A preliminary economic and environmental analysis of virtual fencing for intensive lowland grazing

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Abstract

Virtual fencing is an unseen boundary created using Global Navigation Satellite Systems and managed remotely to control grazing livestock without physical fences. The animals experience the virtual boundaries as audio or vibration cues and possibly as electric shocks administered through battery-powered collars.

The aim of this study is to compare the economic performance and environmental impact of two stocking strategies and three fencing types on a mixed farm in the UK West Midlands. The two stocking strategies include set stocking and rotational stocking for intensive beef finishing operations. The three fencing types are woven wire, electric, and virtual fencing.

This is the first bioeconomic analysis of virtual fencing based on whole-farm resource planning. Farmer grazing management choices and trade-offs between farm profitability and carbon footprint are explored via multi-objective optimisation.

Results show that the cost of the virtual fencing system studied almost completely negates the economic benefits achieved with rotational stocking in intensive grazing systems. Environmental impact, defined as carbon footprint of total farm output, is higher in rotational grazing than in set stocking systems, but comparable between electric and virtual fencing scenarios.

In intensive beef finishing systems, virtual fencing does not provide sufficient advantages compared to electric fencing. To make virtual fencing more competitive on this type of farm, technology providers should reduce its adoption cost. A hypothesis for future research is that virtual fencing is a promising solution on extensive grazing enterprises located in sensitive landscapes or remote areas where installing physical fences is uneconomical or not allowed.

Keywords: Virtual fencing, Profitability, Carbon footprint, Multi-objective optimisation

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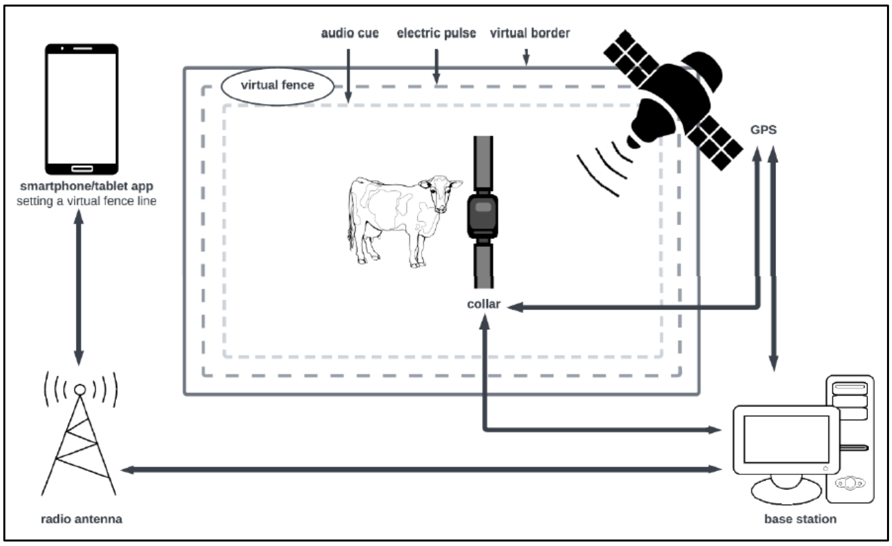
1. Introduction

Virtual fencing is an invisible boundary managed remotely and in real-time by technology which allocates animals to target areas without physical fences (DEFRA, 2022; Golinski *et al.*, 2023). Animals experience virtual fencing as audio or vibration cues and potentially as electric shocks administered through battery-powered collars (DEFRA, 2022). This technology exploits the cognitive activation theory of stress whereby animals learn to respond to non-aversive stimuli to avoid an aversive stimulus such as an electric shock (Golinski *et al.*, 2023). To-date, virtual fencing is being adopted in a context of increasing environmental restrictions, growing consumer trends towards grassfed meat, and rising concerns about animal welfare (Behrendt and Weeks, 2019). Globally, O'Donoghue (2022) estimated that more than 40,000 collars are in use on more than 3,000 farms. In the UK, there were more than 140 virtual fencing users as of 2022, with this number expected to increase, especially for conservation graziers (ADAS, 2023; DEFRA, 2022). A visual representation of a general virtual fencing system is provided by Golinski *et al.* (2023) (**Figure 1**).

Figure 1 – A virtual fencing system (Golinski *et al.*, 2023: p.3)



The first concept of using audible cues emitted by a collar-mounted device appeared about 50 years ago, but this was initially restricted to companion animals (Golinski *et al.*, 2023). In 1987, Peck's Invisible Fence manufactured the first virtual control devices for domestic livestock in the US (Golinski *et al.*, 2023). Today, several virtual fencing products for cattle and small ruminants are available worldwide (Golinski *et al.*, 2023). Established virtual fencing technology providers include eShepherd® (Australia), Halter® (New Zealand), Nofence® (Norway), and Vence® (US) (Golinski *et al.*, 2023). These systems use electric pulses ranging from 600 to 4000 V that last from less than a second to 10 seconds (Golinski *et al.*, 2023). The virtual fencing collars rely on Global Navigation Satellite Systems (GNSS) for locating livestock (Golinski *et al.*, 2023). The collars are equipped with batteries that may be either charged via photovoltaic cells or grid electricity (Golinski *et al.*, 2023). Their weight is usually below 2 kg (Golinski *et al.*, 2023). Virtual fencing systems enable precision livestock farming (PLF) i.e., technology-aided practices for management and monitoring of livestock to improve their production, reproduction, health, welfare and environmental impact (Vranken and Berckmans, 2017).

In the UK, grazing operations have traditionally relied on set stocking practices (DEFRA, 2022). Set stocking consists of allowing animals to access a grazing area for a relatively long period of time without interruption (Allen *et al.*, 2011; DEFRA, 2022). This type of pasture management may lead to the following problems: (i) patch grazing due to animals feeding on more palatable grass species; (ii) soil compaction and overgrazing owing to animals being continuously present on the same unit of land; and (iii) high-trafficked areas leading to soil poaching, possibly increasing risks of animal infections and injuries (DEFRA, 2022). From an economic perspective, hosting livestock continuously in the same grazing area requires lower labour inputs, but the absence of resting periods negatively affects pasture growth rates and potentially botanical composition in the longer term. As a result, set stocking systems carry lower stocking rates (i.e., the number of animals grazing on a given amount of land for a specified time), or require substantial amounts of supplementary feed to maintain productivity, especially during periods of limited pasture supply.

Alternative livestock management practices are generally referred to as rotational stocking (or rotational grazing). Allen *et al.* (2011: p.17) define rotational stocking as "a method that utilises recurring periods of grazing and rest among three or more paddocks in a grazing management unit throughout the time when grazing is allowed". Rotational stocking enables higher stocking rates due to an increased efficiency in forage consumption as a result of improved management control (Allen *et al.*, 2011; Gillespie *et al.*, 2008; Meat & Livestock Australia, 2023). Some authors argue that rotational stocking may provide several environmental benefits, but scientific evidence is contrasting. A literature review by McDonald *et al.* (2023) reported that rotational stocking promotes several drivers of soil carbon sequestration such as ground cover maintenance, appropriate pasture residual, beneficial botanical composition, and lower plant damage from persistent trampling (McDonald *et al.*, 2023). However, the direct impact of grazing management on soil carbon sequestration was found to be statistically insignificant (McDonald *et al.*, 2023). Economic drawbacks of rotational stocking include higher infrastructure and labour requirements as well as a greater investment risk (Gillespie *et al.*, 2008; Meat & Livestock Australia, 2023). PLF technologies such as virtual fencing may help mitigate these aspects while also contributing to positive environmental impacts.

A recent independent economic analysis conducted by the British Agricultural Development and Advisory Service (ADAS) focused on the economics of virtual fencing on four cattle grazing farms adopting this technology in the UK (ADAS, 2023). This analysis used a partial budgeting approach. The tested farm types included: (i) a farm introducing cattle into an arable rotation; (ii) a farm focusing on regenerative agriculture; (iii) a farm already using rotational stocking managed with electric fencing; and (iv) a farm transitioning from set to rotational stocking. The analysis reported that rotational stocking managed via virtual fencing led to positive economic outcomes on the first and fourth farms, but not on the second and third (ADAS, 2023). However, ADAS acknowledged that, without grant support, virtual fencing companies will continue to encounter price resistance from all kinds of commercial farmers (ADAS, 2023). ADAS concluded by encouraging social science researchers to further investigate into the economics of virtual fencing technology. The present study provides a first economic analysis of virtual fencing based on whole-farm resource planning while taking into account the carbon footprint of cattle liveweight produced under three types of intensive lowland grazing systems in the UK West Midlands.

2. Materials & methods

The three types of intensive lowland grazing systems analysed in this study include: (i) a mixed beef finishing farm managed via a set stocking approach (scenario 1); (ii) a mixed beef finishing farm relying on rotational stocking and conventional electric fencing (scenario 2); and (iii) a mixed beef finishing farm using rotational stocking supported by virtual fencing (scenario 3). For each scenario, the return on operator labour, management and risk taking (ROLMRT) and the carbon footprint of total farm output are quantified. The economic performance and environmental impact of each scenario are compared to answer the following research question: does virtual fencing enable a better economic outcome and a lower total carbon footprint compared to set stocking and/or rotational stocking managed via electric fencing? The hypotheses are: (i) rotational stocking is more profitable than set stocking, but less so when managed with virtual fencing due to the cost of the virtual fencing technology; and (ii) rotational stocking helps reduce the total farm carbon footprint regardless of fencing type.

These hypotheses are tested with the Hands Free Hectare multi-objective linear programming model (HFH-MOLP). Multi-objective linear programming models identify trade-offs among conflicting economic, environmental, and social goals by quantifying the unwanted deviation from a target based on decision-maker preferences (Cocklin *et al.,* 1986; Ignizio, 1983). These models are usually solved by software packages and may rely on different mathematical structures depending on the problem at hand. 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. The HFH-MOLP uses the goal programming approach described in Hazel and Norton (1986: p.72). It is coded in the General Algebraic Modelling System (GAMS) (GAMS Development Corporation, 2023). For more information on the original single-objective HFH-LP model, see Lowenberg-DeBoer *et al.* (2021).

The composite objective function used in the analysis is as follows:

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

where, G is the objective variable to be minimised, which represents the loss of utility for the decision-maker; w_1 is the weight assigned to the economic goal, with values of 1, 0.8, or 0.6 depending on the decision-maker type; w_2 is the weight assigned to the ecological objective, with values of 0, 0.2, or 0.4 depending on the decision-maker type; G_1^- and G_2^- are so-called deviational variables required to calculate the percentage deviation from target values for the two tested goals; G_{opt} is the maximum ROLMRT generated on farm across scenarios (G_{opt} = £45,786); and G_{wrs} is the maximum carbon footprint of total farm outputs across the range of crop and grazing enterprise combinations (G_{wrs} = 71 kgCO_2eq).

The modelled farm is a 295-ha mixed lowland farm located in the UK West Midlands. 50% of the available land is allocated to winter wheat, 25% to winter field bean (break crop), and the remaining 25% is equally divided between an intensive summer beef finishing enterprise and maize silage production used as supplementary feed. Pasture is assumed to be sown in August or September following local practice (AHDB, 2018) and reseeded every 4 years (Redman, 2022). Mixed sexed cattle are purchased at 8 months old, grazed for 300 days and sold at 18 months old (Redman, 2022). The initial and final cattle liveweights are 280 kg and 595 kg, respectively (Redman, 2022). Cattle liveweight price is £2.30/kg (Redman, 2022). The animals are assumed to feed on a 4-year grass ley with a nutritional value of 12.8 MJ per kg of dry matter (DM) (60% of cattle diet) and on supplementary feed (40% of cattle diet) (Redman, 2022). Supplementary feed is composed of 3,000 kg of maize silage and 330 kg of concentrate feed per head per year (Redman, 2022). Beef variable costs include concentrate feed, veterinary expenses, forage and maize production costs, purchased stores, and miscellaneous expenses (Redman, 2022). In the two rotational stocking scenarios, the grazing area is assumed to be divided into 10 rectangular paddocks of equal size (3.3 ha) whose length is assumed to be twice as long as their width. Cattle are moved to adjoining paddocks every 2 days i.e., 150 times a year. Stocking rates, cattle growth rates and feed intakes are calculated using an adapted version of the GRAZPLAN animal biology model based on UK, EU and US feeding standards for domesticated animals (Freer *et al.*, 2007; 2012). Mean stocking rates are 3.52 cattle/ha for the set stocking system (mean herd size = 116) and 4.95 cattle/ha for the two rotational stocking systems (mean herd size = 163). The mean yearly pasture consumption is 1,872 kg DM/head in the set stocking scenario, and 1,732 kg DM/head in the rotational stocking scenarios.

Table 1 – Key parameters for beef finishing enterprises across scenarios

	Set stocking (Scenario 1)	**Rotational stocking (Electric fencing) (Scenario 2)**	**Rotational stocking (Virtual fencing) (Scenario 3)**
Mean stocking rate	3.52 cattle/ha	4.95 cattle/ha	
Pasture growth rates	Average values from AHDB (2018: p.8)	30% higher than in Scenario 1 following Rouquette *et al.* (2023)	
Mean pasture consumption	1,872 kg DM/head per year	1,732 kg DM/head per year	
Mean labour time requirements	1.19 person days/ha/year	1.51 person days/ha/year	1.49 person days/ha/year
Fencing costs	£ 1,435/year	£ 2,300/year	£ 19,692/year

Note: Mean parameters indicate minor variations between pasture sown in August or September. Mean labour time requirements are for both crop and beef production enterprises combined (1 person day =

8 hours). Fencing costs include insurance and maintenance of conventional woven wire fencing erected along the outer pasture edges in all scenarios.

As shown in **Table 1**, the set and rotational stocking systems are differentiated by stocking rates, pasture growth rate, and pasture consumption. Scenarios 2 and 3 are further differentiated by mean labour time requirements and the type of fencing used to manage cattle. Labour times were obtained from multiple literature sources, including Redman (2022) and Gillespie *et al.* (2008). Fencing costs of woven wire and electric fencing follow estimates by ABC (2022), while those of virtual fencing are based on quotations by real-world virtual fencing suppliers.

Data are coded into the GAMS software and results generated for three hypothetical decision-maker types to test the impact of farmer preferences on fencing and stocking system choice. These include: (i) a profit-oriented farmer (w_1 = 1, w_2 = 0; where w_1 = economic weight and w_2 = ecological weight); (ii) a moderately ecologically oriented farmer (w_1 = 0.8, w_2 = 0.2); and (iii) a strongly ecologically oriented farmer (w_1 = 0.6, w_2 = 0.4).

Carbon footprint estimates are calculated using the Cool Farm® Tool, which relies on Tier 1 and 2 methods developed by the UN Intergovernmental Panel on Climate Change (Cool Farm Alliance, 2024). The input data to measure the carbon footprint of crops includes yields per hectare; fertiliser, herbicide, fungicide, and pesticide rates and their chemical composition; fuel and electricity consumption; and soil acidity, texture, drainage and organic matter parameters. For beef, data inputs include grazing period; number of purchased and sold animals; grazing area; pasture fertilisation rates; supplementary feed types and intakes in kg DM/day; and fuel and electricity consumption for pasture and livestock management. The carbon footprint estimates excluded emissions generated off-farm such as fertiliser production and transportation of farm resources.

3. Results

Model results indicate that farmland allocation does not vary across scenarios or decision-maker types. Out of the total 295 ha, 10% of the land is assumed to include non-productive features such as farm buildings, rights of way or other unproductive land following Lowenberg-DeBoer *et al.* (2021). The remaining 265.5 ha are assumed to be productive land. The HFH-MOLP model approximately allocates 133 ha to winter wheat, 66 ha to winter field bean, 33 ha to maize silage, and 33 ha to cattle grazing. Pasture is always planted in August rather than September because the former allows for longer pasture establishment before the grazing season begins in March. This enables August sown pasture to carry higher stocking rates in the first year and it is therefore preferred. Across all scenarios, winter wheat is sown one month late on 14% of the available land, resulting in a 0.06% total wheat yield loss. This is owing to tractor availability being partly constrained for winter wheat October planting.

Annual farm operator labour requirements are 201 person days in the set stocking scenario, and 213 person days in the two rotational stocking scenarios. Casual labour requirements are substantially higher in the two rotational stocking scenarios. 117 days of casual labour are needed to manage a set stocking system compared to 190 and 186 days required in the electric and virtual fencing rotational grazing systems, respectively. In all scenarios, August is the most labour intensive month due to winter wheat harvesting, pasture sowing, and routine cattle management operations. Total annual labour requirements are 318 days in Scenario 1, 403 days in Scenario 2, and 399 days in Scenario 3. Annual labour times by enterprise are provided in **Table 2**. Depending on fencing type, rotational stocking requires between 42% and 44% additional labour compared to set stocking. Adoption of virtual fencing saves approximately 2% of total labour inputs compared to electric fencing.

Table 2 – Annual labour times by enterprise expressed in 8-hour person days

	Set stocking (Scenario 1)	**Rotational stocking (Electric fencing) (Scenario 2)**	**Rotational stocking (Virtual fencing) (Scenario 3)**
Maize silage	11	11	11
Winter wheat	76	76	76
Winter field bean	36	36	36
Cattle grazing	195	280	276
TOTAL PERSON DAYS	**318**	**403**	**399**

The economic and environmental performance of the three tested grazing systems highlight two major differences. Rotational stocking managed with electric fencing is 63% more profitable than set stocking and 54% more profitable than virtual fencing. The total farm carbon footprint is 16% higher in rotational stocking systems compared to set stocking. Although the carbon footprint per kg of cattle liveweight in rotational stocking is 7% lower than in the set stocking scenario, the higher productivity of rotational stocking leads to a higher total farm carbon footprint. Because of the almost negligible effect of electricity consumption on greenhouse gas emissions, fencing choice in the rotational stocking scenarios does not affect their total farm carbon footprint. Model goal results are provided in **Table 3**.

Table 3 – ROLMRT and total farm carbon footprint across scenarios

	Set stocking (Scenario 1)	**Rotational stocking (Electric fencing) (Scenario 2)**	**Rotational stocking (Virtual fencing) (Scenario 3)**
ROLMRT (GBP)	28,141	45,786	29,826
Carbon footprint ($kgCO_2eq$ * total farm output^{-1})	56.8	65.8	65.8

Total cattle liveweight production in scenario 1 is 70.6 tonnes, while 98.8 tonnes of cattle liveweight are produced in the rotational stocking scenarios i.e., 40% higher. This leads to £65,174 more revenue generated in rotational stocking, but also results in £39,052 more costs for the additional agricultural inputs required to sustain higher stocking rates and in about £9,800 increased labour costs for managing a more intensive grazing system. The investment in movable electric fences is estimated at about £6,406 with a 20-year useful life (Windh *et al.*, 2019), while the virtual fencing system is priced at £53,405 with an estimated 6-year useful life. Such a substantial investment required to purchase a virtual fencing system almost completely negates the additional revenue achieved with higher cattle liveweight production compared to set stocking. However, when the imputed cost of family labour is taken into account, set stocking economically outperforms the virtual fencing scenario (**Table 4**). Likewise, comparison of electric and virtual fencing indicates that the former is more profitable despite the £361 labour savings and the £1,101 lower electricity costs achieved in the latter system (**Table 5**).

Table 4 – Virtual fencing effect on profit in comparison to set stocking

Increased revenue	Increased cattle liveweight output	£65,174
Increased costs	Agricultural inputs	£39,052
	Labour	£9,841
	Electricity	£1
	Overhead costs	£18,287
TOTAL EFFECT ON PROFIT (GBP/year)		**- £2,007**

Table 5 – Virtual fencing effect on profit in comparison to electric fencing

Saved costs	Labour	£361
	Electricity	£1,101
Increased costs	Overhead costs	£17,422
TOTAL EFFECT ON PROFIT (GBP/year)		**- £15,960**

The carbon footprint of the cattle finishing enterprise calculated for the set stocking scenario is 3.53 kgCO_2eq per kg of liveweight. In rotational stocking, this value is 3.29 kgCO_2eq per kg of liveweight. Almost 90% of the carbon footprint is generated by methane emissions as a result of enteric fermentation. Other main contributors are cattle excretions produced while grazing (6%) and grassland fertilisation (6-8%), whereas a minor contribution is caused by on-farm manure management (< 0.1%). Cattle liveweight carbon footprints by scenario are provided in **Table 6**.

Table 6 – Cattle liveweight carbon footprint by scenario (kgCO_2eq per kg of liveweight)

	Set stocking (Scenario 1)	Rotational stocking (Electric fencing) (Scenario 2)	Rotational stocking (Virtual fencing) (Scenario 3)
Enteric fermentation	3.04	2.90	
Cattle excretions	0.21	0.19	
Grassland fertilisation	0.27	0.19	
Manure management	0.01	0.01	
TOTAL CARBON FOOTPRINT	**3.52**	**3.29**	

Lastly, farmer utilities across scenarios vary according to the decision-maker type considered (**Table 7**). Because of the higher profitability achieved, the preferred scenario is rotational grazing managed via electric fencing for all three decision-maker types. This is despite the 16% higher carbon footprint of total farm output in rotational stocking. The second best choice depends on the importance assigned to carbon footprint minimisation. For the profit-oriented farmer (w_1 = 1, w_2 = 0), the second best choice is rotational grazing managed via virtual fencing. For the moderately ecologically oriented farmer, the utilities achieved in the set stocking and virtual fencing scenarios are comparable (±1%). Conversely, the strongly ecologically oriented farmer prefers set stocking because of the lower total farm carbon footprint resulting from a lower cattle liveweight output. Sensitivity testing on the economic and environmental weights suggests that no trade-off occurs between ROLMRT and carbon footprint when the economic weight ranges from 0.3 to 1. However, trade-offs exist when carbon footprint minimisation becomes extremely important (i.e., when w_1 is lower than 0.3), but this is not expected to occur on commercial farms. If w_1 is 0.1 or lower, the HFH-MOLP model switches to no production and all available farmland is left unused.

Table 7 – Farmer utility achieved by decision-maker type

	Set stocking (Scenario 1)	Rotational stocking (Electric fencing) (Scenario 2)	Rotational stocking (Virtual fencing) (Scenario 3)
Profit-oriented farmer (w_1 = 1; w_2 = 0)	61%	100%	65%

Moderately ecology oriented farmer **($w_1 = 0.8$; $w_2 = 0.2$)**	53%	82%	54%
Strongly ecology oriented farmer **($w_1 = 0.6$; $w_2 = 0.4$)**	45%	63%	42%

4. Discussion

Farmland allocation does not vary across scenarios and decision-maker types. This indicates that the HFH-MOLP model is able to optimally allocate farm resources regardless of grazing system, fencing type, and importance of carbon footprint minimisation. Tractor time is constrained in October in all scenarios resulting in almost negligible winter wheat yield losses. Under the equipment ownership scenario assumed in this study, purchasing an additional tractor is not economically optimal and leads to further utility loss for the decision-maker. Total labour inputs are 42-44% higher in rotational stocking compared to set stocking. These include 12 additional person days of farm operator labour, and 69-73 additional days of casual labour. Electric fencing approximately requires 4 more casual labour days compared to virtual fencing.

Although moving physical fences is expected to be substantially more time consuming than managing virtual fences via mobile app, some farm operations in the latter system require additional labour inputs. For example, helping cattle to adapt to electric fences requires a one-day training compared to an estimated 2.5-day training needed in a virtual fencing system (McDonald, 1981; O'Donoghue, 2022). Moving electric fences with the aid of a quad bike is relatively quick, especially when this is performed during routine cattle management operations without requiring an additional trip to the farm. Moving the herd across paddocks takes 45 minutes per move when the farmer relies on electric fences (ADAS, 2023). In a virtual fencing system, moving the herd is assumed to require 50% of that time and that 2 moves out of 3 are managed remotely. However, while the absence of physical fences may speed up cattle movement, a virtual fencing system requires additional actions such as assigning the collars to a new paddock via mobile app, checking the collars battery level, ensuring the collars are correctly worn by the animals, and ground-truthing the invisible boundaries to avoid animal welfare issues and system malfunctions. Electric fencing absorbs 3.50 labour hours per ha per year for repair and maintenance (Gillespie *et al.*, 2008), but a virtual fencing system has two additional operational requirements. These are collar battery replacement, which is assumed to take place once a year in October because of decreased solar radiation, and returning cattle escapees to their assigned paddock or grazing area. The latter are assumed at 0.76 escape events per head per month following Confessore *et al.* (2022), with 90% of cattle expected to rejoin their herd without human intervention (DEFRA, 2022). Although more accurate data are needed to validate many of these assumptions, this preliminary analysis suggests that labour requirements to operate electric and virtual fencing systems are not substantially different.

Rotational grazing managed with electric fencing is the scenario generating the highest ROLMRT. Owing to the higher productivity of rotational stocking, the virtual fencing scenario has a 6% higher ROLMRT compared to the set stocking scenario. However, when the imputed cost of operator labour is taken into account, the adoption of virtual fencing leads to a farm income loss of about £2,000. This is mainly because of the high investment cost required to purchase a virtual fencing system. For the same reason, virtual fencing is almost £16,000 more expensive than electric fencing annually. The first hypothesis of this study is accepted for lowland intensive grazing systems in the UK West Midlands. However, a more complete economic analysis should aim to assign a monetary value to the data collected via the virtual fencing mobile app and to the increased work flexibility enabled by remote cattle management.

In terms of environmental performance, set stocking has the lowest total farm carbon footprint. This is regardless of the lower carbon footprint of cattle liveweight output under rotational stocking. On a mixed farm, the higher proportion of liveweight output in total farm production when cattle are rotationally stocked results in a 16% higher overall carbon footprint for the objective function weights considered. Therefore, the second hypothesis is rejected for lowland intensive grazing enterprises. However, three limitations in the carbon footprint assessment might have biased these estimates in favour of set stocking, namely: (i) soil carbon sequestration may be greater in rotational stocking and this was not taken into account; (ii) cattle diet was kept constant across scenarios while lower intakes of supplementary feed could be assumed in rotational stocking; and (iii) effects of stocking system on forage quality was not captured in the adapted version of the GRAZPLAN animal biology sub-model even though pasture resting period dynamically interacts with pasture growth, forage digestibility and nutritional value.

The farmer utilities shown in **Table 7** suggest that rotational grazing managed with conventional electric fencing is the preferred choice regardless of the importance of carbon footprint minimisation. The additional ROLMRT achieved in this scenario outweighs its 16% higher total farm carbon footprint. The second best choice depends on the weight assigned to the economic goal. A profit-oriented farmer would choose a virtual fencing system, a moderately ecologically oriented farmer would be indifferent to adopting rotational stocking managed with virtual fencing or set stocking, while a strongly ecology oriented farmer would prefer set stocking. Interestingly, no trade-off between economic and environmental farm performance exists as long as the economic weight is at least 30%, which is expected to be the case on all commercial farms. In other words, the total carbon footprint cannot be minimised any further without severely compromising farm production. However, it is important to highlight that the findings of this preliminary analysis are only applicable to mixed farms located in the UK West Midlands, and to lowland intensive grazing beef finishing enterprises. For example, farmer preferences as well as economic and environmental performances may be very different on extensive grazing beef farms situated in less favoured areas. This may especially be the case in ecology conservation grazing systems and upland farms where installing electric fences might be infeasible, impractical, or not allowed.

For intensive lowland mixed farms, the overall conclusion of this analysis aligns with what has been reported by ADAS (2023); namely, virtual fencing companies are likely to continue to encounter price resistance from commercial farmers. A single virtual fencing collar costs about £300. In this study, it was assumed that one spare battery for every five collars was required to minimise the number of trips during collar battery replacement operations in October. Additionally, two battery chargers (£80 each) and annual subscription costs to the virtual fencing app (£28 per collar per year) were included as part of the investment cost. After accounting for opportunity cost of capital, depreciation, insurance, and maintenance, adoption of virtual fencing resulted in an annual cost of £18,257 if collars are assumed to have a 6-year useful life. For virtual fencing technology providers, it would be recommended to extend the useful life of the collars beyond 6 years and to reduce the overall cost of the system. The latter could be achieved by reducing the collars purchase cost, by reducing annual subscription fees for the virtual fencing app, and by supporting the eligibility of this technology under grant schemes such as the UK Farming Investment Fund.

5. Conclusion

To the best of the authors' knowledge, this preliminary analysis is the first multi-objective study of virtual fencing systems using a whole-farm resource planning approach. It focused on assessing the economic performance and environmental impact of a 295-ha mixed farm in the UK West Midlands while comparing grazing management choice between set and rotational stocking enabled by three fencing options. ROLMRT and total farm carbon footprint were estimated using the HFH-MOLP model developed at Harper Adams University.

Results showed that the cost of the virtual fencing system studied negates the economic benefits achieved with rotational stocking in intensive grazing systems. Although managing electric fencing is expected to incur higher labour requirements than virtual fencing, labour inputs of these two systems were comparable. This is because supervising a virtual fencing system involves additional farm operations such as longer animal training, ensuring correct wearing of cattle collars and sufficient collar battery power, as well as ground-truthing of invisible boundaries. The electricity savings achieved in a virtual fencing system do not compensate for its high investment cost. As a result, rotational stocking managed with electric fencing is 54% more profitable than virtual fencing. However, this estimate does not take into account the monetary value of data collected by the virtual fencing technology or the benefit of increased work flexibility when livestock is monitored remotely.

The environmental impact, defined as carbon footprint of total farm output, is higher in rotational grazing than in set stocking systems, but comparable across the two fencing types considered. Cattle liveweight output in a set stocking system has a 16% higher carbon footprint compared to rotational stocking, but a higher proportion of cattle liveweight in the total farm output in the latter case leads to increased on-farm greenhouse gas emissions. Nevertheless, this preliminary analysis did not consider the effects of grazing management on soil carbon sequestration, supplementary feed intake, and forage quality. These aspects may further reduce the carbon footprint of rotationally grazed cattle and diminish the overall environmental impact of rotational stocking.

In lowland intensive beef finishing systems, virtual fencing does not provide sufficient economic or environmental benefits to be preferred over rotational stocking managed with electric fencing. For strongly ecology oriented decision-makers, the utility achieved when adopting virtual fencing is also lower than that in the set stocking scenario. However, in less favoured areas where installing electric fences is infeasible, impractical, or not allowed, virtual fencing may make rotational grazing under extensive conditions more profitable than set stocking while also better promoting environmental conservation. This hypothesis will be tested in future research. For virtual fencing technology providers, it is advised to extend the useful life of the cattle collars beyond 6 years and to reduce the investment required to adopt the system. Decreasing the cost of the collars, lowering the annual subscription fees of the virtual fencing mobile app, and encouraging the eligibility of this technology under available Government grants will reduce price resistance from intensive grazing commercial farmers in the UK West Midlands.

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Conflict of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The data that support the findings of this study are available from the corresponding author, Elias Maritan, upon request.

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