Economics of Field Size for Autonomous Crop Machines

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Abstract.

Field size constrains spatial and temporal management of agriculture with implications for farm profitability, field biodiversity and environmental performance. Large, conventional equipment struggles to farm small, irregularly shaped fields efficiently. The study hypothesized that autonomous crop machines would make it possible to farm small non-rectangular fields profitably, thereby preserving field biodiversity and other environmental benefits. Using the experience of the Hands Free Hectare (HFH) demonstration project, this study developed algorithms to estimate field times (hr/ha) and field efficiency (%) subject to field size in grain-oil-seed farms of the United Kingdom using four different equipment sets. Results show that field size had a substantial impact on technical and economic performance of all equipment sets, but autonomous machines were able to farm small 1 ha non-rectangular (i.e., right-angled triangular) fields profitably. Small fields with equipment of all sizes and types required more time, but for HFH equipment sets (i.e., 28 kW conventional machine with human operator and 28 kW autonomous equipment set) field size had the least impact. HFH linear programming model solutions show that autonomous machines decreased wheat production cost by £21/ton to £40/ton for small non-rectangular fields, while 112 kW and 221 kW equipment sets with human operators were not profitable for small fields. Technical and economic feasibility in small fields imply that autonomous machines could facilitate biodiversity and improve environmental performance.

Keywords.

Autonomous machine; Field size; Field efficiency; Economic feasibility; Economies of size, Profitability.

Introduction

Field size has substantial consequences for environmental management (Clough et al., 2020; Konvicka et al., 2016; Marja et al., 2019), technical (Fedrizzi et al., 2019; Griffel et al., 2018; Griffel et al., 2020; Islam et al., 2017; Janulevičius et al., 2019; Luck et al., 2011) and economic feasibility (Batte and Ehsani, 2006; Carslaw, 1930; Larson et al., 2016; Miller et al., 1981; Sturrock et al., 1977). To facilitate conventional agricultural mechanization, comparatively large rectangular fields are needed and most of the land consolidation around the world in the last decades has been motivated by the desire for larger fields (Kienzle et al., 2013; Van den Berg et al. 2007). In the United Kingdom, field size has increased through removing hedgerows and in field trees to allow increasing use of larger machinery and ensure economics of size (MacDonald and Johnson, 2000; Pollard et al., 1974; Robinson and Sutherland, 2002). On the contrary, small fields are often neglected and considered as non-economic. For instance, in the United States many small irregular-shaped fields were abandoned in the 20th Century. The European Union and Switzerland retained small fields in production with subsidies (Lowenberg-DeBoer et al., 2021). Nevertheless, under the umbrella of landscape management, small fields are promoted by researchers. Research in Canada and the United States found increasing biodiversity in smaller fields (Fahrig et al., 2015; Flick et al., 2012; Lindsay et al., 2013). Likewise, studies in the United Kingdom and the European Union, also showed that small fields and more fragmented landscapes have higher biodiversity (Firbank et al., 2008; Gaba et al., 2010; González-Estébanez et al., 2011). This study hypothesized that autonomous crop machines would make it possible to farm small non-rectangular fields profitably, thereby preserving and potentially enhancing the environmental benefits of farming landscapes with small non-rectangular fields.

Autonomous crop machines in this study refer to the mechatronic devices which have autonomy in operation usually through a predetermined field path. More specifically, the autonomous machines are mobile, having decision making capability, and accomplish arable farm operations (i.e., drilling, seeding, spraying fertilizer, fungicide and herbicide, and harvesting) under the supervision of humans, but without the involvement of direct human labour (Lowenberg-DeBoer et al., 2021, 2020). Autonomous machines are precision agriculture technology because they have the potential to cost effectively increase the precision of input applications and to collect very detailed data on agricultural production. The autonomous machines, demonstrated by the HFH project used swarm robotics concepts in which multiple smaller robots are used to accomplish farm work usually done by larger conventional machines with human operators. The autonomous swarm robotics of the HFH project are developed by retrofitting conventional machines (for details see Hands Free Hectare (HFH), 2021; Lowenberg-DeBoer et al., 2021).

Autonomous machines are considered as a game changing technology that could revolutionize precision agriculture (PA) and facilitate the 'fourth agricultural revolution' often labelled ‘Agriculture 4.0’ (Daum, 2021; Klerkx and Rose, 2020; Lowenberg-DeBoer et al., 2021). Owing to population and economic growth, agricultural labour scarcity, technological advancement, increasing requirements of operational efficiency and productivity, and mitigating environmental footprint, autonomous machines are suggested as a sustainable intensification solution (Duckett et al., 2018; Future Farm, 2021; Guevara et al., 2020; Santos sand Kienzle, 2020). Robotic systems for intensive livestock and for protected environments have been commercialized more rapidly than for arable cropping. Research on autonomous arable crop machines has mostly concentrated on the technical feasibility, not economics (Fountas et al., 2020; Shamshiri et al., 2018). Understanding the economic implications of autonomous machines is key to their long-term adoption. Economic feasibility plays a crucial role in attracting investment, guiding adoption decisions, and further understanding of environmental and social benefits (Grieve et al., 2019; Lowenberg-DeBoer et al., 2020).

Most production economic studies on autonomous crop machines prior to 2019 focused on horticultural crops or rarely on cereals using prototype testing and experimental data (Edan et al., 1992; Gaus et al., 2017; McCorkle et al., 2016; Pedersen et al., 2017, 2008, 2006; Sørensen et al., 2005). Lack of information on economic parameters and machinery specifications has been a bottleneck in economic feasibility assessment because autonomous machines are at an early stage of the development and commercialization processes (Lowenberg-DeBoer et al., 2021; Shockley et al., 2021). Most of the earlier economic studies used partial budgeting, in which only the changes in cost and revenue linked to automation of a single field operation were analysed, omitting the economic consequences of farming systems changes resulting from use of autonomous machines (Lowenberg-DeBoer et al., 2020). To date, four studies have considered systems analysis of autonomous machines (e.g., Al-Amin et al., 2021; Lowenberg-DeBoer et al. 2021; Shockley et al. 2019; C. G. Sørensen and Nielsen 2005).

Using a Linear Programming (LP) model with data from prototypes at the University of Kentucky, United States, Shockley et al. (2019) showed that relatively small autonomous machines are likely to have economic advantages for medium and small farms. The most comprehensive study so far was reported by Lowenberg-DeBoer et al. (2021). They assessed the economic feasibility of autonomous machies from seeding to harvesting operations using on-farm demonstration data and estimated equipment times based on methodology from the agricultural engineering textbook of Witney (1988). The study assumed 70% field efficiency from drilling to harvesting operations for both autonomous machines and conventional equipment sets with human operators. They showed that autonomous machines are technically and economically feasible for medium and small sized farms. The study concluded that autonomous machines diminished the rule of thumb of mechanized agriculture that is “get big or get out”. The study hypothesized that in the context of the United Kingdom, autonomous machines would be economically feasible in small fields. Nonetheless, the study was unable to test the hypothesis because of field efficiency estimates by field size and shape were not available.

To help fill this knowledge gap, the objective of the study is to assess the economics of field size for autonomous machines. Using the experience of the HFH demonstration project, the study developed algorithms to estimate equipment times and field efficiency for different sized non-rectangular (i.e., right-angled triangular) fields. Historically in the United Kingdom, non-rectangular (i.e., triangular) fields were among the least efficient to farm (Carslaw, 1930; Sturrock et al., 1977). To analyse the economic scenarios, the study adopted and re-estimated the Hands Free Hectare-Linear Programming (HFH-LP) model (Lowenberg-DeBoer et al., 2021) by incorporating equipment times and field efficiency parameters estimated with field size algorithms. The HFH-LP model facilitated farm management and machinery selection decisions. A parallel study with preliminary results for rectangular fields of different sizes is available from Al Amin et al. (2021).

Methods

Field time and efficiency estimation subject to field size

To date the production economics studies on autonomous machines did not consider field size because of lack of data (Lowenberg-DeBoer et al., 2021; Shockley et al., 2019; Sørensen et al., 2005). Over time, the performance of arable field machinery has received growing attention for farm management and the ability to model field times has accelerated through the development of the technology and modelling approaches (Bochtis et al., 2010; Sørensen et al., 2005; Sørensen, 2003; Sørensen and Nielsen, 2005). Nonetheless, existing studies on arable crop machinery performance lack information of equipment times and field efficiency subject to field size.

Even though logistics software is well developed in trucking and other transportation sectors (Software Advice, 2021), there is no readily available commercial software in the United Kingdom to estimate equipment times and field efficiency encompassing fields and machines heterogeneity. In the farm equipment path planning research literature, field times were sometimes generated as a by-product (Hameed, 2014; Jensen et al., 2012; Oksanen and Visala, 2007; Spekken and de Bruin, 2013). The agri-tech economic studies often rely on the general estimates of agricultural engineering textbooks like Hunt (2001) and Witney (1988). In conventional mechanization and PA literature, few studies estimated field efficiency, but prior studies treated the headlands of the field as non-productive areas, excluded overlap percentage, amalgamated productive field times (i.e., field passes, headlands turning, and headlands passes) and non-productive field times (i.e., replenish inputs, refuelling, and blockages), and ignored the headland turning patterns. Studies suggested that future research should separately calculate the headlands turning time, and stoppages time because productive times and non-productive times play a significant role in field efficiency estimation. Keeping these points in consideration, the study developed field time approximation algorithms by field size for 28 kW, 112 kW and 221 kW conventional equipment sets with human operators, and for the HFH sized 28 kW autonomous equipment set. The combine harvesters were assumed to have head widths of 2 m, 4.5 m and 7.5 m respectively. Using the experience of the HFH demonstration project, the algorithms addressed the research gaps identified from the prior studies. The study estimated field efficiency as the ratio of theoretical field time based on machine design specifications like the estimates of theoretical field time to its actual field productivity as follows:

$$E_f = [T_T / (T_{obs} + \mathrm{T_h} + \mathrm{T_{sf}})] * 100 \ldots \ldots (1)$$

where, E_f is the field efficiency, T_T is the theoretical field time, T_{obs} is the total observed time in the interior field and passes, T_h is the total headland round time, and T_{sf} total stoppage time "within" in the field. Details of the algorithms are available on request from the first author.

The algorithms were calibrated for 1 ha, 10 ha, 20 ha, and 25 ha sized non-rectangular (i.e., right-angled triangular) fields assuming the height equalling twice the base. The study assumed that the equipment enters the field at the 90˚ angle corner and completes the headlands first for all field operations (i.e., drilling, spraying, and harvesting). Afterwards, the machine makes a "flat turn" to start the interior passes. Subsequently, follows the "flat turn" to complete the interior headland turns. Finally, the study assumed that the equipment ends on the entry side of the fields. as shown in Fig. 1.

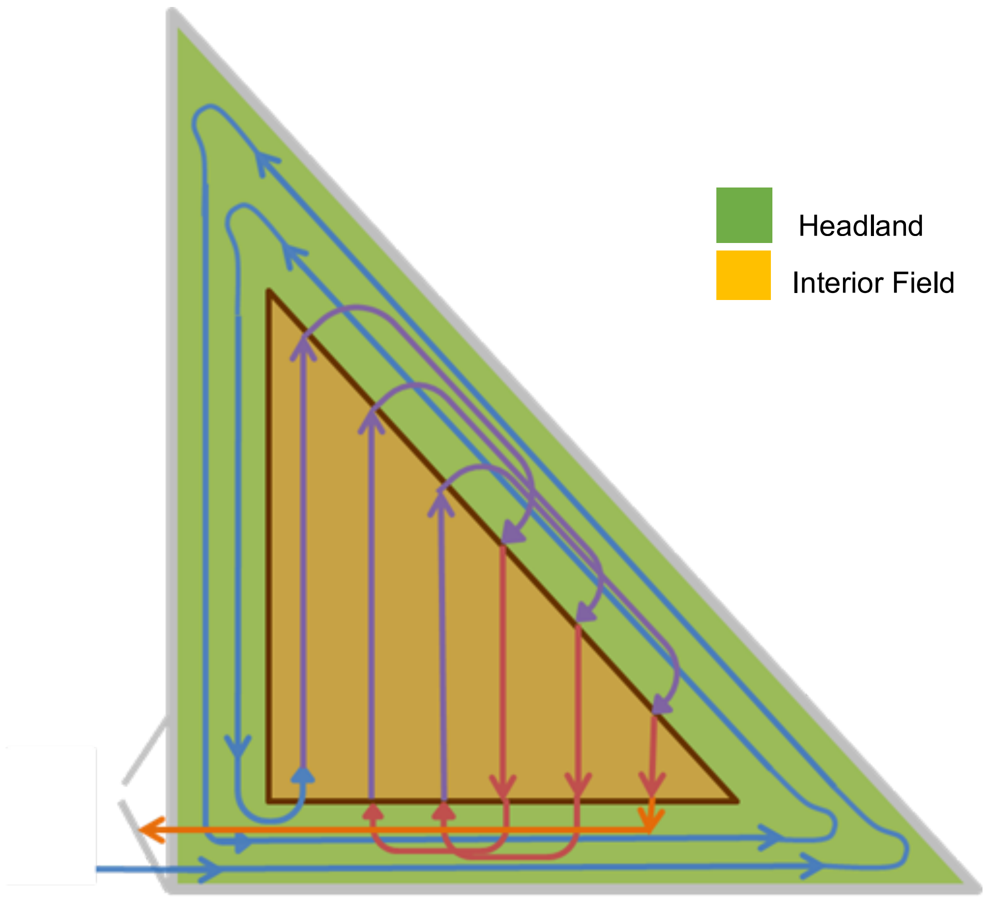

Fig. 2 Typical field path for non-rectangular (i.e., right-angled triangular) fields considered in the study based on the HFH demonstration project experience.

Modelling the economics of field size

To understand the whole farm effects of field size with different types of farm equipment, the study adopted and re-estimated the Hands Free Hectare - Linear Programming (HFH-LP) model (for details see Lowenberg-DeBoer et al., 2021). The HFH-LP model is a decision-making tool which assesses the economics of autonomous machines compared to conventional equipment sets with human operators. Consistent with typical neoclassical microeconomic farm theory, the objective function of the HFH-LP model was to maximize gross margin (i.e., return over variable costs) subject to primary farm resource constraints in the short-run. In the subsequent stages, using the outcome of the HFH-LP model, the study examined net return to operator labour, management and risk taking and evaluated the wheat cost of production to explore the cost economies (i.e., economies of size) (Debertin, 2012; Duffy, 2009; Hallam, 2017; Miller et al., 1981). The HFH-LP model is a one-year "steady state" model for arable grain-oil-seed farm, where the model assumes a monthly time step from January to December. It is steady state in the sense that it is assumed that solutions would be repeated annually long term. The concept of "steady state" was carried over from the Orinoquia model (for details see Fontanilla-Díaz et al., 2021) which used the same software. Following Boehlje and Eidman (1984), the HFH-LP deterministic economic model can be expressed as:

The objective function:

$$Max\ \pi = \sum_{j=1}^{n} c_j X_j \qquad \ldots\ldots(2)$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i \ for\ i = 1, \ldots \ldots, m; \qquad \ldots\ldots(3)$$

$$X_j \geq 0\ for\ j = 1, \ldots \ldots, n; \qquad \ldots\ldots(4)$$

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

The constraints of the HFH-LP model encompassed land, human labour, equipment times (i.e., tractor use time for drilling and spraying, and combine use time for harvesting), and cashflow. The initial HFH-LP scenarios encompassed four farm sizes: 66 ha, 159 ha, 284 ha and 500 ha farms, but did not model field size. This study re-estimated the human labour and equipment times assuming non-rectangular large fields (10 ha) or small fields (1 ha). The 10 ha size was selected for the large fields, because the field efficiency algorithm estimates showed that over 10 ha, field efficiency does not vary much by field size. A 1 ha field size was selected to represent small fields, because relatively few fields in the United Kingdom are smaller than 1 ha. The triangular shape was selected as this is among the least efficient (Carslaw, 1930). For details of the land, human labour, cash flow constraints, field operation and equipment time by crop month and equipment sets at optimum yields, and the programming code see Lowenberg-DeBoer et al. (2021). The HFH-LP model was coded in the General Algebraic Modelling System (GAMS) (https://www.gams.com/).

Case study and data sources

The study was conducted based on the experience of the HFH project at Harper Adams University, Newport, Shropshire, United Kingdom. The HFH-LP model represented an arable grain-oil-seed farm in the West Midlands of the United Kingdom. To calibrate the HFH-LP model, the study used parameters from different sources. The information about commodity produced and the costs estimates were from the Agricultural Budgeting and Costing Book (Agro Business Consultants, 2018) and the Nix Pocketbook (Redman, 2018). Details of the machine inventory, costs of machines, hardware and software, crop rotations and key baseline assumptions are available at Lowenberg-DeBoer et al. (2021). Field operation timing was adopted from Finchet al. (2014) and Outsider's Guide (1999).

Equipment timeliness (i.e., HFH 28 kW conventional equipment set with human operator and autonomous machines, 112 kW and 221 kW conventional equipment sets with human operators) were estimated through the developed algorithms, where the equipment and field specifications were collected from HFH demonstration experience (https://www.handsfreehectare.com/), conventional machine specifications from John Deere (https://www.deere.co.uk/en/index.html), and Arslan et al. (2014) and Lowenberg-DeBoer et al. (2021). Details of the technical parameters used and data sources are available on request from the first author at abdullah.alamin@live.harper.ac.uk.

Results

Effects field size on field efficiency and times

The study evaluated the technical feasibility of the HFH 28 kW conventional equipment with human operator and autonomous machines, and 112 kW and 221 kW conventional equipment sets with human operators for all field operations including direct drilling, five spraying applications of liquid fertilizer, fungicide and herbicide, and harvesting operation. The average whole farm field efficiency for non-rectangular fields differed substantially between 1 ha and 10 ha fields, but for a given equipment set the average whole farm field efficiency was almost the same for 20 ha and 25 ha fields (Fig. 2). The technical feasibility (i.e., field times and field efficiency) results show that HFH 28 kW equipment sets were more technically feasible for all sized non-rectangular fields even in small 1 ha fields, whereas conventional 221 kW and 112 kW equipment set with human operators were less efficient in non-rectangular fields.

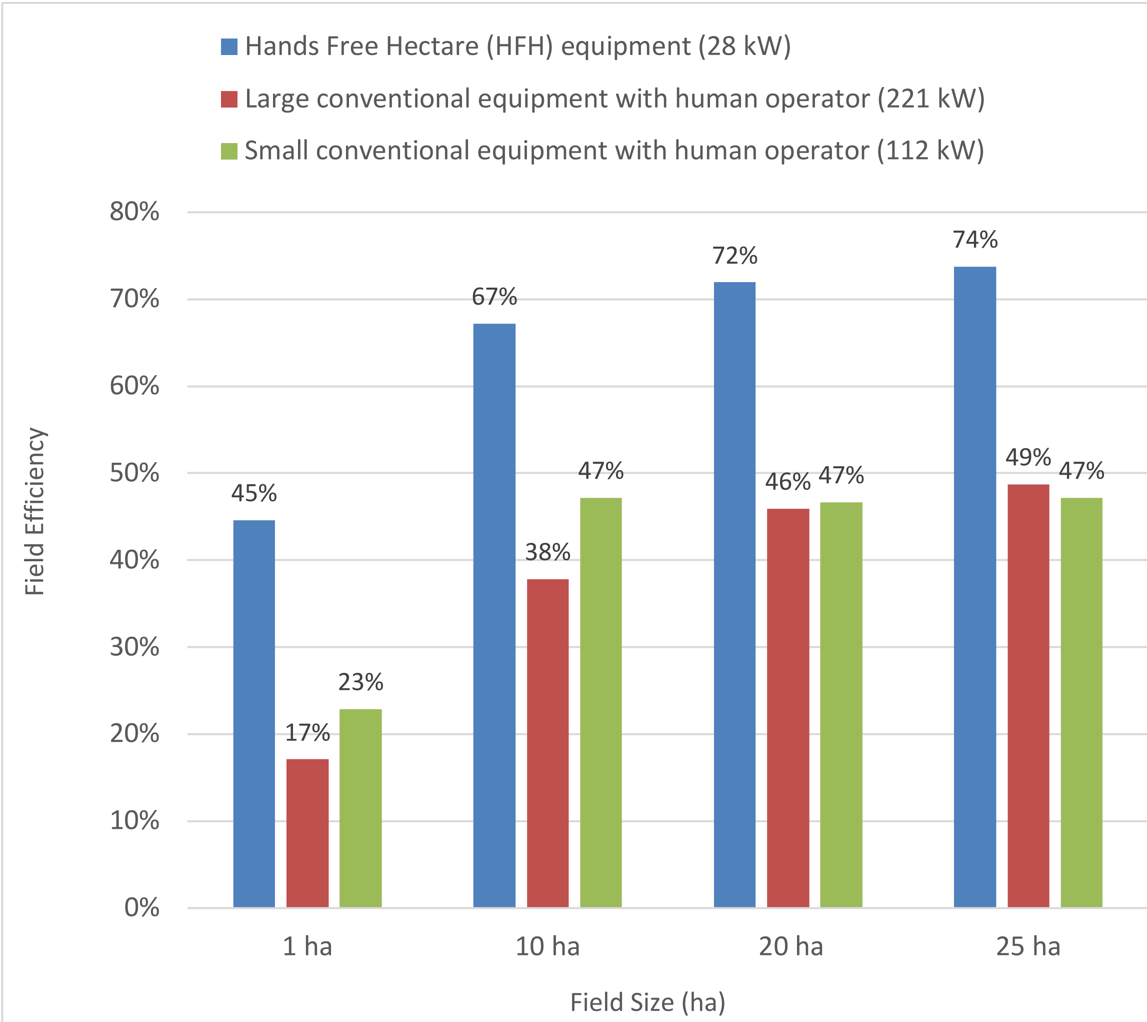

Fig. 2 Estimated (weighted average) whole farm field efficiency of HFH equipment (i.e., 28 kW conventional equipment with human operators and autonomous machine), large conventional and small conventional technology with human operators in different sized non-rectangular fields.

The equipment times were longer for all operations in small 1 ha fields equipped with equipment of all sizes and types, but field sizes had least impact for the HFH equipment sets (Table 1). The higher time for small 1 ha fields was largely due to the fact that the full width of the larger equipment could not be used effectively in the smaller fields. Drilling operations required the highest equipment times and subsequently followed by harvesting and spraying in case of HFH 28 kW equipment sets, whereas for conventional equipment sets with human operators (i.e., 221 kW and 112 kW) irrespective of field sizes, harvesting consumed more time, afterwards, drilling and spraying. Small 1 ha non-rectangular fields required more time for field operations due to the varying interior length of the passes, higher interior headlands turning time. The comparatively lower times for spraying compared to drilling and harvesting operations was associated with the field and equipment specifications of the sprayer because the sprayers were the widest implement. This also resulted in the lower field efficiency for spraying small fields.

Table 1 Equipment times of the machinery sets for non-rectangular fields of 1 ha and 10 ha

Equipment	Width of the implement (m)**	Overlap percentage **	Field speed (km/hr)**	Field Efficiency (%)***	hr/ha
1 ha Non-rectangular Field					
HFF equipment set (28 kW)*:					
Drill	1.5	10%	3.25	47%	4.85
Sprayer	7	10%	5	44%	0.72
Combine	2	10%	3.25	45%	3.80
Larger conventional set (221 kW):					
Drill	6	10%	5	20%	1.85
Sprayer	36	10%	10	16%	0.19
Combine	7.5	10%	3	19%	2.60
Small conventional set (112 kW):					
Drill	3	10%	5	27%	2.74
Sprayer	24	10%	10	22%	0.21
Combine	4.5	10%	3	24%	3.43
10 ha Non-rectangular Field					
HFF equipment set (28 kW)*:					
Drill	1.5	10%	3.25	70%	3.26
Sprayer	7	10%	5	66%	0.48
Combine	2	10%	3.25	71%	2.41
Larger conventional set (221 kW):					
Drill	6	10%	5	43%	0.86
Sprayer	36	10%	10	36%	0.09
Combine	7.5	10%	3	41%	1.20
Small conventional set (112 kW):					
Drill	3	10%	5	54%	1.37
Sprayer	24	10%	10	46%	0.10
Combine	4.5	10%	3	48%	1.71

Note: * HFH equipment sets are28 kW conventional machines with human operators and 28 kW autonomous machines. **The machine specifications and overlap assumptions were collected from the HFH experience and Lowenberg-DeBoer et al. (2021). *** The authors developed algorithms to estimate the field efficiency of non-rectangular fields (details of the estimation procedures and algorithms are available on request from the first author at abdullah.alamin@live.harper.ac.uk).

Economic implications of field size on machinery use

HFH-LP solutions for the farm size, field size and equipment set scenarios for non-rectangular fields are presented in Table 2. The identical gross margin for 66 ha farms with 10 ha sized non-rectangular fields is because the smallest farms did not face any operator and labour time constraints, therefore they planted, maintained and harvested the wheat-OSR rotation at optimal times. On the contrary, gross margins for 66 ha farm with 1 ha non-rectangular fields were higher for autonomous machines and larger conventional equipment compared to 28 kW and 112 kW conventional equipment sets because these two conventional sets faced operator time constraints and required more hired labour for farm operations.

Economic scenarios of non-rectangular fields incorporating fixed costs show that net returns to operator labour, management, and risk taking were higher for autonomous machines irrespective of field sizes, except for the smallest 66 ha farm in the West Midlands equipped with 28 kW conventional machine with human operator. This is because the autonomous machines required extra cost for retrofitting equipment for autonomy. The higher net return to operator labour, management and risk taking for the conventional 66 ha farm may be an illusion because of the higher labour requirement. For the 66 ha farm with 10 ha fields, no labour is hired in either conventional or autonomous scenarios, but the conventional farm requires 3 times more operator labour time than the autonomous farm. For the 66 ha farm with 1 ha fields, the conventional farm requires 3 times more operator labour, plus 16 days more hired labour. A small conventional 28 kW equipment set is not the sustainable solution given the growing labour scarcity in arable farming in the United Kingdom.

Table 2 HFH-LP outcomes on the economic viability of technology choice subject to different sized non-rectangular fields.

Scenario*	Arable area (ha)**	Field size (ha)	Labour hired in the farm (days per annum)	Operator time required in the farm (days per annum)	Whole farm gross margin (£ per annum)	Return to operator labour, management and risk taking (£ per annum)	Wheat cost of production with allocated operator labour (£ per ton)
Conv. 28 kW	59.4	10	0	80	47048	15848	169
Conv. 28 kW	59.4	1	16	106	45817	14617	188
Conv. 28 kW^{2}	143.1	10	71	121	107796	36381	151
Conv. 28 kW^{2}	143.1	1	144	149	98792	27377	168
Conv. 28 kW^{3}	255.6	10	195	147	187200	64886	140
Conv. 28 kW^{4}	255.6	1	355	169	174736	43259	153
Conv. 28 kW^{4}	450.0	10	415	188	301867	98268	141
Conv. 28 kW^{7***}	450.0	1	743	180	298465	67379	145
Autonomous 28 kW	59.4	10	0	24	47048	12301	139
Autonomous 28 kW	59.4	1	0	38	47048	12301	148
Autonomous 28 kW	143.1	10	3	55	113076	47276	125
Autonomous 28 kW^{2}	143.1	1	31	60	110943	32433	137
Autonomous 28 kW^{2}	255.6	10	41	63	199274	79027	122
Autonomous 28 kW^{3}	255.6	1	90	72	195464	62507	130
Autonomous 28 kW^{3}	450.0	10	105	77	348225	143146	118
Autonomous 28 kW^{4}	450.0	1	191	94	341516	123728	124
Conv. 112 kW	59.4	10	0	40	47048	-26001	220
Conv. 112 kW	59.4	1	3	76	46539	-26510	246
Conv. 112 kW	143.1	10	17	78	112004	7903	161
Conv. 112 kW^{2}	143.1	1	93	99	106052	-49061	211
Conv. 112 kW	255.6	10	74	96	196659	50820	139
Conv. 112 kW^{2}	255.6	1	231	112	184397	-12453	168
Conv. 112 kW^{2}	450.0	10	193	107	341365	72393	138
Conv. 112 kW^{4***}	450.0	1	470	135	319779	-51216	170
Conv. 221 kW	59.4	10	0	28	47048	-70973	296
Conv. 221 kW	59.4	1	0	60	47048	-70973	317
Conv. 221 kW	143.1	10	0	67	113343	-35731	192
Conv. 221 kW	143.1	1	49	96	109520	-39554	202
Conv. 221 kW	255.6	10	33	87	199900	9089	155
Conv. 221 kW^{2}	255.6	1	149	109	190802	-95993	204
Conv. 221 kW^{2}	450.0	10	106	105	348122	-10796	158
Conv. 221 kW^{3***}	450.0	1	325	130	331055	-123847	188

Note: *The superscript with equipment specification under scenario indicates the number of equipment sets. **Based on the experience of HFH demonstration project, the study assumed that the arable crop farm was 90% tillable, where remaining 10% were occupied for ecologically focused area such as, lanes, hedgerows, drainage ditches, farmstead, etc. ***The study baseline scenarios assumed a maximum of 100 person-days/month of temporary labour available, but in the sensitivity testing that was raised to 200 person-days/month.

The wheat cost of production curves with non-rectangular fields shows that irrespective of field sizes, farms with autonomous machines had cost advantages (i.e., lower cost of production) and reduced economies of size compared to farms with conventional equipment sets with human operators (Fig. 3). More specifically, the autonomous cost curves scenarios reveal that small 1 ha non-rectangular fields required higher wheat cost of production compared to 10 ha fields, which are associated with comparatively higher hired labour, operator time and equipment scenarios. The equipment scenarios show that small non-rectangular fields required more autonomous equipment sets to optimally operate the same farm, except for the smallest farm. Likewise, for conventional equipment sets, small 1 ha fields had substantially higher wheat production costs compared to 10 ha fields. For larger 500 ha farms equipped with conventional sets, the minimum unit cost of production was achieved with seven-units of 28 kW equipment set for 1 ha fields, whereas 10 ha fields had minimum unit cost scenarios with two units of 112 kW equipment set. The wheat cost scenarios by equipment set shows that autonomous machines reduced wheat cost of production by £21/ton to £40/ton in small 1 ha non-rectangular fields, indicating that autonomous equipment has cost advantages (i.e., lower cost of production) and reduced economies of size compared to conventional equipment sets with human operators.

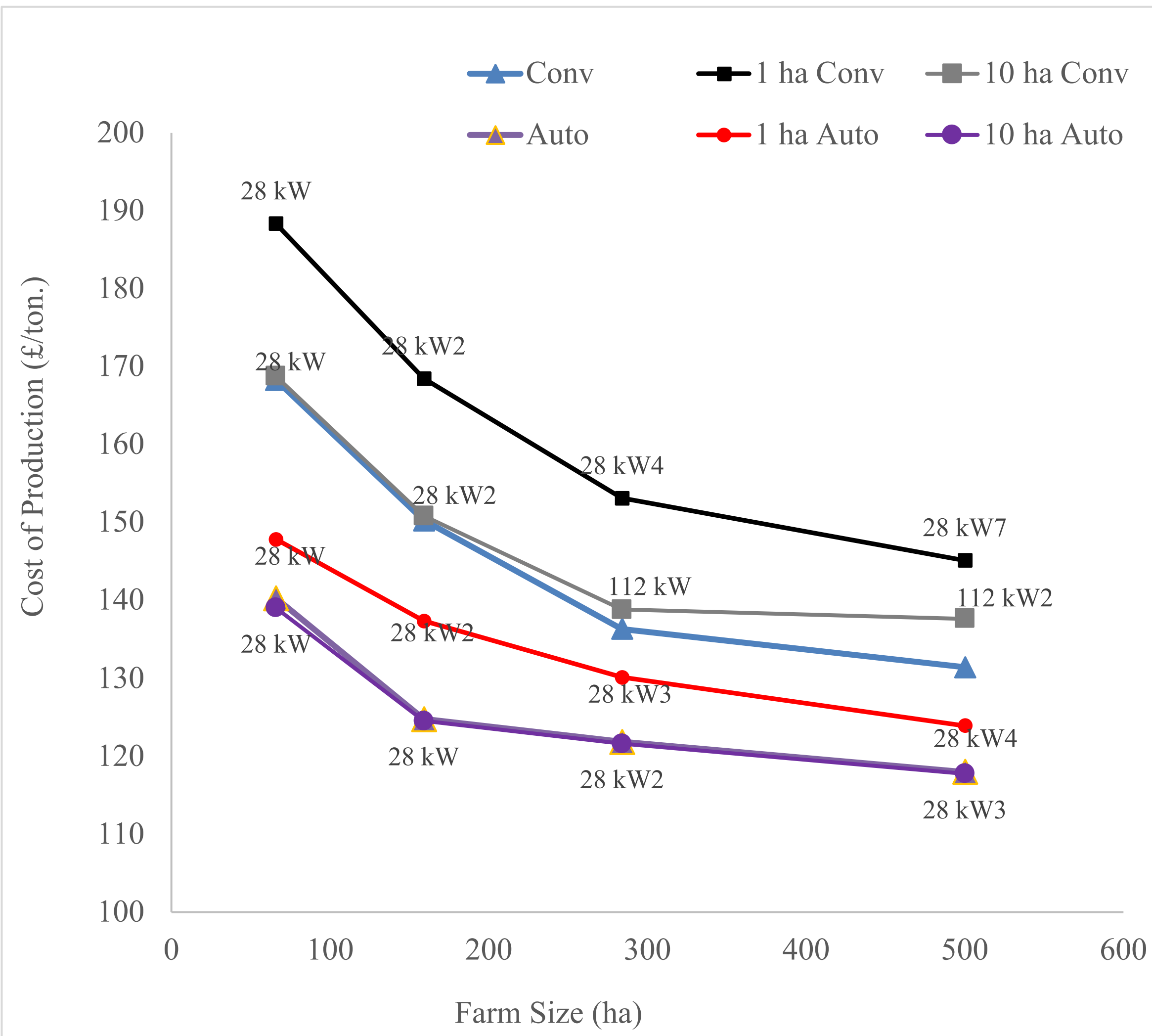

Fig. 3 Wheat unit cost of production in pounds per ton for farms with non-rectangular fields of different sized farms. The labels on the data points for 1 ha and 10 ha fields are the size of the tractor used and the number of equipment sets. The curves without labels are the baseline analysis which was done without field size and shape modelling.

Discussion

The scenarios analysed show that for a given farm size and machinery use, gross margin and net return to operator labour, management and risk taking were similar irrespective of field size, whereas net returns differed more by equipment set than field size. Further investigation of the economies of size, with a reference to field size, contributes to the cost economies literature as prior production economies studies missed out the implications of non-rectangular fields for autonomous machinery (Al-Amin et al., 2021). Assuming a 2018 wage rate to allow comparison to the baseline study by Lowenberg-DeBoer et al. (2021), the study shows that autonomous machines had lower wheat production cost and reduced economies of size compared to conventional equipment sets with human operators irrespective of field size.

The results support the hypothesis of the study that autonomous machines offer the possibility of farming small non-rectangular fields profitably, implying the potentials of biodiversity enhancement and environmental performance of such small fields as a side effect (Fahrig et al., 2015; Firbank et al., 2008; Konvicka et al., 2016). This suggests that autonomous arable crop farms could support the United Kingdom's agricultural transition plan for sustainable farming, as the economic feasibility of small autonomous farms favours the recent government initiative of the Environmental Land Management Schemes (ELMS) which is grounded on three fundamental components of sustainable farming incentive, local nature recovery and landscape recovery (DEFRA, 2020; DEFRA, 2021). Likewise, the study supports agri-environment schemes (AES) which encourage small fields for biodiversity in the European Union and elsewhere (Geppert et al., 2020).

The findings of the study also provide guidelines to farmers, agribusinesses, technology developers, and policymakers. More specifically, the study guides "*farm size policy*" generally associated with *"agricultural mechanization policy"* and *"biodiversity conservation policy"* of large (i.e., Brazil, Argentina, United States, Australia, and Mexico) and medium (i.e., United Kingdom and Europe) scale farming systems in developing policies considering environmental performance in arable farming. Conventional mechanization with human operators encourages field enlargement and farm size growth, but the profitability of autonomous farms with small non-rectangular fields irrespective of field size indicates that the pressure to "get big or get out" and remake rural landscapes will be reduced with autonomous machines.

However, despite having significant contributions in PA, farm management, agri-tech economics, and environmental management literature, the study had some limitations in the development of algorithms and existing economic modelling scenarios. Because of lack of data, the algorithms assumed zero down time due to machine problems (e.g., seed tines blocked with crop residue, plugged sprayer nozzles, damp straw wrapping a combine harvester drum). Hands Free Hectare (HFH) was a demonstration project, so it was difficult to separate stops for research purposes and those that would have occurred on any farm. Future research could reinvestigate this assumption based on farm experience. In terms of technical and economic modelling scenarios, the study only considered four equipment sets. There may be other equipment sizes that may better fit the given circumstances, especially for small 1 ha non-rectangular fields. In addition to the large and medium scale economies, considering the context of small scale economics (i.e., Asia and Africa), future research could incorporate various field sizes of less than 10 ha, even less than 1 ha as the small scale economies are subsistence and uneconomical with tiny fragmented arable lands on farms of less than 2 ha, where autonomous machines may be technically and economically profitable solution with their existing labour scarcity, especially in peak production seasons (Al Amin and Lowenberg-DeBoer, 2021; High Level Panel of Experts (HLPE) 2013; Lowder et al., 2016). Even though, the technical and economic feasibility of autonomous machines in small non-rectangular fields reveal the environmental management potentials, for further understanding of the on-field scenarios of field biodiversity impacts on machinery use, future research may incorporate field inclusions, such as in field trees and wetlands, to examine the economic implications of biodiversity enhancement. These inclusions may address field topography issues like grass waterways (Batte and Ehsani, 2006) and/or encourage non-crop habitat within the field or around the field alike aboveground environmental diversification (Bellon-Maurel and Huyghe 2017; Boeraeve et al., 2020; Tamburini et al., 2020). Last but not least, future endeavours may consider the economic implications of autonomous machines on mitigation of environmental degradation.

Conclusions

Considering the field biodiversity and environmental performance potentials of small fields, the study hypothesized that autonomous crop machines would make it possible to farm small non-rectangular fields profitably. To test the hypothesis, the study developed algorithms to estimate field efficiency (%) and equipment times (hr/ha) for different sized non-rectangular (i.e., right angled triangular) fields. The technical feasibility analysis on non-rectangular fields shows that HFH 28 kW conventional equipment set with human operator and autonomous machines (i.e., autonomous swarm robotics) had comparatively higher field efficiency irrespective of field size, compared to the conventional equipment sets with human operators (i.e., 221 kW and 112 kW). Economic scenarios (i.e., return over variable costs and net return to operator labour, management, and risk taking) examined through mathematical programming (i.e., HFH-LP model) show that autonomous machines were a profitable solution for arable farms with small fields considering the scarcity of agricultural labour, and given the substantial amount of hired labour and operator time required by the conventional equipment sets with human operators. The wheat production cost curves comparison show that autonomous machines reduced cost of production by £21/ton to £40/ton for small non-rectangular fields. The ability of autonomous crop machines to profitably farm small non-rectangular fields make them potentially useful in achieving the goals of the Environmental land management schemes in the United Kingdom and agri-environment schemes in the European Union and elsewhere.

Availability of materials

The GAMS code, model parameters and the field size and shape algorithms are available on request from the first author, A. K. M. Abdullah Al Amin at abdullah.alamin@live.harper.ac.uk.

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