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# Autonomous regenerative agriculture: Swarm robotics to change farm economics

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ABSTRACT

Regenerative agriculture (RA) with mixed cropping is suggested to promote soil health. Combining crops with livestock adds another element of the RA paradigm. The simplest mixed cropping system is strip intercropping but use on conventional mechanized farms is limited by higher labour and capital investment. The objective of this study was to assess the comparative competitiveness of RA practices with and without livestock operated using conventional mechanized farm with human drivers and swarm robotics. Modelling livestock component considered intensive cattle feed using harvested forage because grazing in narrow strips is difficult. The profit maximizing optimization model of a 500 hectare (ha) British West Midlands farm found that per annum profitability of regenerative strip intercropping system was £56.88 $ha^{-1}$ higher for farm operated using smaller swarm robotics than farm operated using smaller conventional mechanization with human drivers. The conventional whole field sole cropping system operated using larger machines with human drivers returned £128.36 $ha^{-1}$ per annum less than regenerative strip intercropping operated using swarm robotics. Adding livestock component with crop only regenerative strip intercropping system resulted negative return per annum (- £26.72 $ha^{-1}$). The added labour for livestock rearing, forage and manure transport, and higher machine costs challenged competitiveness of regenerative system with livestock. This reinforcing the need to more completely automate public road transport and intensive livestock rearing. Results indicate that swarm robotics have potential to change the cost calculus of RA practices, while livestock integration needs careful cost-effective designs to reinforce farm profitability.

## 1. Introduction

Swarm robotics are expected to revolutionize arable open field operations, while helping to reconcile the production goals of productivity and profitability, and environmental goals of limiting environmental footprints [1–3]. Swarm robotics here refers to multiple mobile, autonomous machines (or more colloquially known as “crop robots”) that can simultaneously perform arable farm operations such as soil preparation, seeding, transplanting, weeding, spraying, fertilizing, and harvesting with predetermined field paths under direct and indirect human supervision, but without direct human labour [5,6]. The techno-economic feasibility of swarm robotics in whole field sole cropping (monoculture) system is shown in research [4]. The intercropping potential of swarm robotics are advocated, but little research has been done on the economics of this practice [8,9].

The intercropping systems were predominant in labour intensive manual arable farming systems [10]. But intercropping practices usually disappear when animal power or motorized mechanization with human drivers are introduced to maximize labour productivity [11–16]. Conventional mechanization challenged use of intercropping due to higher labour and capital investment requirements [8]. Labour-saving swarm robotics are suggested as part of farm management systems intensification [15,16]. However, autonomous machines to date are unable to address the engineering challenges of complex intercropping systems. For example, agroecological farming [16] with pixel cropping have encountered field operation complexity due to the varying plant growth and height patterns [17]. Strip intercropping, the simplest mixed cropping system is considered as the low-hanging fruit to optimize

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agroecological benefits [18–20,92].

Strip intercropping is defined as the farming practice of growing two or more crops simultaneously in adjacent strips, where the adjacent strips are wide enough to be cultivated independently and narrow enough to optimise crop interactions [21–23]. Worldwide strip intercropping agronomic research focusing on varying height crops found edge effects benefits of increasing yields for taller plants and penalties for shorter plants [24–25]. The edge effects benefits are also expected for similar height plants typical in the UK due to different crops maturity cycles over the year [26]. Simultaneously, the ecological benefits of strip intercropping are also well documented in research [27–29]. Research found that strip intercropping enhances biodiversity and ecosystem services, while it reduces pest densities, input use, and disease infestation [30–34,56].

Strip intercropping managed with swarm robotics have the potential to help achieve the five soil-health principles of regenerative agriculture (RA) [35,36]: minimization of soil disturbance, maximization of crop diversity, keeping soil covered, maintaining living roots year-round and integrating livestock [37,38]. Swarm robotics are hypothesized to bring a paradigm shift in RA practices [39–43,45,84]. For example, current cropping system research has already considered corn-soybean [9], wheat-barley-beans [26], and cereal-vegetable strip intercropping with swarm robotics to promote RA [27,28]. Strip intercropping research suggested different enterprise mixes including grass leys to achieve synergy between agricultural production and environmental sustainability [46]. Soil health is critical to achieve the multiple objectives of arable farming [48]. Research advocated integrated crop-livestock systems through grazing livestock or harvested forage and animal manure returned to the soil for achieving the five soil health principles [46–48]. Beyond research, worldwide the RA practices received growing attention by the civil society, NGOs, media, policy makers, and multinational food companies [49–54,85,86]. Worldwide RA practices have been initiated [55,58,59] which embrace the ecological, economic, and social principles of arable farming [46,60,61].

The economic literature on RA practices are not yet rich enough to guide evidence-based policy decisions, but the production economics literature shows mixed results [57–61]. The state of the art found that RA practices are sensitive to enterprise selection, farming systems, technologies, and regional context of farming [38,40,43,44,62]. Although livestock is one of the vital components of RA practices, including livestock in strip intercropping systems adds farm management complexity. Initially, livestock grazing seems to be the best alternative. But grazing cost-effectively in narrow strips is challenging, whereas narrow strips are suggested to optimize strip intercropping benefits [63,66,68]. Grazing strips with movable pens is advocated for small scale RA [64], but it does not scale to commercial herds. Permanent physical fencing would be expensive for narrow strips. Electric fencing is another option, but in narrow strips cattle could hardly turn around without touching a live wire. Virtual fencing requires a wide buffer strip, as much as 25 m wide [65].

To address the research gaps, the objective of this study was to assess how labour-saving smaller autonomous machines change the farm economics of RA practices. In doing so, the production economics and farm management of regenerative strip intercropping systems operated using conventional small machines with human drivers and conventional small machines retrofitted for autonomy were examined. Both conventional and autonomous RA practices farm economics were compared with whole field sole cropping (monoculture) system operated using larger machines with human drivers. This study hypothesized that swarm robotics would make regenerative strip intercropping system profitable in both the crop only regenerative cropping system without livestock and integrated crop-livestock regenerative farming system, thereby reducing the increasing labour and capital requirements of conventional mechanized farms.

## 2. Materials and methods

### 2.1. Cropping and farming systems modelling

To improve the production economics and farm management understanding, this study modelled RA practices without and with livestock using regenerative strip intercropping system. As the definition of RA is still being debated, struggling whether to consider processes (i.e., incorporating cover crops, livestock and tillage reduction or elimination) or outcomes (i.e., improvement of soil health, carbon sequestration and biodiversity enhancement) and/or a combination of both [62,38], this study adopted a definition considering both the processes and outcomes. In this study, RA refers to a year-round sustainable farm management strategy that diversified crop production within the same field in strips that improves resource use efficiency by reducing synthetic chemical input use, improving soil health, biodiversity, and farm productivity.

This study modelled 'crop only regenerative cropping systems' and 'integrated crop-livestock regenerative farming systems'. The crop only regenerative cropping systems (without livestock systems) specified a five-year winter wheat (WW)-winter barley (WB)-nectar flower mix (NFM)-winter wheat (WW)-spring field bean (SB) yearly rotation. In crop only regenerative cropping systems, three production alternatives were compared: whole field sole cropping system, conventional strip intercropping system, and autonomous strip intercropping system. The whole field sole cropping system here referred to growing a single crop in a year in a field, while the strip intercropping system referred to growing multiple crops in strips every year [4,9].

The integrated crop-livestock regenerative farming systems (with livestock systems) adapted the crop only regenerative cropping systems by substituting the NFM with grass ley (GL) production to support winter beef finishing for seven months with sale of the cattle in spring. Therefore, the integrated crop-livestock regenerative farming systems modelled a five-year WW-WB-GL-WW-SB yearly rotation [35,67]. Like the crop only regenerative cropping systems, the integrated crop-livestock regenerative farming systems also modelled three production alternatives: whole field sole cropping system, conventional strip intercropping system, and autonomous strip intercropping system.

Both the crop only regenerative cropping systems and integrated crop-livestock regenerative farming systems modelled a 500 ha typical West Midlands UK farm. In this study about 90 % of the land is assumed to be arable. The remaining 10 % was used for ecologically focused areas including hedgerows, drainage ditches and the farmstead [7]. A total of 45 fields were assumed for a 450 ha arable area. Each field assumed a roughly 10 ha rectangular shape with the length of the field about 10 times the width. The whole field sole cropping system assumed that each enterprise occupied 1/5 of the arable land area. The strip intercropping systems required a different field layout to allow repeated access to field interiors for managing different crops.

The crop only regenerative strip intercropping systems assumed that headlands (i.e., 0.14 ha, 1 % of the field) were planted with NFM for easy access to the interior field. The interior fields (i.e., 9.86 ha) were assumed cultivated with 2.0 m strips of WW-WB-NFM-WW-SB annual rotations. The sequence of the five strips (i.e., WW-WB-NFM-WW-SB) were assumed to be repeated across the whole interior field as shown in Fig. 1, where strips were assumed to be rotated annually to optimize the edge effect benefits. For example, starting in the first year, WW in strip 2 (i.e., each strip 1.972 ha, 20 % of the field) was assumed to be benefited from one side edge effect of SB. Similarly, in strip 4, WW hypothesized to benefit from both sides of SB and NFM. Subsequently, in second year, WB in strip 2 was assumed to be benefited from both sides, for being next to NFM and being before WW [35].

In the integrated crop-livestock regenerative farming systems, NFM was assumed to have been replaced with GL to support the intensive winter beef finishing activity. The two headlands of the integrated crop-livestock regenerative farming systems were seeded to medium term GL,

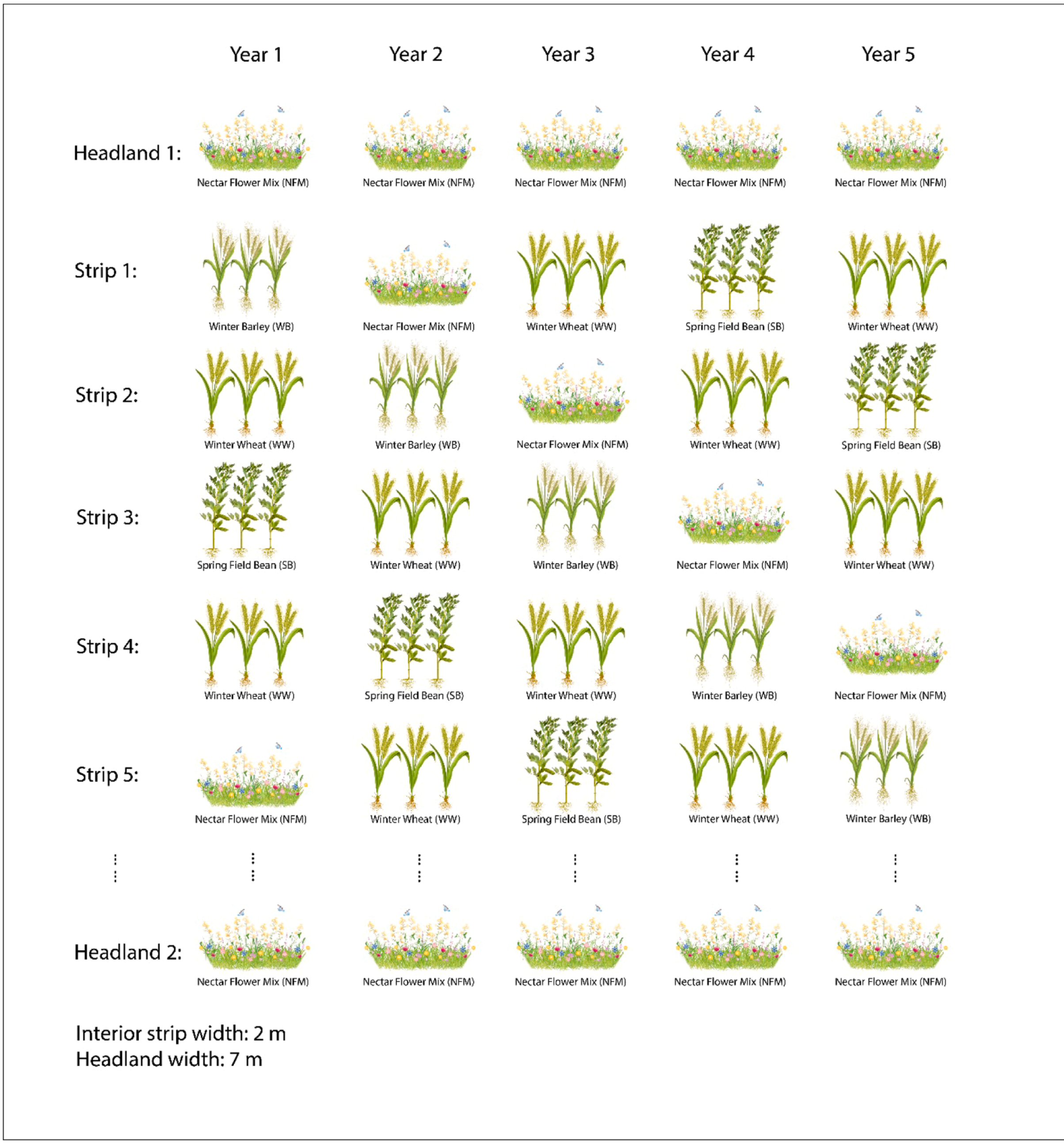


**Fig. 1.** Field layout of crop only regenerative strip intercropping system without livestock.

while the interior field GL strips were one-year GL.

### 2.2. Modelling mechanized farm management alternatives

Post-war agricultural intensification in Great Britain encouraged increasing equipment power and field enlargement [69]. Over time, agricultural tractor power in the UK has increased [70,71]. Recent research suggested small autonomous machines (i.e., swarm robotics) as a profitable alternative to conventional mechanization with human drivers for whole field sole cropping system [7]. Since 2017, Harper Adams University in the UK has demonstrated whole farm commercial operations from tilling to harvesting using small autonomous 28 kW machinery sets [26].

Considering available conventional and autonomous mechanized farm management alternatives in Great Britain, the crop only regenerative cropping systems (without livestock system) and integrated crop-livestock regenerative farming systems (with livestock system) in this study modelled three mechanization alternatives: (i) conventional larger machines (221 kW) operated with human drivers for whole field sole cropping system, (ii) small conventional machines (28 kW) operated with human drivers for conventional strip intercropping system, and (iii) small conventional machines (28 kW) retrofitted for autonomy (i.e., swarm robotics) for autonomous strip intercropping system.

The 221 kW equipment set inventory included a 221 kW tractor, a 6.0 m width drill, a 36 m trailed boom sprayer, a 24 m width twin disc spreader, a 5.0 m width header associated combine, a chaser bin, and a trailer for hauling to farmstead. The integrated crop-livestock regenerative farming system's whole field sole cropping equipment inventory included the same machinery sets plus a 9.9 m width mower was added for GL production operations. Other whole field operations related to GL production such manure spreader, silage and hay making assumed use of contract hire services, (i.e., custom hire services) as typical for larger conventional farms in Great Britain. Further details in Table A1 in Appendix A.

The crop only regenerative cropping system's equipment inventory of small conventional 28 kW equipment sets operated with human drivers included a 28-kW hydrostatic tractor, a 2 m width drill, a 7.0 m width trailed boom sprayer, a 2.0 m width headed combine, and a trailer for hauling to farmstead. The equipment inventory of the conventional regenerative strip intercropping in the integrated crop-livestock system included all machinery used for crop only conventional regenerative strip intercropping plus the equipment inventory needed for GL production and beef finishing such as a 2.0 m width manure spreader, a skid-steer loader, a 1.9 m width mower, and a 2 m width self-loading wagon. Further machine details are found in Table A2 in Appendix A.

The swarm robotics inventory included the equipment inventory of the small 28 kW conventional machinery sets which were assumed to have been retrofitted for autonomy using the real-time kinematic positioning (RTK) autopilot systems. The autonomous equipment costs included the costs of safety equipment (e.g., laser, remote emergency stop, stop button system), control systems (e.g., GPS, autopilot), control adaptations (e.g., steering motor, drive control, linkages control), closed-circuit television camera (CCTV) cams for camera feedback, communications (e.g., wifi, Radio control (RC) system), consumables (boxes/connectors, etc.). Details of the item specific hardware and software costs are reported by [7]. Further retrofit details are found in Table A2 in Appendix A.

### 2.3. The deterministic LP model

Agricultural systems modelling is used for complex farming problems and decision making [73]. Farming systems decisions considering agronomic, economic, technical, and environmental characteristics can be done efficiently with optimization modelling [74,75]. Farm profit maximization models are widely used throughout the world. For instance, linear programming (LP) models similar to the one used in this study have been widely used for extension programs in the US [76]. Also used for the selection of profitable enterprises in Colombia [73] and Cameroon [77], selecting of alternative technologies for crop production in the UK [7] and the US [72], cropping systems and technology selection alternatives in the UK [35], and the economic assessment of regulatory scenarios [78].

The ex-ante modelling approach used for technology and enterprise selection decisions were applied in this study. This study used the farm level Hands Free Hectare-Linear Programming (HFH-LP) model [7] to identify profit maximizing combinations through the allocation of available farm resources in both the crop only regenerative cropping systems and integrated crop-livestock regenerative farming systems. The HFH-LP is a one-year deterministic 'steady state' model. Here 'steady state' refers to the assumption that yearly solutions of this model could be indefinitely repeated over time. The HFH-LP model is like the Audsley (1981) LP model [75] of British farming, albeit using the more advanced General Algebraic Modelling Systems (GAMS) software [79]. Details of the GAMS coding are available in the Lowenberg-DeBoer study [7].

Mathematically, following Boehlje and Eidman (1984) [80], the standard notation of the HFH-LP gross margin maximization could be expressed as follows:

$$Max\ \pi = \sum_{j=1}^{n} c_j X_j \tag{1}$$

Subject to:

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

$$X_j \geq 0\ for\ j = 1,\ \dots \dots,\ n; \tag{3}$$

where, $\pi$ refers to the whole farm gross margin (GM), $X_j$ refers to the level of $j$th production activities, $c_j$ refers to the gross margin per unit over fix farm resources, $a_{ij}$ refers to the amount of $i$th resource required per unit of $j$th activities, $b_i$ refers to the amount of $i$th resource available.

The return to operator labour, management and risk taking (ROLMRT) was estimated by subtracting cereal farm fixed costs from the $GM$ as follows:

$$ROLMRT = \pi - \Sigma\ \mathrm{FC} \tag{4}$$

where, $FC$ refers to the annual per farm fixed costs which include the annual costs of the machinery sets required, rent for the arable farm, property and building repairs, professional fees and subscriptions, water, electricity, building depreciation and miscellaneous fixed costs.

The per ha work rate (h ha$^{-1}$) [81], used for farm operations both in the crop only regenerative cropping systems and integrated crop-livestock regenerative farming systems were estimated using the following algorithm:

$$= \left(\left(W_m * V_p * 1000\right) * \left(1 - \text{Pass to pass overlap percentage}\right) * E_f\right) / \mathrm{A} \tag{5}$$

where, $W_m$ is the width of the implement (m), $E_f$ is the field efficiency (%), $V_p$ is the running speed of the implement (Km $h^{-1}$), and $A$ is the area of the field (m$^2$).

The equipment times needed in the integrated crop-livestock regenerative farming systems included the tractor use time to complete drilling, spraying, manure application, and mowing for the operations of WW, WB, WW, GL and SB, as well as the combine use time for harvesting WW, WB, WW, SB and self-loading wagon time for GL. Manure spreading in both conventional and autonomous strip intercropping systems for winter wheat (0.1972×2 % of land) was assumed to occur prior to the month of drilling with a farmer owned spreader because contractor manure spreading on narrow strips is not available in the UK.

The base modelling assumed that a maximum 800 h per month of temporary hired labour per farm (i.e., 1.78 h ha$^{-1}$) is available to operate the 450 ha arable farm. The human labour time here in the integrated crop-livestock regenerative systems considered both the farm operation times for producing WW, WB, WW, GL and SB plus the time required for intensive beef finishing. The temporary labour time included regular feeding and/or supervision over seven months leading up to the sale of the cattle. The labour was required for seven months of the year because the winter finishing of suckler bred store calves of 12 months age were purchased in autumn (November) and reared for 215 days. i.e., approximately 7 months (from November to May).

The GL in the interior field, modelled as a one-year GL, assumed three harvest times where June was the optimum. The GL in the two side headlands was assumed to be medium-term. The base modelling assumptions assumed direct drilling as typical on West Midlands' sandy loam soils. The optimum planting and harvesting time, yield at optimum harvesting time, and enterprises prices are detailed in Table 1. For more details of the crop only regenerative cropping systems modelling assumptions and coefficient estimation processes refer to the coefficient's estimation spreadsheets in Appendix B. Details of the integrated crop-livestock regenerative farming systems modelling assumptions and coefficient estimation processes are shown in the coefficient's estimation spreadsheets in Appendix C.

The time window available for farming activities is important as farming operations are sensitive to weather conditions. Considering the context of British farming, good field days available four years out of five was considered a reasonable assumption for planning [67]. This study also assumed that all conventional equipment sets were able to operate for a total of 10 h day$^{-1}$. The autonomous tractors for all operations were able to operate for 22 h day$^{-1}$ with two h allowed for repair, maintenance and refuelling. The exception to this was the autonomous harvesting operations which were limited to 10 h day$^{-1}$ because of

**Table 1**
Key baseline modelling assumptions of crop only regenerative cropping systems without livestock and integrated crop-livestock regenerative farming systems.

| Parameter | Unit | Value |
|---|---|---|
| *Enterprises* | | |
| Winter wheat (WW) yield | t ha$^{-1}$ | 9.10 |
| Winter barley (WB) yield | t ha$^{-1}$ | 7.40 |
| Nectar flower mix (NFM); | ha | 1.00 |
| Grass ley (GL) yield | t ha$^{-1}$ | Interior fields: 6.70 (1st cut), 4.11 (2nd cut), 2.89 (3rdcut) and Two-sided headlands: 7.38 (1st cut), 4.53 (2nd cut), 3.19 (3rd cut) |
| Spring field bean (SB) yield | t ha$^{-1}$ | 4.00 |
| *Output prices* | | |
| Winter wheat (WW) | t ha$^{-1}$ | 155 |
| Winter barley (WB) | t ha$^{-1}$ | 143 |
| Nectar flower mix (NFM); | £ ha$^{-1}$ | 511 |
| Suckled calf | £ head$^{-1}$ | 1242 |
| Spring bean (SB) | t ha$^{-1}$ | 185 |
| *Optimum planting and harvesting dates* | | |
| Winter wheat (WW) | Month | Planted in October and harvested in August |
| Winter barley (WB) | Month | Planted in October and harvested in August |
| Nectar flower mix (NFM); Grass ley (GL) | Month | Planted in March and subsidy in December or Planted in March and harvested in June |
| Spring bean (SB) | Month | Planted in March and harvested in September |
| Soil type | – | Slightly stony sandy loam soil (Salop series) |
| Drilling | – | Assumed direct drilling |

overnight dew common in the UK.

The study assumed 10 % on-farm human supervision time for swarm robotics following the HFH-LP model [7]. The base modelling of the regenerative strip intercropping system operated with swarm robotics assumed that manure application and the self-loading wagon was operated with a full-time operator time (100 %) instead of a 10 % human supervision time assumption. This was because transporting forage and manure typically requires travel on public roads and self-driving farm machine technology is unlikely to be available any time soon for use on public roads. Considering the 2.0 m strips, the forage silage harvest was assumed to occur with a self-loading wagon because this was the lowest cost option for the narrow strips. The more commonly used trailed or self-propelled silage cutter with a trailed wagon was >2.0 m wide. The self-loading wagon was assumed to be equipped with a chopper to cut the grass for ensiling. Each self-loading wagon load was assumed to be driven by a human operator to the farmstead to unload into a silage bunker.

The sensitivity tests in both the crop only regenerative cropping systems and integrated crop-livestock retentive farming systems modelled 10 % yield benefits and 10 % inputs costs reduction because the agronomic and ecological benefits of strip cropping systems are well documented. Moreover, the sensitivity of integrated crop-livestock regenerative strip intercropping system operated with swarm robotics was assessed assuming autonomous manure, forage, and field to farmstead movement.

### 2.4. Model framework

The choice of time step is one of the fundamental elements in 'steady state' LP modelling because arable farming operations have seasonal heterogeneity. The HFH-LP model used in this study considered a monthly time step. The consideration of daily, weekly, and quarterly time steps would be possible, but daily or weekly time steps would expand the model size and require more detailed data. Quarterly time steps would reduce the granularity required to account for resource constraints in the case of a quarterly time step. The monthly time steps are a compromise that makes the model relatively simple and adaptable. For details see Appendix B and Appendix C.

The crop only system modelling considered predrill herbicide application and direct drilling, two times top dressing and three times spraying, and harvest operation for WW. The same operations were assumed for WB with two times top dressing and spraying. The NFM only used predrill herbicide and drilling. The SB assumed predrilled herbicide and drilling, two times spraying and harvesting operation. The integrated crop-livestock regenerative farming systems modelling assumed the same crop operations for WW, WB, SB as for the crop only system with GL produced and harvested instead of NFM. The GL operations considered three GL harvests and seven months intensive beef finishing labour time for supervision of beef finishing rearing.

The LP coefficients are loaded into excel spreadsheet format which is then used in GAMS to model the whole field sole cropping, conventional regenerative strip intercropping and autonomous regenerative strip intercropping systems.

### 2.5. Data

Both the crop only regenerative cropping systems and the integrated crop-livestock regenerative farming systems modelling used 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 (NFM)) payments, and intensive beef finishing costs and animal numbers (steer) was taken from Agro Business Consultants [67]. The 2018 dataset were used to make comparison easier with other production economics studies published following the HFH demonstration experiences [7,9]. Revenue for the NFM in this study was valued through British countryside stewardship subsidy (CSS) programmes [82].

The timing of arable field operations and management of intensive beef finishing on a monthly time step. The offsetting of fertiliser requirements for winter wheat (WW) from the application of manure for both whole field sole cropping practices and strip intercropping practices was based on the data of Agro Business Consultants [67]. For details of the monthly timing of operations and associated estimations see the coefficients estimation spreadsheets in Appendix B and Appendix C.

The HFH swarm robotics were the first publicly demonstrated commercial autonomous whole farm operations for whole field sole cropping [83] and strip intercropping practices [26]. The equipment specifications data were from the HFH experiences, Agro Business Consultants, Millcreek (https://www.millcreek.co.uk/), Reform (https://www.reform.at/en/products) and Pottinger (https://www.poettinger.at/en_in). For the small 28 kW equipment set scenarios, the mower and self-loading wagon specifications were from Reform and Pottinger type front mounted mower, Senator type self-loading wagon, and from Witney [81]. In case of the larger 221 kW equipment set, the mower data is based on the capacity suggested by the machinery manufacturers, e.g., John Deere, Claas and from Witney [81]. For example, the John Deere R990R Rear Mount Mower with Conditioner for a maximum 9.9 m cutting width requires 185 kW of power. The HFH equipment modelling included a manure spreader from Millcreek.co.uk for regenerative strip intercropping practices. The costs of all contract hire services were based on Agro Business Consultants [67].

The present study assumed zero overlap percentage based on the recent Hands Free Farm (HFF) demonstration experience for strip intercropping [26]. The yield penalties for crop enterprises in case of non-optimum planting and harvesting operations were based on Witney [81].

## 3. Results

### 3.1. Equipment times: Small and larger equipment sets

The estimation of per hectare equipment time (h ha$^{-1}$) shows that the small 28 kW conventional and autonomous machinery sets used for strip intercropping systems required substantially more time for farm operations compared to the larger 221 kW conventional equipment sets used for whole field sole cropping (Table 2). For instance, drilling time per ha of the 28 kW trailed drill was five times greater than with the 221 kW trailed drill. The small combine assumed in 28 kW equipment sets required four times longer per hectare compared to the larger combine assumed in 221 kW equipment sets. The higher time for small 28 kW machinery sets was associated with the narrow working width of the machines. During farming operations, the smaller machinery sets also had to turn on the headlands more often to cover the same field area.

### 3.2. Revenue maximization: crop only regenerative cropping systems without livestock

The baseline solutions for crop only regenerative cropping systems without livestock components show that regenerative strip intercropping with 28 kW swarm robotics was a profitable system compared to conventional regenerative strip intercropping with 28 kW machinery sets and whole field sole cropping practice with 221 kW machinery sets (Table 3). The sensitivity scenarios of 10 % yield increase and 10 % inputs cost reduction also indicates the economic competitiveness of strip intercropping operated with swarm robotics compared to conventional strip intercropping and whole field sole cropping systems. Even though the experimental evidence of yield increases and input cost reductions for the same height plants are not yet rigorously documented in the UK, this study hypothesized that temporal differences in crop growth could lead to such benefits. For example, winter wheat (WW) and winter barley (WB) stop growth in late June and July, while spring field bean (SB) is in peak growth stage with active photosynthesis during July and early August. Optimization of crop varieties and agronomic practices may lead to yield increases and input cost reductions.

In baseline modelling, two units of the 28 kW retrofitted autonomous machines (i.e., swarm robotics) were able to do strip intercropping on the 450 ha British crop farm with 1.17 h ha$^{-1}$ temporary hired labour. The conventional regenerative strip intercropping required four units of 28 kW machinery sets operated with human drivers. More machine units were required because of the 10 h workdays for the conventional strip intercropping. The whole field sole cropping system was able to optimally operate the whole farm with one unit of 221 kW conventional machines operated with human drivers with a slightly higher gross margin (GM) mainly due to lower hired labour. However, this did result in a lower return to operator labour, management and risk taking (ROLMRT) because of higher machinery costs for the conventional system compared to the strip intercropping scenarios.

The analysis showed that conventional regenerative strip intercropping required four times higher temporary labour time and two times more operator time than swarm robotics operated regenerative strip intercropping. Compared to autonomous regenerative strip intercropping, the whole field sole cropping required 0.8 h ha$^{-1}$ less temporary labour, but the operator time was 0.18 h ha$^{-1}$ higher for whole field sole cropping. The GM results indicate that whole field sole cropping was £28.45 ha$^{-1}$ higher than swarm robotics operated regenerative strip intercropping (£615.88-£587.43). This is mainly due to the comparatively higher temporary labour time for autonomous strip intercropping, especially for the harvesting operation in August. The GM for swarm robotics operated regenerative strip intercropping was £31.93 ha$^{-1}$ higher compared to conventional regenerative strip intercropping (£587.43-£555.50) because the conventional regenerative strip intercropping required substantially higher temporary hired labour.

When fixed costs are deducted, the ROLMRT was £56.88 ha$^{-1}$ and £128.36 ha$^{-1}$ higher for swarm robotics operated regenerative strip intercropping than conventional regenerative strip intercropping (£159.94-£103.06) and whole field sole cropping (£159.94-£31.58). This is because of higher machine and labour cost for conventional strip

**Table 3**
Profitability of crop only regenerative cropping systems without livestock.

| Equipment scenario* | Temporary hired labour time (h ha$^{-1}$ yr$^{-1}$) | Equipment operator time (h ha$^{-1}$ yr$^{-1}$) | Gross margin (GM) (£ ha$^{-1}$ yr$^{-1}$) | Return to operator labour, management and risk taking (ROLMRT) (£ ha$^{-1}$ yr$^{-1}$) |
|---|---|---|---|---|
| *Baseline:* | | | | |
| Conv. 221 kW: Whole field sole cropping | 0.37 | 1.30 | 615.88 | 31.58 |
| Conv. 28 kW$^4$: Regenerative strip intercropping | 4.98 | 2.40 | 555.50 | 103.06 |
| Autonomous 28 kW$^2$: Regenerative strip intercropping | 1.17 | 1.12 | 587.43 | 159.94 |
| *10 % Yield advantage sensitivity scenarios:* | | | | |
| Conv. 28 kW$^4$: Regenerative strip intercropping | 4.98 | 2.40 | 645.55 | 193.11 |
| Autonomous 28 kW$^2$: Regenerative strip intercropping | 1.17 | 1.12 | 676.96 | 249.48 |
| *10 % Cost reduction sensitivity scenarios:* | | | | |
| Conv. 28 kW$^4$: Regenerative strip intercropping | 4.98 | 2.40 | 590.78 | 138.34 |
| Autonomous 28 kW$^2$: Regenerative strip intercropping | 1.17 | 1.12 | 622.71 | 195.22 |

**Note**:.
* The superscript after kW indicates the number of equipment sets needed for timely operations of a 450 ha arable farm.

**Table 2**
Equipment times of the machinery sets used in crop only regenerative cropping systems without livestock and integrated crop-livestock regenerative farming systems.

| Equipment | Width of the implement (m) | Overlap percentage (%) | Field speed (km $h^{-1}$) | Field Efficiency (%) | Field capacity (ha $h^{-1}$) | Work rate (h ha$^{-1}$) |
|---|---|---|---|---|---|---|
| *Small equipment sets (28 kW) for strip intercropping* | | | | | | |
| Drill | 2.00 | 0 | 3.25 | 70 | 0.46 | 2.20 |
| 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 | 2.00 | 0 | 7.00 | 70 | 0.98 | 1.02 |
| Self-loading wagon | 2.00 | 0 | 4.00 | 70 | 0.56 | 1.79 |
| *Conventional large equipment set (221 kW) for whole field sole cropping* | | | | | | |
| 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 |

intercropping and whole field cropping. The conventional strip intercropping faced severe driver time constraints in March, April, May, August, September and October. The larger 221 kW machine set required a higher initial investment than the small 28 kW machine sets. The larger equipment set farm operation also faced operator time constraints during peak harvesting in August.

### 3.3. Revenue maximization: integrated crop-livestock regenerative farming systems

Optimization of the integrated crop-livestock regenerative farming systems show that adding cattle finishing enterprise based on harvested GL production instead of NFM increased GM slightly for whole field and swarm robotics operated scenarios, but ROLMRT was negative (Table 4). Despite the additional revenue from beef finishing, GM for the conventional strip intercropping system was down because of the substantial labour requirement. ROLMRT is negative because of increased machine and labour costs, including contractor fees.

The swarm robotics operated regenerative strip intercropping system solution show four units of 28 kW swarm robots were required to optimally operate the 450 ha British farm, while the crop only system needed two units of 28 kW swarm robotics. This is because of the additional mechanized farm operations for forage and manure handling. The GL required predrill herbicide, drilling, top dressing, spraying, manure spreading, and three forage harvests, while NFM only needed once predrill herbicide and the drilling operation. Because of the 10 h workday, the conventional regenerative strip intercropping needed seven 28 kW conventional machinery sets with human drivers to optimally operate the British farm, but which required four sets in crop only regenerative strip intercropping system without livestock component. Like the crop only regenerative cropping systems, the whole field sole cropping practice in integrated crop-livestock regenerative farming systems required one unit of larger 221 kW machinery set. This was largely because forage harvesting, and manure spreading was assumed to be done by a contractor.

Adding the livestock enterprise substantially increased operator and hired labour requirements in all scenarios. Although the whole field sole cropping optimization modelling found a profitable solution assuming a maximum of 800 h per month of temporary hired labour for a 450 ha farm (i.e., 1.78 h ha$^{-1}$), the regenerative strip intercropping with conventional machines and swarm robotics were able to operate the 450 ha farm assuming a maximum of 1600 h per month temporary hired labour (i.e., 3.56 h ha$^{-1}$).

For the whole field scenario most of the increased labour was for the feeding of animals, because forage and manure were handled by a contractor. For the regenerative strip intercropping scenarios, the increase in labour includes animal feeding, forage harvesting and manure handling. The increase was also noticeable for the swarm robotics because of the added human labour required for livestock rearing, and transport of forage and manure on public roads.

Even the sensitivity scenarios of 10 % yield increase and 10 % input cost reduction found that integrated crop-livestock regenerative farming systems were less competitive than crop only regenerative cropping systems due to increased labour for beef finishing, forage harvesting and field to farmstead transitions (Table 4). The base modelling of integrated crop-livestock swarm robotics operated regenerative strip intercropping system assumed 10 % supervision for all operations except for manure spreading, grass harvesting, and movement between field and farmstead. Consistent with previous studies [7], these operations assumed 100 % operator time for public road transportation. Sensitivity scenarios modelling assumed that field-to-field and field-to-farmstead transport could be autonomous and consequently the 10 % human supervision assumption could be applied to manure spreading and grass harvesting. The sensitivity test results show that with autonomous transport and manure application, the ROLMRT was positive with per ha return estimated as £24.82. Interestingly, the tests found that with autonomous manure application, grass harvesting, public road transport a 450 ha farm was able to optimally operate with an assumption of a maximum 800 h per month temporary hired labour (i.e., 1.78 h ha$^{-1}$).

**Table 4**
Profitability of integrated crop-livestock regenerative farming systems.

| Equipment Scenario* | Temporary hired labour time (h ha$^{-1}$ yr$^{-1}$) | Operator time (h ha$^{-1}$ yr$^{-1}$) | Gross margin (GM) (£ ha$^{-1}$ yr$^{-1}$) | Return to operator labour, management and risk taking (ROLMRT) (£ ha$^{-1}$ yr$^{-1}$) |
|---|---|---|---|---|
| *Baseline:* | | | | |
| Conv. 221 kW: Whole field sole cropping | 3.48 | 3.23 | 630.10 | −54.53 |
| Conv. 28 kW$^{7}$: Regenerative strip intercropping | 14.01 | 4.04 | 552.22 | −200.23 |
| Robot 28 kW$^{4}$: Regenerative strip intercropping | 6.76 | 3.94 | 628.06 | −26.72 |
| *10 % Yield advantage sensitivity scenarios:* | | | | |
| Conv. 28 kW$^{7}$: Regenerative strip intercropping | 14.01 | 4.04 | 642.68 | −109.77 |
| Robot 28 kW$^{4}$: Regenerative strip intercropping | 6.76 | 3.94 | 719.04 | 64.25 |
| *10 % Cost reduction sensitivity scenarios:* | | | | |
| Conv. 28 kW$^{7}$: Regenerative strip intercropping | 14.01 | 4.04 | 579.39 | −173.06 |
| Robot 28 kW$^{4}$: Regenerative strip intercropping | 6.76 | 3.94 | 655.24 | 0.45 |
| *Autonomous manure, forage, and field to farmstead movement sensitivity scenarios:* | | | | |
| Robot 28 kW$^{3}$: Regenerative strip intercropping | 4.77 | 3.29 | 628.66 | 24.82 |

**Note**:.
[*] The superscript after kW indicates the number of equipment sets needed for timely operations of a 450 ha arable farm.

## 4. Discussion

This research found that swarm robotics changed the cost calculus of arable RA practices. It is long hypothesized that inclusions of precision agriculture technologies would change the farming paradigm of RA practices [35,39,42]. In Great Britain, RA practices are advocated by experts [40,87,94,95,97]. Considering West Midlands British farming context, this study found that the simplest mixed cropping system, that is the regenerative strip intercropping system without livestock components operated with swarm robotics achieved higher profitability as compared to regenerative strip intercropping system operated with smaller conventional machines with human drivers and whole field sole cropping system operated with larger conventional machines with human drivers. The cost reduction potentials of RA practices are already documented [90], the sensitivity modelling found that with 10 % input costs reduction, regenerative strip intercropping system operated with swarm robotics increased profit margin. This supports the existing state of the art that technology would help farmers to adopt RA practices [91]. The yield premiums of strip intercropping is well documented [9,8] and for RA practices are expected [61]. The sensitivity test of 10 % increased yield indicate that swarm robotics would encourage wide scale adoption of RA practices because of higher profit margin. Indicating that if RA practices can ensure increased yield and input costs saving, therefore, swarm robotics will change the cost calculus of arable RA practices through labour saving and reduction of farm fixed costs.

However, with the integrated crop-livestock regenerative strip intercropping system (i.e., with livestock system), farm profitability was lower than crop only intercropping systems, even with swarm robotics. The integrated crop-livestock regenerative farming systems with harvested forage for winter beef finishing were not profitable because of added labour for livestock rearing, forage and manure transport, and higher machine costs. Grazing might make whole field integrated systems more profitable, as winter grazing of the strip intercropping fields would reduce labour and machine costs [93,99–101]. This might be done as whole fields or controlled grazing perpendicular to the strips. In case of large animals grazing, poaching of soils would be a risk with cattle, which may result in soil damage and potentially reduced grazing yields [96,98,102]. Sheep grazing of winter cereals or cover crops could be an alternative option that is traditional practice in British agriculture, where technology could help ahead [100,101,104]. Alternatively, cereals can be grazed before stem extension (that is growth stage 30, indicating end of tillering) [102]. Potentially a field with GL, grazable cover crops and winter cereals could be grazed during the winter/spring with no need to restrict animals within strips in regenerative strip intercropping system. Or the whole field could be sown with a rotational grass ley for two to three years to promote alternative grazing before being returned to the regenerative strip intercropping system [88,89].

Linking with other precision agriculture literature, this study also suggests autonomy for public roads transportation apart from on-farm operations [103] and mechatronic automation for livestock rearing [104] that could help make the integrated crop-livestock regenerative farming systems more competitive. Sensitivity modelling results of this study found that autonomous manure, forage, and field to farmstead movement increased farm economics in integrated crop-livestock regenerative strip intercropping system. In the longer run custom hire services for autonomous machines [105] in strip intercropping forage harvest and manure handling could become a cost-effective alternative. While autonomous farm machines on public roads may be a distant prospect because of regulatory challenges, autonomous movement between contiguous farm fields is a current possibility. Large 500+ ha contiguous farms are relatively common in the US, Canada, Australia, Brazil and some other countries [106]. Some such farms exist in the UK [69]. The sensitivity test suggests those larger contiguous farms could be early candidates for testing integrated crop-livestock regenerative strip intercropping with swarm robotics.

This research indicates that swarm robotics operated regenerative strip intercropping system has economic potential in the UK, but it leaves many questions unanswered. To better understand the economics of regenerative strip intercropping system, research should consider on-farm experimentation. Such demonstration would give a clearer picture of edge effects, input cost changes and biodiversity benefits for the same height plants typical in the UK. The production economics analysis of this study should be extended to add agroecological benefits of strip intercropping systems as compared to whole field sole cropping system including soil health, biological diversity and eco-system resilience. Integrated crop-livestock regenerative strip intercropping system needs to be rethought. Are there potentially practical alternative grazing systems? Would other livestock species (e.g. small ruminants, poultry) fit better into a narrow strip crop system? Could intensive beef finishing operations be automated enough to make such a system profitable? Future economic analyses should consider agricultural labour scarcity, increasing wage rate resilience in the face of supply chain disruptions and vulnerability to financial stresses (e.g. high interest rates, lending issues, etc.).

## 5. Conclusions

Worldwide regenerative agriculture (RA) is promoted as an alternative agriculture paradigm for transforming food production, while reconciling agronomic, economic, and environmental synergies. However, scaling up of RA practices are modest. Research suggests that RA practices are sensitive to enterprise combination, farming systems, technology and regional context of farming. To guide future scaling up potential, RA practices design, and to identify profitable farm mechanization and production economics alternatives, this study modelled regenerative strip intercropping system without livestock and with livestock components. The regenerative practices were further compared with whole field sole cropping systems operated using larger conventional machines with human drivers. The ex-ante profit maximizing deterministic economic modelling in a 500 ha West Midlands British farm found that swarm robotics operated crop only regenerative strip intercropping system without livestock was more profitable than conventional strip intercropping system operated using small conventional machines with human drivers and whole field sole cropping system operated using larger conventional machinery sets operated with human drivers.

Compared to crop only regenerative cropping systems without livestock, the integrated crop-livestock regenerative farming systems (with livestock systems) had lower return to operator labour, management and risk taking (ROLMRT). Conventional regenerative strip intercropping practices in both systems were not economically attractive because of substantial labour and machinery sets requirements. The swarm robotics operated crop only regenerative strip intercropping system without livestock reduced machine costs and on-farm labour requirements. But swarm robotics operated integrated crop-livestock regenerative strip intercropping system needed human drivers for transportation on public roads and temporary human labour for intensive beef feeding that made the autonomous integrated system less competitive. Research is suggested to consider autonomous intensive livestock rearing, alternative grazing systems, inclusion of small ruminants, and experimentation on farms with contiguous fields to avoid road transport. Regenerative strip intercropping experimentation is also advocated for same height plants typical in the UK to optimize edge effects, input cost reductions and promote greater biodiversity. This research indicates the potentials of swarm robotics to help British agricultural transition plan for food security, improving soil health, biodiversity and achieving carbon net zero target. This evidence-based modelling would help guide RA practices including field layout and logistics of RA practices, mechanized farm management alternatives, and enterprise selection decisions. This study would guide worldwide farmers, agri-businesses, agri-tech innovators, and start-ups in autonomous prototypes development and optimization field layout to address within field heterogeneity.

## Ethics statement

Not applicable: This manuscript does not include human or animal research.

## CRediT authorship contribution statement

**A.K.M. Abdullah Al-Amin:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **James Lowenberg-DeBoer:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Kit Franklin:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Edward Dickin:** Writing – review & editing, Supervision, Conceptualization. **James M Monaghan:** Writing – review & editing, Supervision, Conceptualization. **Karl Behrendt:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

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.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.atech.2025.101005.

## Data availability

Data will be made available on request.

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