserving the positive environmental impacts of rotational stocking such as lower greenhouse gas (GHG) emission intensities and improved ecology conservation.

This study uses a range of economic and biological models to simulate two grazing farms producing beef either via set or rotational stocking and using different fencing types. The first farm is a lowland mixed farm with an intensive beef finishing enterprise located in the UK West Midlands. The second farm consists of an extensive suckler cow grazing farm situated in the Welsh uplands. On the intensive grazing farm, rotational stocking is either managed via electric or virtual fencing. On the extensive grazing farm, rotational stocking only relies on virtual fencing because installing electric fences in the UK uplands is impractical or not allowed by environmental regulations imposing shared resource management regimes on habitats such as common land and national parks. On each farm type, the economic and environmental performances of different stocking methods and rotation intensities are compared to quantify trade-offs between monetary returns and GHG emissions across fencing strategies. The hypotheses of this analysis are: (i) in intensive beef finishing systems, virtual fencing adoption negates the economic benefits achieved with rotational stocking, but preserves GHG emission savings thanks to a higher beef productivity per hectare; and (ii) on extensive suckler cow grazing farms, virtual fencing enables increased profitability from beef production while mitigating GHG emissions and promoting environmental conservation. This study builds on and expands the previous multi-objective analysis of virtual fencing published by Maritan *et al.* (2024).

2. Material and methods

2.1 Description of the two modelled farms

2.1.1 Intensive lowland beef finishing grazing farm

The first farm case study is a 295-hectare cereal and protein crop farm located in the UK West Midlands and willing to convert to a mixed farming system by incorporating a beef finishing enterprise on one eighth of the available land. The farm operator is assumed to work full-time in agriculture. Maize silage for cattle supplementary feeding is grown on farm on another eighth of the land, while high-protein concentrates are purchased off-farm. Winter wheat and winter field bean are grown on 50% and 25% of the farm, respectively. Agricultural equipment is assumed to be owned, except for the maize silage harvester. The owned equipment set includes a 112-kW tractor, a 4.5-m combine harvester, a quad bike, a 12-Mg grain trailer and several tractor implements. Maize silage is assumed to be harvested by a farm contractor.

Beef finishing cattle are grazed on a 4-year grass ley for 300 days each year. The grazing enterprise is surrounded by woven wire fencing to prevent cattle from damaging the surrounding crops. Livestock are purchased at 8 months old at 280-kg liveweight and sold at 18 months old (Redman, 2023). Supplementary feeding supplies 40% of the herd dietary requirements and includes 3,000 kg of maize silage and 330 kg of concentrate feed per head per year (Redman, 2023). Cattle liveweight at sale spans from 514 kg in set stocking to 542 kg in rotational stocking. The rotational stocking system includes 10 paddocks of equal size (3.3 hectares). Cattle are moved across paddocks every 2 days i.e., 150 times a year. This system allows paddocks to rest for 18 days, thus enabling higher forage production and consequently higher stocking rates per hectare (4.08-4.21 head ha^{-1} versus 3.95-4.07 head ha^{-1} in set stocking). Rotational stocking operations are assumed to rely either on electric or virtual fencing. Beef variable costs are estimated following Redman (2023) and include concentrates, veterinary expenses, forage and maize production costs, purchased animals, and miscellaneous expenses.

2.1.2 Extensive upland suckler cow grazing farm

The second farm case study consists of a 300-hectare extensive grazing farm situated in the Welsh uplands, where conservation grazing is common. The farm operator works part-time in agriculture and has off-farm employment or other sources of income. The herd is assumed to be self-replacing and composed of suckler cows with a 0.84 fertility rate (Redman, 2023). Calves are born in March and sold at the end of October (Redman, 2023). 50% of heifer calves are retained on farm to replace old or cull cows. Herd mortality rate is assumed at 2%. Herd size is based on stocking rate recommendations for conservation grazing in semi-natural habitats following Chapman (2017). Thus, stocking rates are fixed regardless of the stocking system due to the known carrying capacities of semi-natural upland pastures. Because physical fences in UK upland areas are generally impractical or not allowed, virtual fencing is the only type of fencing used for rotational stocking on this farm. The economic effects of improved pasture management via rotational stocking are captured via increased final liveweights and a reduction in supplementary feed intakes during winter housing. In set stocking, adult cows and newborn calves achieve a final liveweight of 499-502 kg and 229-231 kg, respectively. In rotational stocking, these values are 504-518 kg for adult cows and 230-238 kg for newborn calves. Adult cows and replacement heifers are offered 21-34 kg hd^{-1} day^{-1} of supplementary feeding during winter housing depending on their relative pre- and post-grazing condition. During grazing, lactating cows are offered mineral licks in the first three months to compensate for nutritional imbalances.

2.2 Description of the models used

2.2.1 Hands Free Hectare Multi-Objective Linear Programming (HFH-MOLP) model

The HFH-MOLP model is a decision-making support tool used for whole-farm resource planning in situations of conflicting farmer objectives. It was developed as part of the Digitalisation for Agroecology project and applied to a range of digital technologies to identify their economic, environmental, and social potential to achieve agroecological farming in Europe. These types of models identify trade-offs among incommensurable goals by quantifying the unwanted deviation from one or more targets (Cocklin *et al*., 1986; Ignizio, 1983). The HFH-MOLP is an expansion of the single-objective Hands Free Hectare linear programming model (HFH-LP) developed at Harper Adams University, Newport, UK (see Lowenberg-DeBoer *et al.*, 2021). It uses the goal programming approach described in Hazel and Norton (1986: p.72) and it is coded via the General Algebraic Modelling System (GAMS Development Corporation, 2023).

Linear programming models consist of several algebraic equations that maximise or minimise target variables to find one or more optimal solutions that are satisfied without violating user-defined constraints. In farm management analysis, constraints are often used to impose limits on finite resources such as available land and labour days in a year. The key equation in a linear programming model is referred to as the objective function. In multi-objective linear programming, multiple objective functions are combined in a composite objective function each maximising or minimising a secondary target variable. In this analysis, the secondary target variables are two i.e., farm return and GHG emissions, henceforth referred to as goals. Farm return is expressed as return to operator labour, land, management, and risk taking (ROLLMRT), while GHG emissions are expressed in $MgCO_2eq$. Tested decision-makers include: (i) a profit-oriented farmer (100% of importance on maximising farm return); (ii) a moderately ecology-oriented farmer (80% of importance on maximising farm return and 20% on minimising GHG emissions); and (iii) a strongly ecology-oriented farmer (60% of importance on maximising farm return and 40% on minimising GHG emissions). The composite objective function used in the present analysis is:

$$\min G = w_1\left(\frac{G_1^-}{G_{opt}}\right) + w_2\left(1 - \frac{G_2^-}{G_{wrs}}\right) \quad (1)$$

where G is the primary target variable to be minimised, representing the loss of utility for the decision-maker; w_1 is the weight assigned to the farm return goal and with values of 100%, 80% or 60% depending on decision-maker preferences; G_1^- is a deviational variable calculating the percentage deviation from a target value G_{opt}, which is the maximum ROLLMRT generated across scenarios for each of the two farm types; w_2 is the weight assigned to the GHG emissions goal and with values of 0%, 20% or 40% depending on decision-maker preferences; and G_2^- is a deviational variable estimating the percentage deviation from a target value G_{wrs}, which is the minimum quantity of GHG emissions generated across scenarios for each of the two farm types.

2.2.2 Cool Farm® Tool

GHG emission estimates used in the HFH-MOLP model are calculated via the Cool Farm® Tool

(CFT) (Cool Farm Alliance, 2024a). This tool uses Tier 1 and Tier 2 methods developed by the UN Intergovernmental Panel on Climate Change for a wide range of agricultural outputs (Cool Farm Alliance, 2024b). Input data requirements to measure GHG emissions of crop production include, among others, yields per hectare, fertiliser and pesticide rates, energy consumption, and soil parameters. Input data for beef production include, among others, grazing period, initial and final herd sizes, pasture fertilisation rates, and supplementary feed intakes. GHG emissions generated off-farm such as transportation of farm resources were deducted from CFT outputs because the focus of this analysis is on direct farm emissions.

2.2.3 Grazing systems models

To estimate animal parameters such as daily liveweight gain, forage biomass consumption, and livestock liveweights at sale, two standalone models were used and their outputs incorporated into the HFH-MOLP model. Parameters for the intensive lowland beef finishing grazing farm were quantified with an adapted version of the GrazFeed decision support tool developed by Freer *et al.* (2007; 2012). For the extensive upland suckler cow grazing farm, animal parameters were calculated via the StageTHREE Sustainable Grasslands Model (StageTHREE SGM) developed by Behrendt *et al.* (2020).

The GrazFeed decision support tool is based on UK, EU and US feeding standards for domesticated animals (Freer *et al.* 2007; 2012). The adapted version used in this analysis is particularly suited for herds that are not self-replacing such as beef finishing enterprises hosting castrated male cattle. Based on standard reference weights for continental crossbreeds, the adapted GrazFeed model estimates forage biomass consumption and final cattle liveweights depending on available forage biomass, maximum daily dry matter intakes, and relative daily growth conditions of the herd. Grazing target residuals were set to 1,500 kg dry matter (DM) ha^{-1} in rotational stocking and 2,000 kg DM ha^{-1} in set stocking following AHDB recommendations for beef cattle (AHDB, 2018). Stocking rates were iteratively adjusted in each stocking system until grazing target residual matched the desired value. The adapted GrazFeed model was developed and run in Microsoft® Excel® (Microsoft Corporation, 2024).

The StageTHREE SGM is a dynamic tool that simulates interactions of grassland resource conditions with livestock management and climate risk (Behrendt *et al.*, 2020). It is suited for self-replacing herds and for habitats characterised by a diverse botanical composition. It simulates soil processes and erosion, grassland growth, grassland botanical composition and livestock performance (Behrendt *et al.*, 2020). It also accounts for the substitutional effects of forage consumption on supplementary feeding by allowing animals to be housed in the winter or at the end of each grazing day based on user-defined supplementary feeding rules (Behrendt *et al.*, 2020). The grassland resource is divided into desirable and less desirable species, whose dynamics may vary depending on growth rates, rainfall, self-competition, grazing days, and other factors (Behrendt *et al.*, 2020). The grazing target residual assumed in this case was 1,800 kg DM ha^{-1} based on recommendations for lactating cows (AHDB, 2018). StageTHREE SGM input parameters were constructed for a range of stocking rates and rotation intensities to understand the interaction among management decisions, labour inputs, beef production, GHG emissions and ecological conservation. The StageTHREE SGM is run in Matlab® (The MathWorks Inc., 2024).

2.3 Scenarios and main assumptions

The present study tested five scenarios whose key differences are the stocking method and the fencing type used to manage livestock in rotational stocking. On the intensive lowland beef finishing grazing farm, tested scenarios include: (i) set stocking (Scenario 1), (ii) rotational stocking managed with electric fencing (Scenario 2), and (iii) rotational stocking managed with virtual fencing (Scenario 3). On the extensive suckler cow grazing farm, it was assumed that electric fencing would be impractical due to the uneven terrain of upland less favoured areas (LFA) or not allowed owing to common land regulations governing resource management in these types of habitat in the UK (e.g., UK Commons Act, 2006). Therefore, the scenarios in this case are only two: (i) set stocking (LFA) (Scenario 4), and (ii) rotational stocking (LFA) managed with virtual fencing (Scenario 5). Key information about the five scenarios is provided in **Table 1**. Fencing costs on the intensive lowland beef finishing grazing farm include woven wire fencing as well as electric or virtual fencing where applicable. On the extensive suckler cow grazing farm, fencing costs only include virtual fencing in Scenario 5 i.e., no woven wire fencing is erected by the farm operator around the grazing enterprise.

Table 1. Key information of the tested scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Mean herd size (adults)	131-135	135-139	135-139	54-90	72
Mean herd size (calves)	N/A	N/A	N/A	30-64	52
Stocking rates (head ha^{-1})	3.95-4.07	4.08-4.21	4.08-4.21	0.18-0.30	0.27
Final liveweight (adults) (kg)	514	542	542	499-502	504-518
Final liveweight (calves) (kg)	N/A	N/A	N/A	229-231	230-238
Mean pasture consumption (kg DM ha^{-1} year^{-1})	6,026-6,410	6,409-6,792	6,409-6,792	460-616	655-690
Grazing pasture residual	2,257-2,265	1,498-1,503	1,498-1,503	1,799-1,837	1,810-1,845
Supplementary feeding (kg DM head^{-1} year^{-1})	3,300	3,300	3,300	3,110-5,198	4,117-4,132
Cattle management labour time (hour ha^{-1} year^{-1})	3.65	3.96	3.81	2.88	3.28
Fencing costs (£ year^{-1})	5,898	6,617	19,435	0	7,180

Lastly, main scenario assumptions include:

- Revenue; beef price is £ 2,40 kg^{-1} while winter wheat and winter field bean prices are £ 207 Mg^{-1} and £ 241 Mg^{-1}, respectively (Redman, 2023).
- Fencing annual costs; the lowland mixed farm is assumed to be rectangular with length twice its width and enclosed by 8,065 m of woven wire fencing costed at £ 6.75 m^{-1} (ABC, 2023). Woven wire fencing is assumed to have a 30-year useful life. The farm is divided into 8 fields of equal size, one of which hosts grazing cattle and is divided into 10 paddocks of 3.3 hectares each. To enclose a single paddock, 807 m of electric fencing are required. Following ABC (2023), electric fencing is costed at £ 6.75 m^{-1} plus a mains energiser priced at £313. The electric fencing system is assumed to have a 20-year useful life. Based on personal communication with a virtual fencing provider in the UK, the virtual fencing system costs £ 295 per collar, plus £ 28 collar^{-1} year^{-1} for mobile application subscription charges. The virtual fencing system also requires 2 battery chargers and 28 spare batteries in Scenario 3, and 1 battery charger and 24 spare batteries in Scenario 5. These are priced at £ 80 each. The useful life of the virtual fencing system is assumed to be 6 years.
- Area left out of production; following Lowenberg-DeBoer *et al.* (2021), 10% of the mixed farm in Scenarios 1, 2 and 3 is assumed to be unproductive land. On the extensive grazing upland farm in Scenarios 4 and 5, the landscape is assumed to be composed of semi-natural grassland (90 ha), rush pasture (90 ha), dry heathland (90 ha) and wet heathland (30 ha). In Scenario 5, the wet heathland is treated as a protected habitat and excluded from grazing. As a compensation for habitat protection, the farm receives two Government subsidy payments for a total of £ 74 ha^{-1} (DEFRA, 2024a; 2024b).
- Moving herds across paddocks; Scenario 3 assumes that 66% of herd moves are done remotely through the virtual fencing mobile application over the 10-month grazing season. In Scenario 5, the farm operator manages herd moves in-person during the first 3 grazing months because of the requirement to fill and move mineral buckets. Once mineral licks are no longer required by the lactating cows (i.e., from July onwards), 50% of herd moves are managed remotely.

3. Results

The HFH-MOLP model was able to identify optimal solutions across all scenarios without encountering land, labour or machinery time constraints. On the intensive lowland beef finishing farm, 133 hectares of winter wheat, 66 hectares of winter field bean and 33 hectares of maize silage were planted and harvested at the respective optimal times. Cattle grazing operations were conducted on 33 hectares of land on pasture sown in August. Pasture sown in September resulted in lower stocking rates in the first year and therefore this rotation did not appear in model solutions. About 30 casual labour days were required between August and December when annual crops were either harvested or planted. On the extensive upland suckler cow farm, 300 hectares were allocated to grazing cattle in Scenario 4 and 270 hectares in Scenario 5. The only casual labour days required were encountered in the virtual fencing scenario in April i.e., when cattle begin grazing and undergo a 2.5-day-training to become familiar with the virtual fencing system. During the rest of the year, one farm operator was sufficient to manage farm operations. Among the tested rotation intensities (i.e., 5, 10, or 15 paddocks rotated every 3, 7, or 14 days), the optimal solution was 15 paddocks rotated every 3 days despite being the most labour-intensive stocking strategy.

Farmer preferences were estimated for three hypothetical decision-maker types. Because the two farm types considered are substantially different, results are separately interpreted for intensive and extensive grazing enterprises. A farmer utility of 100% indicates that decision-maker preferences were fully satisfied. This condition only occurred in two instances for the profit-oriented farmer achieving maximum ROLLMRT. For the two ecology-oriented farmers, maximum utility was lower than 100% because the farms were not able to achieve net zero emissions. This would only be possible if the farmer implemented GHG mitigation measures such as mixing supplementary feed with innovative products capable of reducing livestock methane emissions (e.g., Bovaer®). However, the adoption of GHG mitigation measures was beyond the scope of this study.

As shown in **Figure 2**, the preferred scenarios were rotational stocking managed with electric fencing on the lowland beef finishing farm (Scenario 2) and set stocking on the upland suckler cow farm (Scenario 4). On the beef finishing farm, farmer utilities were comparable between set stocking and rotational stocking managed with virtual fencing. On the upland suckler cow farm, the virtual fencing scenario had a very low utility compared to set stocking, but these values did not take into account the fact that the virtual fencing scenario was able to protect the wet heathland habitat. In future research, the HFH-MOLP model will be further adapted to also incorporate an agricultural biodiversity goal to test the effects on farmer utility when combining ecology conservation with the GHG emissions goal.

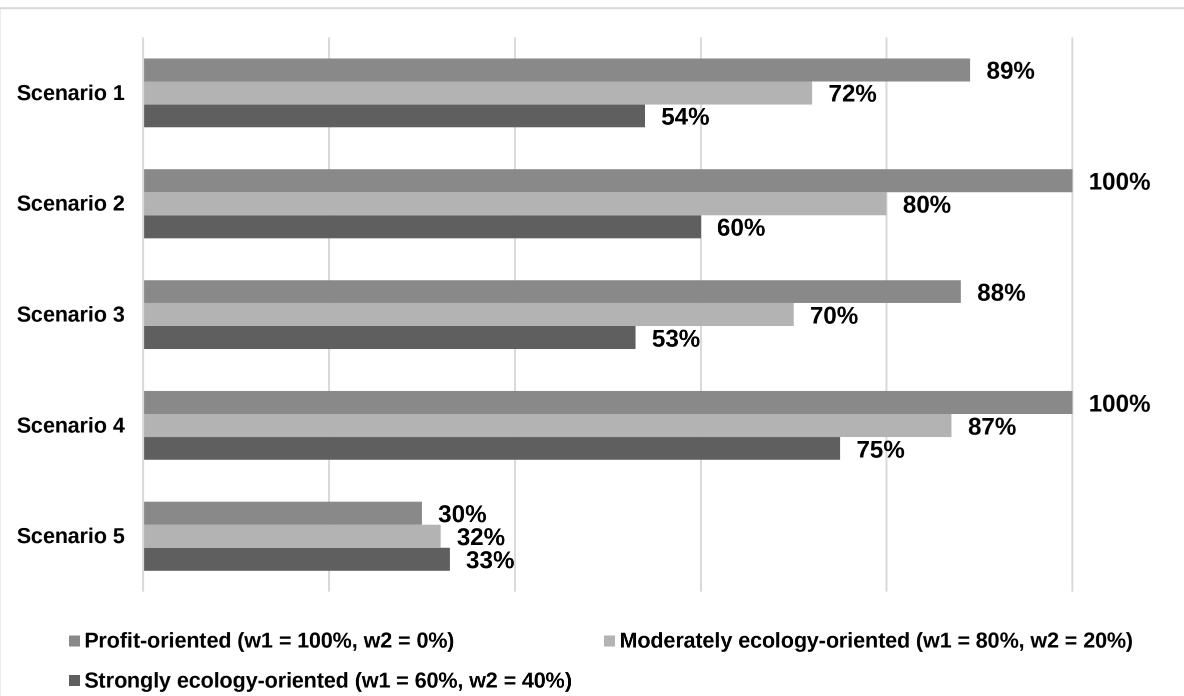

Figure 2. Farmer utility achieved across scenarios. Scenario 1: set stocking, intensive grazing. Scenario 2: rotational stocking (electric fencing), intensive grazing. Scenario 3: rotational stocking (virtual fencing), intensive grazing. Scenario 4: set stocking, extensive grazing. Scenario 5: rotational stocking (virtual fencing), extensive grazing.

Annual whole farm budgets by scenario are provided in **Table 2**. The highest ROLLMRT across farm types coincided with the scenarios preferred by the three tested decision-makers. On the lowland beef finishing farm using virtual fencing, ROLLMRT was about 1% lower than set stocking. This is despite the 3% higher revenue achieved thanks to more beef being produced in rotational stocking. The main contributor to the poor economic performance of the virtual fencing scenario on intensive beef finishing farms was the cost of the virtual fencing system. Indeed, fencing costs in Scenario 3 were about three times those in Scenarios 1 and 2. The rotational stocking scenario managed via electric fencing was the most profitable despite variable costs being the highest across scenarios and overhead costs being higher than set stocking. Virtual fencing completely negated the economic benefits achieved with rotational stocking.

On the upland suckler cow farm, the highest ROLLMRT was achieved in the set stocking scenario, which was more than thrice that in the virtual fencing scenario. The latter scenario would incur a monetary loss if the Government subsidy payment was excluded from the farm budget. Considering the higher beef production revenue in the virtual fencing scenario despite 10% of land being excluded from grazing, virtual fencing adoption might become economically competitive if fencing costs were subsidised. Alternatively, profit-oriented farmers would prefer not to protect environmentally sensitive areas and at least partially recover the investment in the virtual fencing system by allocating the entire farm to grazing operations.

Table 2. Annual whole farm budgets by scenario.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Revenue (A)	**£ 471,835**	**£ 486,524**	**£ 486,524**	**£ 37,147**	**£ 40,621**
Beef production	£ 166,729	£ 181,418	£ 181,418	£ 37,147	£ 38,401
Crop production	£ 305,106	£ 305,106	£ 305,106	-	-
Government subsidy payment	-	-	-	-	£ 2,220
Variable costs (B)	**£ 235,510**	**£ 238,814**	**£ 237,757**	**£ 23,204**	**£ 23,181**
Agricultural inputs	£ 210,772	£ 212,761	£ 212,761	£ 23,204	£ 23,165
Casual labour	£ 2,648	£ 3,147	£ 2,901	£ 0	£ 13
Fuel & electricity	£ 15,234	£ 16,050	£ 15,239	£ 0	£ 3
Silage maize contract harvest	£ 6,857	£ 6,857	£ 6,857	-	-
Overhead costs (C)	**£ 149,305**	**£ 150,024**	**£ 162,860**	**£ 8,633**	**£ 15,827**
Fencing costs	£ 5,898	£ 6,617	£ 19,435	-	£ 7,180
Other overhead costs	£ 143,407	£ 143,407	£ 143,425	£ 8,633	£ 8,647
ROLLMRT (D = A – B – C)	**£ 87,020**	**£ 97,685**	**£ 85,907**	**£ 5,310**	**£ 1,614**

The low utility achieved by ecology-oriented farmers would also question the adoption of virtual fencing for improving a farm's environmental performance. GHG emission values by enterprise and by scenario are provided in **Table 3**. On the intensive beef finishing farm, grazing livestock was the most emitting enterprise, with cattle enteric fermentation being the main contributor to livestock emissions (~90%). In the CFT methodology, enteric fermentation is directly related to animals' gross energy intake from pasture consumption and supplementary feeding. Since supplementary feeding was held constant across the three intensive beef finishing scenarios, enteric fermentation emissions were higher in rotational stocking as a result of higher pasture biomass consumption. This is why the set stocking system (Scenario 1) produced approximately 3% lower GHG emissions compared to rotational stocking on the intensive beef finishing farm. This finding contradicted the expectations that rotational stocking would reduce GHG emissions. However, GHG emissions become lower in rotational stocking in the case they are converted to carbon emission intensities expressed in $kgCO_2eq$ per kg of beef produced. The carbon emission intensity of beef produced in the set stocking scenario is 2.09 $kgCO_2eq$ kg $beef^{-1}$ compared to 1.92 $kgCO_2eq$ kg $beef^{-1}$ in Scenarios 2 and 3.

On the extensive suckler cow farm, rotational stocking generated lower GHG emissions than set stocking because supplementary feed intakes were slightly lower, thus reducing both animal enteric fermentation and nitrogen excretion rates while grazing. Nonetheless, the GHG emission savings in Scenario 5 were close to negligible since supplementary feed consumption was only 0.3% lower compared to set stocking. In terms of carbon emission intensity, the virtual fencing scenario generated 4.08 $kgCO_2eq$ kg $beef^{-1}$, which was 2.4% lower than the 4.18 $kgCO_2eq$ kg $beef^{-1}$ emitted in the set stocking scenario.

Table 3. Annual GHG emissions ($MgCO_2eq$) by enterprise and by scenario.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Grazing livestock	116.67	120.06	119.97	65.27	65.06
Maize silage	25.20	25.20	25.20	-	-
Winter wheat	60.52	60.52	60.52	-	-
Winter field bean	16.36	16.36	16.36	-	-
Total	**218.75**	**222.14**	**222.05**	**65.27**	**65.06**

4. Discussion

As recently reported by ADAS (2023), virtual fencing providers are likely to encounter price resistance from potential adopters in the UK. This is also reflected in the HFH-MOLP model results. A mixed farm simultaneously managing crop operations and grazing livestock would improve its profitability by switching from set to rotational stocking managed with electric fencing rather than virtual fencing. For ecology-oriented farmers, the second best option would be to retain set stocking practices to avoid increasing total farm GHG emissions. Economic outcomes might change if the initial investment in the virtual fencing system and recurring mobile application subscription costs were reduced. Alternatively, virtual fencing collars could be Government-subsidised under schemes such as the UK Farm Investment Fund. Besides, there is also scope to extend the useful life of the collars, which is relatively short compared to physical fences.

An important advantage of the virtual fencing technology is the option to manage livestock remotely, at least during part of the grazing season. Moving cattle across paddocks in the intensive grazing electric fencing scenario requires 0.07 h ha^{-1} of labour, while in the virtual fencing scenario this value is 0.02 h ha^{-1}. However, the virtual fencing system absorbs additional labour time for cattle training compared to electric fencing. In electric fencing systems, animals can adapt to visible fences in as quickly as one day, whereas for livestock to become familiar with virtual fencing takes on average 2.5 days (Maritan *et al.*, 2024). Furthermore, even though electric fences require labour time for moving and maintaining them, a virtual fencing system has two additional tasks. These are the replacement of collar batteries at least once a year and the management of cattle escaping paddocks when they fail to respond to virtual fencing collar cues. Animal escapee rates are negligible in intensive beef finishing systems, but in conservation grazing this operation absorbs 0.03 h ha^{-1} on average due to, for example, animals potentially interacting with members of the public and unleashed dogs.

An interesting finding in favour of the virtual fencing technology is that unitary beef production costs may be lower than set stocking in some cases. On the intensive beef finishing farm, beef production costs are £ 1.25 kg^{-1} in the set stocking scenario and £ 1.20 kg^{-1} in the virtual fencing scenario. The latter cost compares to £ 1.18 kg^{-1} when rotational stocking is managed with an electric fencing system, which is the most economically competitive strategy. If electric fencing is not an option in upland conservation grazing systems, farms adopting set stocking are the most competitive. Beef production costs in this case are £ 4.32 kg^{-1} in set stocking and £ 4.92 kg^{-1} in rotational stocking managed via virtual fencing. On extensive grazing farms, apart from reducing virtual fencing costs as previously suggested, alternatives to make this technology more competitive may include premium payments for beef produced with a lower carbon footprint while ensuring sensitive habitats are protected from grazing livestock. Additionally, continuous and real-time collection of individual animal data may improve compliance with animal welfare standards and reduce veterinary and medicine costs if such data can be used for early detection of disease. At the current technology development stage, virtual fencing only provides animal movement data which lack the required detail and frequency to confidently identify the presence of disease. However, virtual fencing might develop into a multi-purpose technology generating additional economic value in the future.

The GHG emission estimates presented in this analysis highlighted how different beef production systems become preferred depending on how GHG emissions are expressed. If farm GHG emissions are provided in absolute terms, rotational stocking generates higher emissions on intensive beef finishing farms, but not on extensive suckler cow farms. If GHG emissions are expressed as carbon footprints per kg of beef produced, the rotational stocking scenarios are preferrable across both farm types. In both cases, the main contributor to beef GHG emissions is animals' enteric fermentation, which depends on forage and feed intakes and their percentage of digestible energy. A limitation of the adapted GrazFeed decision support tool is that it did not account for the substitutional effect of forage consumption on supplementary feed intakes. This will be resolved in future research. Furthermore, forage digestible energy may vary across stocking methods. In set stocking, livestock are more likely to selectively graze desirable and more nutritious grass species thus affecting pasture botanical composition in the medium to long term. This may in turn reduce the overall grassland nutritional value, thus increasing enteric fermentation emissions. However, the documented effects of stocking methods on forage nutritional value are contrasting and no assumption could be confidently made in this study (e.g., McDonald *et al.*, 2023; Rouquette *et al.*, 2023). Lastly, recent research seem to indicate that intensive rotational systems such as cell grazing lead to increased carbon sequestration in soil, while set stocking practices deplete soil carbon stocks over time (Rivero *et al.*, 2024). The CFT used in this study does not account for potential effects of stocking method on soil carbon dynamics, which would make the estimated GHG emissions questionable in light of the recent findings of Rivero *et al.* (2024).

The present multi-objective analysis hypothesised that virtual fencing adoption would negate the economic benefits achieved with rotational stocking on intensive lowland beef finishing farms. Indeed, the rotational stocking scenario managed with electric fencing generated a farm return of £ 97,685 year^{-1} compared to £ 87,020 year^{-1} in set stocking, while the correspondent virtual fencing scenario generated the lowest farm return (£ 85,907 year^{-1}) due to the £ 13,537 year^{-1} virtual fencing adoption costs. However, the hypothesis that rotational stocking would generate GHG emission savings on lowland intensive beef finishing farms is rejected. Rotational stocking provided increased pasture biomass availability and consequently higher forage intakes and final cattle liveweights, but this resulted in higher GHG emissions due to higher enteric fermentation values. This was regardless of the fencing type used to manage livestock. Beef produced in the modelled rotational stocking systems had a lower carbon footprint than in set stocking, but the total farm emissions were approximately 3.3 $MgCO_2eq$ higher due to increased beef outputs.

The second hypothesis focused on extensive upland suckler cow farms with a conservation grazing approach. Rotational grazing managed with virtual fencing was expected to increase farm profitability, but this was found not to be the case. The upland set stocking scenario generated a farm return of £ 5,310 year^{-1}, while the virtual fencing scenario generated £ 1,614 year^{-1}. This is despite the latter scenario receiving a Government subsidy payment of £ 2,220 year^{-1} for excluding cattle from a sensitive habitat. Revenue from beef production in the upland virtual fencing scenario was higher than in set stocking despite the 10% lower pasture size, but the investment in the virtual fencing technology outweighed this economic benefit. Contrary to the intensive lowland beef finishing system, GHG emissions on the upland extensive grazing farm were found to be lower in rotational stocking regardless if these were expressed as absolute farm emissions or beef emission intensities. The difference in absolute farm emissions between set stocking and rotational stocking managed with virtual fencing was 0.21 $MgCO_2eq$ and hence close to negligible.

5. Conclusion

This multi-objective study identified preferred whole-farm plans for two farm types adopting two stocking methods and three fencing types. On the lowland mixed farm incorporating intensive beef finishing operations, the preferred scenario was rotational stocking managed with electric fencing (Scenario 2). This was regardless of the ecological orientation of the decision-maker, which spanned from 0% for a profit-oriented farmer to 40% for a strongly ecology-oriented farmer. On the extensive upland suckler cow grazing farm, the preferred scenario was set stocking (Scenario 4) for all tested decision-maker preferences. On the first farm case study, virtual fencing negated the economic benefits that are achieved when increasing beef productivity via rotational stocking. Rotational stocking was also found to generate higher total GHG emissions despite the lower carbon footprint values obtained with this stocking method. On the second farm case study, virtual fencing enabled a higher beef productivity and lower GHG emissions while excluding livestock from 10% of the land assumed to host an ecologically sensitive habitat. Nevertheless, farm returns were about 3 times lower than in set stocking due to the high investment cost required to adopt virtual fencing.

Recommendations for virtual fencing providers include economic and technical considerations. From an economic perspective, virtual fencing collars and related mobile application subscription costs should be made cheaper to reduce the likelihood of price resistance from potential adopters. The useful life of the collars is currently 6 years, which is relatively short compared to woven wire and electric fences and could therefore be extended to make this technology more profitable. Lastly, virtual fencing collars could be made approved under schemes such as the UK Farm Investment Fund and their purchase costs subsidised. On conservation-oriented grazing farms, premium payments paid for beef produced with a lower carbon footprint and without damaging sensitive habitats could alternatively make virtual fencing more economically competitive than set stocking. Technical considerations include the possibility to improve the level of detail and frequency of data collected by the collars, thus generating additional value by transforming virtual fencing into a multi-purpose technology. For example, these data may simplify compliance with animal welfare standards and reduce veterinary and medicine costs if reliable early detection of disease became technically feasible.

The limitations of this analysis are mainly related to the quantification of the environmental goal in the HFH-MOLP model, which strongly affected farmer utility levels achieved across scenarios. Firstly, the adapted GrazFeed model used to calculate animal parameters on the lowland beef finishing enterprise did not account for the substitutional effects of pasture consumption on supplementary feed intakes. This aspect had a strong influence on the enteric fermentation impacts estimated by the CFT, which was the main contributor to beef GHG emissions. Secondly, the CFT does not simulate soil carbon stock dynamics, which, according to recent findings, are likely to be affected by stocking method. Rotational stocking strategies may promote carbon sequestration in soil, while set stocking tends to deplete soil carbon stocks over a relatively short time (Rivero *et al.*, 2024). Therefore, GHG emissions in the rotational stocking scenarios might have been overestimated. Lastly, the virtual fencing scenario on the upland conservation grazing farm did not account for the farmer utility benefits achieved by protecting a sensitive area from grazing livestock. Placing importance on an agricultural biodiversity goal accounting for ecological conservation and potentially for the reduced incidence of overgrazed pasture would increase farmer utility in rotational stocking systems. These limitations will be addressed in future research.

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