Profitability of regenerative cropping with autonomous machines: An ex-ante assessment of a British crop-livestock farm

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Abstract.

Farmers, agroecological innovators and research have suggested mixed cropping as a way to promote soil health. Mixing areas of different crops in the same field is another form of precision agriculture's spatial and temporal management. The simplest form of mixed cropping is strip cropping. In conventional mechanized farming use of mixed cropping practices (i.e., strip cropping, pixel cropping) is limited by labour availability, rising wage rates, and management complexity. Regenerative agriculture research suggests that including forages, livestock and manure in the strip crop system can improve soil health, but forages and livestock increase labour and management challenges. This study hypothesized that regenerative narrow strip cropping with swarm robots could be profitable for an integrated British crop-livestock farm, thereby help

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Great Britain meet food security, carbon-net-zero target and other sustainability challenges of biodiversity, animal welfare and rural levelling up. Using the autonomous farming demonstration experience of the Hands Free Hectare (HFH) project at Harper Adams University in the UK, this study modelled a five year 'winter wheat-winter barley-nectar flower mix-winter wheat-spring bean' yearly rotations as termed as 'crop only system' and a five year rotation of winter wheat-winter barley-grass ley-winter wheat-spring bean that is termed as 'integrated crop-livestock system'. The nectar flower mix was valued with a government environmental subsidy payment, and the grass ley was valued in-terms of the support to feed intensive winter finishing suckled calves. Results from the 'steady state' Hands Free Hectare-Linear Programming (HFH-LP) mathematical model applied to a 500 ha British farm shows that strip cropping with a fleet of relatively small autonomous machines (i.e. swarm robots) achieved higher profitability for 'crop only systems', but the added labour and machine costs in the integrated crop-livestock systems made them economically uncompetitive. This study considered intensive beef finishing instead of grazing livestock because grazing in two-meter width strips was not practical. The farm economics analysis of autonomous regenerative practices reveal that crop robots have the potential to enable the adoption of regenerative agricultural practices compared to conventional regenerative practices, but incorporating livestock into those autonomous regenerative systems is challenging.

Keywords.
Crop robots, agricultural diversification, strip intercropping, mixed cropping, regenerative agriculture, economics.

Introduction

Mixed cropping systems are well known to reconcile multifunctionality of arable landscapes including soil nutrients, light, water, reducing pest, diseases infestation, soil erosion and producing more biomass that stabilize and increase yield, enhance biodiversity, and ensure diversified food for all (Raseduzzaman and Jensen 2017; Weltzien and Christinck 2017). In arable farming systems, agroecological farming (FAO 2019) and regenerative agriculture (Tittonell et al. 2022) embrace the mixed cropping integrated ecological principles, together with economic and social principles for greater resilience (Sinclair et al. 2019). Worldwide multiple mixed cropping systems such as pixel, relay, strip cropping has been advocated to maximize spatio-temporal heterogeneity within the field (Juventia et al. 2022). Even though mixed cropping systems were prevalent in manual arable agriculture (Francis et al. 1986), with the advent of mechanization, industrial monoculture (whole field sole cropping) has been scaled up to take the advantage of labour productivity (Hamilton et al. 2022; MacDonald et al. 2018) because mixed cropping substantially increases labour and machinery costs (Ward et al. 2016).

Over the last few decades, capital-labour substitution with autonomous mixed cropping is suggested to take the opportunity costs advantage of mechatronic technology (Davies 2022; Pearson 2007; Rose et al. 2021). However, complex mixed cropping systems increase the engineering challenges even in autonomous farming systems due to varying plant growth and height patterns (Ditzler and Driessen 2022). In this backdrop, considering the technical feasibility, strip cropping is suggested because the technical challenges could easily be handled even with conventional mechanization operated with human drivers (Alarcón-Segura et al. 2022; Exner et al. 1999; van Apeldoorn et al. 2020). Strip cropping is a farming practice where two or more crops are grown simultaneously in adjacent strips. In this system, the strips are wide enough for independent crop cultivation and narrow enough to facilitate crop interactions (Brooker et al. 2015; Hernández-Ochoa et al. 2022; Vandermeer 1989). However, strip cropping system is not usually a profitable solution in conventional mechanized farm because of substantial amount of labour and higher machinery costs requirement (Ward et al. 2016). Based on the limitations of the existing state of the art, recent research found that autonomous strip cropping is a profitable approach to facilitate sustainable intensification solution (Al-Amin et al. 2024). Worldwide several autonomous crops only system demonstration research showed the technical feasibility of strip cropping in cereal-grain (Harper Adams University (HAU) 2023) and cereal-vegetable (Cruz Ulloa et al. 2022; DuckSize 2024; Schoorlemmer and van Apeldoorn 2019) crop only farming systems, whereas the integrated crop-livestock farming systems are yet to be explored.

The integrated crop-livestock farming systems are advocated in regenerative agriculture and receiving growing attention by civil society, NGOs, media, research, policy makers and multinational food companies considering agronomic and ecological challenges (Giller et al. 2021; Gosnell et al. 2019; Tittonell et al. 2022; Umantseva 2022). This integrated farming system could help achieve five soil health principles through minimizing soil disturbance, maximizing crop diversity, keeping soil covered, maintaining living roots year-round and integrating livestock (Jaworski et al. 2023; Manshanden et al. 2023). Using ex-ante modelling in cereal-grain crop only system, Al-Amin et al. (2023) found that regenerative agriculture could be profitably facilitated with autonomous strip cropping system. They considered a five-year winter wheat-winter barley-nectar flower mix-winter wheat-spring bean rotation within strips based on regenerative principles. The nectar flower mix (NFM) in their study was valued through Great Britain’s countryside stewardship subsidy programmes (Agro Business Consultants 2018; United Kingdom Rural Payments Agency 2022). However, this study omitted livestock components to avoid complexity in modelling. They suggested that grass ley production with grazing livestock, harvested forage and animal manure returned to the soil could better represent the regenerative agriculture to achieve the five soil health principles because soil health is the entry point to achieve the multiple objectives of arable farming (LaCanne and Lundgren 2018; Schreefel et al. 2020).

To fill the research gap and to guide regenerative agriculture and precision agriculture literature this study examined the economics of ‘integrated crop-livestock system’ with swarm robots considering grass ley production instead of NFM as considered in the crop only system. This study assumed that intensive winter beef finishing suckled calves was supported with the produced grass ley that also was helped to return the on-farm manure to the soil. While grazing strips is advocated for small scale regenerative farming (e.g. Smith 2024), this study did not consider livestock grazing because two-meter strips are too narrow allow grazing at commercial scale. Movable pens could only accommodate small numbers of animals. Permanent fencing would not be economically feasible in two-meter strips and virtual fencing needs wider strips (Nofence AS 2024). This ex-ante modelling study considering the context of the UK hypothesized that regenerative narrow strip cropping with swarm robots could be profitable for an integrated British crop-livestock farm, thereby help Great Britain to meet the food security, carbon-net-zero target and other sustainability challenges of biodiversity, animal welfare and rural levelling up.

Methods

The ex-ante optimization economic modelling of whole field sole cropping practice and regenerative agriculture through strip cropping practices assumed in this study considered the farming context of Great Britain. The farming practices were modelled through two perspectives: First, the ‘crop only system’ where a five-year winter wheat-winter barley-nectar flower mix-winter wheat-spring bean yearly rotations were considered. The nectar flower mix (NFM) payment was assumed through the United Kingdom’s countryside stewardship programmes subsidy payment. Secondly, the ‘integrated crop-livestock system’ which included the crop only system components supplemented with winter beef finishing suckled calves supported through produced grass ley instead of NFM. Therefore, the integrated crop-livestock system was a five-year winter wheat-winter barley-grass ley-winter wheat-spring bean yearly rotations.

The farm management of both crop only system and integrated crop-livestock system was modelled considering three mechanized farm management systems based on the typical mechanization with larger machine and the HFH demonstration project of the UK as follows: (i) whole field sole cropping (used 221 kW conventional machines operated with human drivers), (ii) conventional regenerative strip cropping (used 28 kW conventional machines operated with human drivers), and (iii) autonomous regenerative strip cropping (used 28 kW machines retrofitted for autonomy).

This study modelled 500 ha farm with 450 ha of arable land (10% was assumed to be occupied by hedgerows and other ecologically focused areas as typical in the UK). The fields were assumed to be rectangular shape roughly with 10 ha in size, where the length of the field about 10 times the width. This study assumed that fields were approximately 2.00 Km away from the farmstead. The whole field sole cropping practice assumed that each enterprise occupied 1/5 of the arable land area. For operational feasibility, regenerative strip cropping needed repeated access to the interior field (excluding two sided headlands) for different crops. The two-sided strip crop headlands were assumed (i.e., 0.14 ha, 1% of the fields). The headlands were assumed to be sown with nectar flower mix in crop only system and with grass ley in the integrated crop-livestock system. The interior of the strip crop fields (i.e., 9.86 ha) were cultivated in two-meter strips. In the interior field, each enterprise encompassed 1.972 ha, i.e. 20% of the field interior.

The timing of production for each enterprise was based on Witney (1988), Outsider's Guide (1999), Finch et al. (2014) and Agro Business Consultants (2018) (for details see Al-Amin et al. 2023; Lowenberg-DeBoer et al. 2021). The crop only system modelling considered predrill herbicide application and direct drilling, two times top dressing and spraying, spraying operation, and harvest operation for winter wheat. The same operations were assumed for winter barley except the single spraying operation. The NFM only used predrill herbicide and drilling operation. The spring field bean assumed predrill herbicide and drilling, two times spraying and harvesting operation.

The integrated crop-livestock strip cropping systems modelling assumed the same crop operations for winter wheat, barley, and field beans as the crop only system with grass ley produced and harvested instead of NFM. Ideally, regenerative farming systems have grazing livestock which eliminates the labour and energy required for forage harvest and transportation, and which distributes manure without added work and machines. However, the narrow strip width essential to optimize strip crop benefits makes grazing difficult. Permanent physical fencing two-meter strips would be very expensive and interfere with crop operations. With electric fencing mature cattle could hardly turn around without touching the fence. Virtual fencing requires a much wider buffer strip, often over 25 meters (Nofence AS 2024). Consequently, this analysis assumed that forage was harvested for silage, transported to the farmstead to be fed to cattle and manure was transported back to the field. The grass ley operations considered seven months intensive beef finishing labour time with three times harvest of grass ley together with field to farmstead transition times of grass ley to support the intensive beef finishing suckled calves. In strip cropping autonomous system, manure application and self-loading wagon assumed full time operator time instead of 10% human supervision time assumption (Lowenberg-DeBoer et al. 2021) because transporting forage and manure required travel on public roads. Forage silage harvest with a self-loading wagon was selected as the lowest cost option to fit in two-meter strips. The more common trailed or self-propelled silage cutter with a trailed wagon would often be wider than two meters.

There would be no space to drive a tractor and wagon, or other vehicle to catch the forage alongside. The self-loading wagon is equipped chopper to cut the grass for ensiling. Each self-loading wagon load is driven to the farmstead to unload into a silage bunker.

Based on the common practice in Britain, the whole field sole cropping system in integrated crop-livestock modelling assumed custom hire services for manure spreading, and silage and hay making. Because strip cropping contract service for forage harvesting and manure spreading are not available in the UK, the strip cropping scenarios assume that the farm is responsible for those operations with owned machines. Further details of the coefficient estimation excel spreadsheets will be provided on request to the first author.

The base model assumed in this study was the crop only system that was adopted from Al-Amin et al. (2023). To keep similarity with the base model data, the integrated crop-livestock model also considered 2018 input and output prices. Data of cereal, grain and grass ley yields, prices, variable costs, and mid-tier Countryside Stewardship Scheme (CSS) (i.e., nectar flower mix) payment, and intensive beef finishing costs and animal heads was collected from Agro Business Consultants (2018).

Machine specifications data were based on Lowenberg-DeBoer et al. (2021), Millcreek (https://www.millcreek.co.uk/), Reform (https://www.reform.at/en/products) and Pottinger (https://www.poettinger.at/en_in). The mower and self-loading wagon specifications of 28 kW tractor scenarios were collected from Reform and Pottinger type front mounted mower, Senator type self-loading wagon and Witney (1988). The mower operated with 221 kW tractor were collected based on the capacity suggested by John Deere, Claas manufacturers and Witney (1988), e.g., John Deere R990R Rear Mount Mower with Conditioner for a maximum 9.9 m cutting width suggested 185 kW power. The HFH equipment considered manure spreader following Millcreek.co.uk for regenerative strip cropping analysis, while whole field sole cropping scenario assumed contract hire service for manure spreader, consequently, no tractor time was assumed. Following the algorithms of Lowenberg-DeBoer et al. (2021) this study estimated the equipment times with zero overlap percentage assumption based on the recent Hands Free Farm (HFF) demonstration experience. The yield penalties for non-optimum planting and harvesting operations were based on Witney (1988).

The optimization model used in this study was based on the Hands Free Hectare – Linear Programming (HFH-LP) 'steady state' model. The concept of steady state implies that the annual solutions of the model would be repeated indefinitely (Lowenberg-DeBoer et al. 2021). Mathematically, the gross margin maximization model could be expressed as:

$$Max\ \pi = \sum_{j=1}^{n} c_j X_j \qquad \dots\dots(1)$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i\ for\ i = 1, \dots \dots, m; \qquad \dots \dots(2)$$

$$X_j \geq 0\ for\ j = 1, \dots \dots, n; \qquad \dots \dots(3)$$

where, π = gross margin, X_j = the level of *j*th production activities, c_j = the gross margin per unit over fix farm resources, a_{ij} = the amount of *i*th resource required per unit of *j*th activities, b_i = the amount of *i*th resource available.

In this study gross margin for a 450 ha arable farm was maximized subject to the binding constraints of land, operator labour time, tractor time and combine time. This study also estimated return to operator labour, management and risk taking (ROLMRT) by subtracting cereal farm fixed costs from the gross margin (Agro Business Consultants, 2018). In the crop-livestock scenario, it is assumed that the farm has existing barns to house the cattle. This steady state ex-ante model assumed monthly time steps from January to December. The HFH-LP model was coded in the General Algebraic Modelling Systems (GAMS) software (GAMS Development Corporation 2020) (for more details of the crop only system modelling please see Al-Amin et al. (2023) and integrated crop-livestock system modelling request the first author).

Results

The equipment times for crop only system included per hectare time (h/ha) for drill, sprayer and combine, while the per ha equipment time for integrated crop-livestock system encompassed the times of the drill, sprayer, combine, manure spreader, mower, and self-loading wagon (Table 1). The equipment times of conventional regenerative strip cropping and autonomous regenerative strip cropping systems was represented with 28 kW machines that incorporated drill, sprayer and combine, while manure spreader, mower, and self-loading wagon was also assumed for one year grass ley in the interior field and medium-term grass ley in two sided headlands. Contrary, the whole field sole cropping operations was assumed to be operated with 221 kW larger conventional machines with human drivers, where only per ha times for drill, sprayer, combine, and mower were estimated. In whole field sole cropping system, manure spreading, silage and hay making operations were assumed to be done with custom hire services (contact service) considering the typical farming scenarios based on Agro Business Consultants (2018). The results of per ha equipment times reveal that small 28 kW HFH type machines required more time compared to 221 kW larger conventional machines operated with human operators. The higher time for small machines was associated with the narrow working width. The smaller machines need to turn on the headlands more often to cover the same field area.

Table 1. Equipment times of the machinery sets.

Equipment	Width of the implement (m)***	Overlap percentage (%)****	Field speed (km/h)***	Field Efficiency (%)***	Area (ha)/h***	h/ha***
HFH equipment set (28 kW):*						
Drill	1.50	0	3.25	70	0.34	2.93
Sprayer	7.00	0	5.00	70	2.45	0.41
Combine	2.00	0	3.25	70	0.46	2.20
Manure spreader**	2.00	0	3.25	70	0.46	2.20
Mower	1.90	0	7.00	70	0.93	1.07
Self-loading wagon	1.50	0	4.00	70	0.43	2.33
Larger conventional equipment set (221 kW):						
Drill	6.00	0	5.00	70	2.10	0.48
Sprayer	36.00	0	10.00	70	25.20	0.04
Combine	7.50	0	3.00	70	1.58	0.63
Mower	9.90	0	7.00	70	4.85	0.21

Note: **The Hands Free Hectare (HFH) equipment sets were 28 kW conventional machines with human operators and 28 kW machines retrofitted for autonomy. **The HFH equipment considered manure spreader following Millcreek.co.uk for regenerative strip cropping analysis, while whole field sole cropping scenario assumed contract hire service for manure spreader. ***The machine specification, field speed, field efficiency and field times estimation algorithm were based on the study of Lowenberg-DeBoer et al. (2021). The mower and self-loading wagon specifications of 28 kW tractor scenarios were collected from Reform and Pottinger type front mounted mower, Senator type self-loading wagon and Witney (1988) - pg., 103. The mower operated with 221 kW tractor were collected based on the capacity suggested by John Deere, Claas and Witney (1988) - pg., 103, e.g., John Deere R990R Rear Mount Mower with Conditioner for a maximum 9.9 m cutting width suggested 185 kW power. ****The overlap percentage assumption was based on the Hands Free Farm (HFF) demonstration experience (https://www.handsfree.farm/).* ***Source:*** *Author's own estimation.*

The baseline summary results of the crop only system modelling for a 450 ha cereal-grain regenerative strip cropped farm reveal that whole field sole cropped farm was capable of operating the full farm with one unit of 221 kW tractor operated with human operators (Table 2). Contrary, the conventional regenerative strip cropped farm required four units of 28 kW tractors operated with human drivers and autonomous regenerative strip cropped farm needed two units of retrofitted crop robots to optimally operate the whole farm.

For the crop only model, the gross margin of the conventional regenerative strip cropped farm was £27,171 (£277,147-£249,976) lower than the whole field sole cropped farm. This is because the conventional strip cropping needed 13 times more temporary hired labour and two times more operator time compared to whole field sole cropped farm. Similarly, autonomous regenerative strip cropped farm's gross margin was £ 12, 804 (£277,147-£264,343) lower than whole field sole cropping which is due to the substantial temporary hired labour requirement, especially for harvesting time. The comparison of conventional and autonomous strip cropping shows that autonomous strip cropped farm gross margin was £ 14,367 (£264,343-£249,976) higher than conventional strip cropped farm which is because conventional strip cropping needed four times higher temporary labour.

A closer look at the return to operator labour, management and risk taking (ROLMRT) for the crop only model indicates that strip cropping with crop robots resulted a profit margin of £57,761 (£71,974-£14,213) higher than whole field sole cropping and £25,597 (£71,974-£46,377) higher than conventional strip cropping when overhead costs of farming were in consideration. Higher machine cost was the prime reason for lower profit in cases of whole field sole cropping and conventional regenerative strip cropping practices. The larger 221kW machine set require a much larger initial investment than the small 28 kW machine sets. The autonomous farm was able to operate longer days and hence could do timely field operations with two 28 kW machine sets, while the conventional strip crop farm required four 28 kW machines sets.

Table 2. Optimization outcomes summary of crop only system modelling.

Equipment scenario*	Labour hired (Person-days per year per farm)	Operator time (Person-days per year per farm)	Gross margin (£ per year per farm)	Return to operator labour, management and risk taking (£ per year per farm)
Conv. 221 kW: Whole farm sole cropping	21	73	277,147	14,213
Conv. 28 kW[4]: Regenerative strip cropping	280	135	249,976	46,377
Autonomous 28 kW[2]: Regenerative strip cropping	66	63	264,343	71,974

Note: **The superscript indicates the number of equipment sets needed (refers swarm equipment and robots).* ***Source:*** *Adopted from (Al-Amin et al. 2023).*

Adding cattle finishing enterprise slightly increased gross margin for whole field sole cropping and autonomous regenerative strip cropping, whereas conventional regenerative strip cropping gross margin was reduced by the added labour and machine costs of beef finishing with harvested forage (Table 3). The gross margin comparisons show that in integrated crop-livestock system whole field sole cropping generated £6,399 (£283,546-£277,147) more return over variable costs compared to whole field sole cropping in crop only model. The autonomous regenerative strip cropping with integrated crop-livestock system also generated £10,014 (£274,357-£264,343) more return over variable costs than autonomous regenerative strip cropping system in only cropping systems. However, when fixed costs were deducted the ROLMRT for all three crop-livestock scenarios was less than in the crop only model. The comparison of crop only systems and integrated crop-livestock systems indicate that added labour and machine cost made the integrated crop-livestock scenarios based on harvested forage less profitable.

Table 3. Optimization outcomes summary of integrated crop-livestock system modelling.

Equipment scenario*	Labour hired (Person-days per year per farm)	Operator time (Person-days per year per farm)	Gross margin (£ per year per farm)	Return to operator labour, management and risk taking (£ per year per farm)
Conv. 221 kW: Whole farm sole cropping	196	182	283,546	11,462
Conv. 28 kW[7]: Regenerative strip cropping	850	227	243,692	-62,649
Autonomous 28 kW[4]: Regenerative strip cropping	486	227	274,357	13,567

Note: **The superscript indicates the number of equipment sets needed (refers swarm equipment and robots).* ***Source:*** *Author's own estimation.*

Discussion

The estimated profitability of crop only autonomous regenerative strip cropping system indicate that swarm robots have the potential to help Great Britain to meet the food security, carbon-net-zero target and other sustainability challenges of biodiversity, animal welfare and rural levelling up (Davies 2022; DEFRA 2021). The crop only cropping system model shows that autonomous regenerative strip cropping overcomes the labour constraint that often limits use of mixed cropping practice (Ward et al. 2016).

Compared to the crop only scenarios, the harvested forage beef finishing systems were not very profitable. The whole field sole cropping scenarios might be more profitable with grazing, but this is not an option with narrow crop strips. Hiring contractors for forage harvest and manure handling helps control costs in the whole field scenario, but such services are not currently available in Britain for strip cropping systems. The added labour and machine ownership costs in both the conventional and autonomous integrated crop-livestock systems reduced returns to farmer operators. Because the analysis assumed that autonomous machines could not be used on public roads, transporting harvested forage, manure hauling and more frequent farm-to-field travel to manage multiple crops created high human labour requirements for both strip cropping scenarios. Autonomous farming with harvested forage would be more economically feasible on farms with contiguous fields that could be reached without movement on public roads, but large farms with contiguous fields are rare in Britain. Autonomous integrated crop-livestock strip cropping systems had lower labour and machine costs than conventional integrated crop-livestock strip cropping, but still less profitable than the crop-only strip crop systems.

To better understand strip cropping potential, future research should consider strip crop yield advantages, input cost reductions from greater crop diversity, labour availability and increasing wage rates in analysis. This study shows that incorporating harvested forage and livestock into strip farming regenerative systems in the UK was technically possible, but economically problematic. Economics will drive the need to look at other approaches integrating livestock into the regenerative farming system including winter grazing that is not managed by crop strip. It might be managed with whole field set stocking or rotational grazing with wider strips that are perpendicular to the crop strips. Another options is a longer arable-crop rotation in which one cycle of strip crops is then rotated to a whole field grass ley which would be managed with set stocking or rotational grazing.

Conclusion

The technical, environmental, and economic feasibility of regenerative agriculture has received growing attention to meet the challenges of food security and climate change. However, studies of the economics of regenerative agriculture shows mixed results, which restricts wide scale adoption of regenerative practices all over the world. This ex-ante modelling assessment based on the context of Great Britain shows that autonomous machines could change the cost calculus of crop only regenerative mixed farming practices. Largely because of lower machine costs, autonomous strip cropping five-year winter wheat-winter barley-nectar flower mix-winter wheat-spring bean yearly rotation was more profitable than a comparable whole field cropping scenario. The conventional crop only strip cropping scenario showed lower returns due to high labour requirements. The harvested forage scenario which modelled a five-year rotation of winter wheat-winter barley-grass ley-winter wheat-spring bean yearly rotation provided lower farm operator returns in all mechanization scenarios. In this harvested forage scenario, the grass ley was harvested and hauled to the farmstead to support intensive winter beef finishing suckled calves. This study found that autonomous regenerative practices are more profitable in both crop only and harvested forage systems as compared to conventional whole field sole cropping and conventional regenerative strip cropping practices operated with human drivers. Conventional regenerative strip cropping systems were not economically attractive because of substantial labour time and machine requirement. Autonomous machines reduced machine costs and the in-field labour requirements of strip crop systems, but the need for human drivers to transport forage and manure on public roads make autonomous harvested forage strip crop systems less profitable than crop only systems. More research is needed to incorporate livestock grazing into strip cropping (and other mixed farming) systems.

Availability of Materials

The GAMS code, coefficient estimation and linear programming (LP) excel spreadsheets are available on request to the first author, A. K. M. Abdullah Al-Amin at: abdullah.alamin@bau.edu.bd

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The study is an extended analysis of the first author's PhD research work, where the crop only system was adopted from Al-Amin et al. (2023), which was compared with integrated crop-livestock system extended by the authors. This research work was modelled based on the Hands Free Hectare (HFH) project demonstrated at Harper Adams University, Newport, Shropshire, TF10 8NB, United Kingdom. The author is grateful to Harper Adams University in the UK, where the author was an Elizabeth Creak Fellow from 2020 to 2023. Acknowledgement also goes to Bangladesh Agricultural University, Mymensingh-2202, Bangladesh, where the author is on the staff as a Professor (Assistant).

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