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Economics of strip cropping with autonomous machines

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Abstract

Autonomous machines have the potential to maintain food production and agroecological farming resilience. However, autonomous complex mixed cropping is proving to be an engineering challenge because of differences in plant height and growth pattern. Strip cropping is technically the simplest mixed cropping system, but widespread use is constrained by higher labor requirements in conventional mechanized farms. Researchers have long hypothesized that autonomous machines (i.e., crop robots) might make strip cropping profitable, thereby allowing farmers to gain additional agroecological benefits. To examine this hypothesis, this study modeled ex-ante scenarios for the Corn Belt of central Indiana, using the experience of the Hands Free Hectare-Linear Programming (HFH-LP) optimization model. Results show that per annum return to operator labor, management, and risk-taking (ROLMRT) was \$568/ha and \$163/ha higher for the autonomous corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] strip crop farm compared to the whole field sole crop and the conventional strip crop farms, respectively, that were operated by human drivers. The conventional strip cropping practice was found challenging as this cropping system required four times more temporary hired labor than autonomous strip cropping and three times more than whole field sole cropping. Even if autonomous machines need 100% human supervision, the ROLMRT was higher compared to whole field sole cropping. Profitable autonomous strip cropping could restore and improve in-field biodiversity and ecosystem services through a sustainable techno-economic and environmental approach that will address the demand for healthier food and promote environmental sustainability.

1 | INTRODUCTION

Autonomous machines are expected to be a game changer for open-field arable crop farming (Gackstetter et al., 2023; Klerkx & Rose, 2020) which would facilitate more diverse, agroecological, and ecosystem services restoring farming practices (Daum, 2021; Pearson et al., 2022). Research suggests that within-field heterogeneous, small-scale, and spatiotemporal mixed cropping systems such as strip cropping (Ghaffarzadeh et al., 1994; Smith & Carter, 1998; Verdelli et al., 2012), pixel cropping (Ditzler & Driessen, 2022), patch cropping (Donat et al., 2022; Grahmann et al., 2021), and

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Abbreviations: HFF, Hands Free Farm; HFH, Hands Free Hectare; HFH-LP, Hands Free Hectare-Linear Programming; LP, Linear Programming; ROLMRT, return to operator labor, management, and risk-taking.

relay cropping (Patel, 2020; Tanveer et al., 2017) enable more diverse cropping practices. However, more complex mixed cropping practices constrain autonomous farm management due to the technical difficulty of automating management with different plant heights and growth patterns (Ditzler & Driessen, 2022). Among different mixed cropping systems, strip cropping is the simplest and most technically feasible with conventional mechanization (Alarcón-Segura et al., 2022; Exner et al., 1999; van Apeldoorn et al., 2020).

Strip cropping refers to a farming practice of simultaneously growing two or more crops in adjacent strips, where the strips are wide enough for independent cultivation and narrow enough for facilitating crop interaction (Brooker et al., 2015; Hernández-Ochoa et al., 2022; Vandermeer, 1989). Strip cropping is considered as a means of sustainable intensification because this cropping system can improve utilization of on-farm resources through increasing land productivity and enabling multifunctionality of agricultural landscapes (Gao et al., 2009; Juventia et al., 2022; Li et al., 2011; Raseduzzaman & Jensen, 2017). To manage spatiotemporal heterogeneity, the same precision agriculture (PA) and variable rate technology used in conventional arable farming could be used in the crop strips, but the dearth of data on PA in crop strips limits analysis of the economics of PA in strip cropping. This analysis assumed that the soil is relatively homogenous and that field operations can be timed consistently throughout any specific field.

Agronomic research on strip cropping with varying height plants has demonstrated the edge effects that increase yields of the taller species and often lead to a yield penalty for shorter crop plants (Jurik & Van, 2004). These studies were conducted in large-scale farming in the United States (Ward et al., 2016; West & Griffith, 1992) and Argentina (Bravo & Silenzi, 2002; Verdelli et al., 2012), medium-scale farming in Germany (Munz, Claupein et al., 2014), and small-scale farming in China (Du et al., 2018; Liu et al., 2022; Munz, Claupein et al., 2014), as well as in Africa (Kermah et al., 2017; Rahman et al., 2021). Research on corn (*Zea mays* L.), grain sorghum [*Sorghum bicolor* (L.) Moench], and soybean [*Glycine max* (L.) Merr.] in the Corn Belt of eastern Nebraska (Lesoing & Francis, 1999), and corn and bush bean (*Phaseolus vulgaris* L. var. nana) research in China and Germany (Munz, Feike et al., 2014), showed that outside border rows of the taller corn plant had increased yield due to the extra sunlight advantage, while smaller subordinate plant yields decreased in border rows because of competition for solar radiation, soil water, and nutrients. Agronomic studies also showed that strip width and orientation have yield impacts (Liu et al., 2022; Tan et al., 2020; van Oort et al., 2020; West & Griffith, 1992). The review of corn and soybean strip cropping experiments based in Eastern and Midwest United States showed that narrow corn strips increased the yield advantage over wider strips (Francis et al., 1986). Studies in Africa also showed that with increasing strip width, the yield advantage of the taller crop decreased (Agyare et al., 2006; Konlan, 2013).

Core Ideas

- Autonomous machines enable use of alternative mixed crop geometries.
- Autonomous strip cropping has higher economic payoffs than sole and conventional strip cropping.
- Even with lower grain prices and full-time supervision, swarm robots have economic benefits.
- Autonomous machines could reconcile economic and agroecological goals.

The ecological benefits of strip cropping include biodiversity enhancement as each small strip is considered as a small field (Alignier et al., 2019; van Apeldoorn, 2020). Recent research using similar height plants in the context of medium-scale farming in Germany, showed that wheat (*Triticum aestivum* L.) and oilseed rape (*Brassica napus* L.) strip cropping enhanced biodiversity and ecosystem services and reduced pest densities (Alarcón-Segura et al., 2022). Research in China by Cong et al. (2015) showed that wheat–corn, wheat–faba bean (*Vicia faba* L.), and corn–faba bean strip cropping had agroecosystem benefits such as carbon sequestration and improvement of soil health. A wheat–alfalfa (*Medicago sativa* L.) strip cropping study in China found biological pest control advantages over sole cropping (Ma et al., 2007). Corn and peanut (*Arachis hypogaea* L.) strip cropping research in China showed that it suppressed pests, indicating the practice is an effective conservation and biological control measure (Ju et al., 2019). Similarly, in the Chinese context, corn–pea (*Pisum sativum* L.) and corn–wheat strip cropping showed reduced soil respiration and lower emission of carbon (Qin et al., 2013). In the United States, researchers have tended to focus on the soil conservation benefits of strip cropping. For example, the study of Schulte et al. (2017) in the US Corn Belt using a catchment-scale experiment found that in corn and soybean fields, prairie strips improve biodiversity and ecosystem services. Hernandez-Santana et al. (2013), considering the context of Iowa, found that in row-crop systems, perennial prairie filter strips reduce runoff. However, few US studies have considered the broad ecosystem impacts of strip cropping. Buckland et al. (2018) examined three quinoa (*Chenpodium quinoa* Willd.) production systems in the Western United States and found that strip cropping provided greater total nitrogen than undersown clover and winter cover crop. Kemmerling et al. (2022) found that in Michigan, prairie strips and lower land use intensity increase biodiversity and ecosystems services. The study of Quinn et al. (2017) in Michigan shows that floral strips increase beneficial insects in arable fields. Although agronomic and ecological (i.e., agroecological) synergies of strip cropping are relatively well understood, capturing the economic benefits of strip cropping are constrained by higher labor requirements in conventional mechanized systems (Ward et al., 2016).

Mixed cropping is common in manual agriculture because it is overall more productive compared to whole field sole cropping (Francis et al., 1986), but the practice usually disappears with conventional mechanization (Qian et al., 2018). Research in the Midwest United States found that higher labor requirements and associated fixed costs of conventional strip cropping systems offset the economic benefits (Ward et al., 2016; West & Griffith, 1992). Even in the smallholders' context of China labor shortages, increasing wage rate and off-farm employment preferences constrained the labor-intensive strip cropping practices (Feike et al., 2012). Over the last few decades, strip cropping researchers have hypothesized that economically feasible agricultural intensification would be possible with new planting equipment (Lesoing & Francis, 1999), precision management (Exner et al., 1999), and autonomous small swarm robotic field operations (Slaughter et al., 2008; van Oort et al., 2020; Ward et al., 2016). Unfortunately, production economics research on PA has concentrated on whole field sole cropping economics (Al-Amin, Lowenberg DeBoer et al., 2023; Lowenberg-DeBoer, Franklin et al., 2021; Shockley et al., 2019).

Existing strip cropping literature has lacked systems analysis, the study measured economic payoffs by using partial indicators such as land equivalent ratio, gross margin ratio, monetary equivalent ratio, and/or harvested yields (Francis et al., 1986; Lesoing & Francis, 1999; Rahman et al., 2021; Smith & Carter, 1998; van Oort et al., 2020; Yu et al., 2015), and/or partial budgeting (Exner et al., 1999; Ward et al., 2016; West & Griffith, 1992). The most up-to-date economic analysis of strip cropping was conducted by Ward et al. (2016), but they were unable to test the hypothesis of strip cropping profitability with autonomous machines due to a lack of autonomous whole farm operations experience and data.

Noting this research gap, the overall objective of this study was to determine if the use of autonomous machines could enable corn and soybean strip cropping to be more profitable compared to whole field sole cropping and conventional strip cropping operated with human operators. Autonomous machines here refer to mechatronic technologies that could autonomously operate arable crop farms through predetermined field paths. Autonomous machines are mobile technology that are capable of farm operations such as drilling, seeding, spraying fertilizer, fungicide and herbicide, and harvesting under human supervision, but without direct human labor and operator involvement (Al-Amin, Lowenberg DeBoer et al., 2023; Lowenberg-DeBoer et al., 2020). This study assumed that conventional small machines were retrofitted for autonomy similar to those used in the strip cropping and whole field sole cropping operations at the Hands Free Hectare (HFH) and Hands Free Farm (HFF) demonstration project in Harper Adams University, UK (HFH, 2021) (for details, see the operations available at https://twitter.com/FreeHectare/status/1659231014022000643 and https://www.handsfreehectare.co.uk/videos.html). This study hypothesized that autonomous machines (i.e., crop robots) might make strip cropping profitable, thereby allowing farmers to gain additional agroecological benefits. If this hypothesis is supported, this study will open the door for research and farmer experimentation to optimize the strip cropping system. That optimization will include strip width, crops in the rotation, headland management, hybrid and variety choice, pest management, machine size, and soil fertility management. Agronomic and engineering optimization of corn and soybean strip crop systems is beyond the scope of the current study.

2 | MATERIALS AND METHODS

2.1 | Approach and data

The study used a whole farm linear programming (LP) optimization approach to examine the economics of autonomous corn and soybean strip cropping considering the context of central Indiana of the US Corn Belt. Both crops being of major importance and widely cultivated in Indiana (Capehart & Proper, 2021; Egli, 2008; Green et al., 2018; Mishra & Cherkauer, 2010; Suyker & Verma, 2012; USDA, 2023). A key reason for considering corn and soybean strip cropping was the availability of agronomic data of edge effects (i.e., yield benefits of corn and penalty of soybean) (Feng et al., 2022; Francis et al., 1986; Verdelli et al., 2012).

The modeling of the whole field sole cropping and strip cropping practices relied on the basic assumptions of Ward et al. (2016). Following their farm size, the present study modeled a 2157 ha nonirrigated corn and soybean farm. The agronomic practices, yields, costs, and output prices per hectare used in this study were based on the 2022 Purdue Crop Cost & Return Guide for rotational corn and soybean in high-productivity soil (Langemeier et al., 2022). To check the sensitivity of results to soybean/corn (i.e., s/c) price ratios, the historical corn and soybean marketing year prices were based on the USDA NASS quick stats data set from 1973 to 2021 (USDA NASS, 2023). The period from 1973 to 2021 was selected to capture the two most recent crop prices (i.e., 1973–2006; 2007–present) (Irwin & Good, 2011) with higher average s/c price ratios of 2.49 and minimum s/c price ratios of 1.99.

The 2022 Purdue Crop Cost & Return Guide did not consider temporary hired labor costs, so the study used the hourly wage rate of the US Corn Belt from the USDA 2021 database for economic class of farm regions and states (USDA NASS, 2021).

The machinery specifications for whole field sole cropping and strip cropping practices followed the assumptions made by Ward et al. (2016). The whole field sole cropping was assumed to be operated with larger conventional equipment sets represented by 228 kW tractors with human operators. Strip cropping with smaller conventional equipment sets was represented by 37.4 kW tractors with human operators, and autonomous strip cropping represented by 37.4 kW conventional tractors retrofitted for autonomy.

The initial investment costs of larger and smaller conventional machines were priced from different equipment manufacturers' sites having available list prices for the United States. If new equipment list prices were not available, prices for recently used equipment were considered.

The strip crop scenarios assumed that urea or other granulated nitrogen would be used for nitrogen because regulatory approval of autonomous anhydrous ammonia (NH_3) application may be problematic. The list price of a fertilizer applicator (urea and other granulated N) was obtained from 1st products.com (https://1stproducts.com/).

The study considered the costs of retrofitting conventional machines for autonomy following the HFH and HFF demonstration experiences (HFH, 2021) as used in the study of Lowenberg-DeBoer, Franklin et al. (2021). There is a lack of data on the market price of autonomous systems for farm machines. The study hypothesized that if this type of retrofit kit became common, there would be commercially available package for any given tractor. Early models of retrofit kits are being commercialized (Future Farming, 2023). It is assumed that when the technology is mature, these retrofit kits will be "plug and play."

This study used working days (i.e., good field days) data for Indiana from Ag Manager (https://www.agmanager.info/), developed by the Agricultural Economics Department of Kansas State University (AgManager.info, 2022).

The variable costs were adopted from the 2022 Purdue Crop Cost & Return Guide (Langemeier et al., 2022). The custom application fee of NH_3 was based on prices cited in Arnall (2017). The granulated urea application rate was considered following Langemeier et al. (2022) and Arnall (2017).

As overhead costs were not included in the 2022 Purdue Crop Cost & Return Guide, this study used fixed costs from "Crop Budgets, Illinois, 2022" for systematic corn and soybean rotations on high-productivity farmland developed by the Department of Agricultural and Consumer Economics of the University of Illinois (Schnitkey & Swanson, 2022). The fixed costs were taken from Langemeier et al. (2022), Agro Business Consultants (2018), and Kuethe (2021). The fixed costs included annual machine cost, rent of land, repair of farm property and buildings, professional fees and subscriptions, fixed utilities, depreciation of buildings, and other miscellaneous fixed expenses. The annual machine costs incorporated initial investment, useful life span, opportunity costs of capital, annual depreciation, insurance as percentage of investment, insurance, repair, and maintenance as percentage of initial investment, repair and maintenance, and fuel and lubricant (for details, see the Supporting Information Text S2). The annual machinery costs included fuel and lubricant costs as fixed costs as is commonly done in the UK farm budgeting (e.g., Lowenberg-DeBoer, Franklin et al., 2021; Redman, 2018; Witney, 1988). Further details of the yield, costs, equipment, and output prices are available in the Supporting Information Text S2.

2.2 | Base economic model

The economic analysis undertaken here goes beyond Ward et al. (2016) because they did not consider systems analysis. Instead, they used partial budgeting where only the change in costs and revenues was considered with all other things remaining under the same assumption.

The study adopted the Hands Free Hectare-Linear Programming (HFH-LP) "steady-state" profit maximization models (Lowenberg-DeBoer, Franklin et al., 2021). The concept of steady-state was adopted from the Orinoquia model and assumed that solutions would be repeated annually over time (Fontanilla-Díaz et al., 2021). The HFH-LP was developed based on the Purdue Crop/Livestock Linear Program model (Dobbins et al., 1994).

The HFH-LP optimization model for corn and soybean farms of central Indiana estimated the gross margin measure of profitability for human-operated larger conventional mechanized whole field sole cropping, human-operated smaller conventional mechanized strip cropping, and autonomous strip cropping system. The maximization model was estimated subject to the binding constraints of land, labor, and equipment times (Lowenberg-DeBoer, Franklin et al., 2021).

The study estimated return to operator labor, management, and risk-taking (ROLMRT) by subtracting fixed costs from farm gross margin (i.e., return over variable costs). The variable costs included the direct costs of seed, fertilizer, pesticide, dryer fuel, custom work fees, and interest and insurance following Langemeier et al. (2022).

Using standard notation of Boehlje and Eidman (1984), the economic model can be mathematically expressed with an objective function as follows:

$$\text{Max} \prod = \sum_{j=1}^{n} c_j X_j. \tag{1}$$

Subject to:

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

$$X_j \geq 0 \text{ for } j = 1, \ldots, n, \tag{3}$$

where $\prod$ is the gross margin, X_j is the level of jth production activities, c_j is the gross margin per unit over fixed farm resources (b_i) for the jth production activities, a_{ij} is the amount of ith resource required per unit of jth activities, and b_i is the amount of available ith resource.

The study modeled 2157 ha of nonirrigated land in roughly rectangular fields with length assumed to be longer than the width. The conventional whole field sole cropping practice was assumed to plant half corn and half soybean following an annual corn and soybean rotation. Including additional crops and non-crop strips in the system could potentially increase biodiversity and improved ecosystem functioning, but they were not included in this analysis for lack of data on yield impacts of strip cropping for those other crops.

The conventional strip cropping operated with human drivers and autonomous strip cropping assumed headlands on the two ends cultivated with continuous soybean to allow equipment access to the interior field strips (i.e., interior field refers to the field except the headlands) as repeated access would be needed for farm operations. Following Ward et al. (2016), the headlands were assumed to be 18 m wide because the sprayer width required enough space to turn the sprayer. The interior strips were assumed to be 5 m wide (Figure 1). The corn and soybean strips were assumed to be rotated annually. Consequently, 47.50% of each interior field was cultivated with corn, 47.50% with soybean, and 5% in headlands with continuous soybean.

The study assumed available labor included a full-time farm operator and temporary hired labor for 800 h per month per farm. The operator time, tractor time, and combine time were estimated for the three equipment sets. The study considered field-to-field travel times following the assumption of Ward et al. (2016) that all fields were 2 km apart for transport with road speed between fields 20 km/h except for the combine at 15 km/h. Because the field time parameters in the model were given on a per hectare basis, the travel time was proportional to the area of the field operation at each visit: 54 ha for the whole field sole crop farming and 27 ha for the strip cropping scenarios. The incorporation of field-to-field logistics time goes beyond the original HFH-LP analysis by Lowenberg-DeBoer, Franklin et al. (2021) as they did not consider field-to-field logistics time.

Following Lowenberg-DeBoer, Franklin et al. (2021), the study considered 22-h operation time on good field days for autonomous tractors (2 h for repair and refueling/refilling) and 10-h operation time for a combine. The conventional larger and smaller equipment sets assumed 10-h operation time daily.

Further details of the constraints and associated scalar and parameter assumptions considered in modeling this study are available in the Supporting Information S2.

The LP model was coded using the General Algebraic Modelling System (https://www.gams.com/) (GAMS Development Corporation, 2020). The programming code used in this study is available through the supplementary materials of Lowenberg-DeBoer, Franklin et al. (2021).

2.3 | Modeling sensitivity scenarios

The first sensitivity scenario considered the historical marketing year (i.e., begins at current year harvest time and continues until the following year harvest time) prices of soybean and corn from 1973 to 2021 to estimate s/c price ratios (Leibold et al., 2022; USDA NASS, 2023). The marketing year s/c price ratio was estimated by dividing each marketing year soybean price with respective marketing year corn price. The base price considered in this study was the rotational corn and soybean price in the 2022 Purdue Crop Cost & Return Guide (Langemeier et al., 2022). The 2022 s/c price ratio is 2.14, only slightly lower than the historical average of 2.49, and thus modestly favorable for corn production. Because strip cropping benefits corn yields more than soybean yields, the hypothesis is that strip cropping will be most profitable when the s/c price ratio is low (i.e., when corn price is comparatively high) and least profitable when the price ratio is high (i.e., when soybean price is comparatively high). Consequently, the price sensitivity test looked at the maximum, average, and minimum s/c prices ratios. To anchor this comparison, corn prices were estimated using the 2022 soybean price at the historical maximum, average, and minimum price ratios, and soybean prices were estimated using the 2022 corn price at the historical maximum, average, and minimum price ratios. Overall, six corn and soybean price combinations were tested.

The second sensitivity scenario investigated the economics of different levels of human supervision as autonomous machines required by law or because the technology is troublesome. The study by Lowenberg-DeBoer, Behrendt et al. (2021) suggested 10%, 50%, and 100% supervision time. Maritan et al. (2023) found economically optimal supervision between 13% and 85% of machine field times depending on the frequency of human intervention required and the supervisor location (i.e., remote and on-site). Using whole field sole cropping context of the United States, Shockley et al. (2021) found that field speed restriction and on-site supervision regulation reduce the profitability of arable crop farming. The economic implications of human supervision

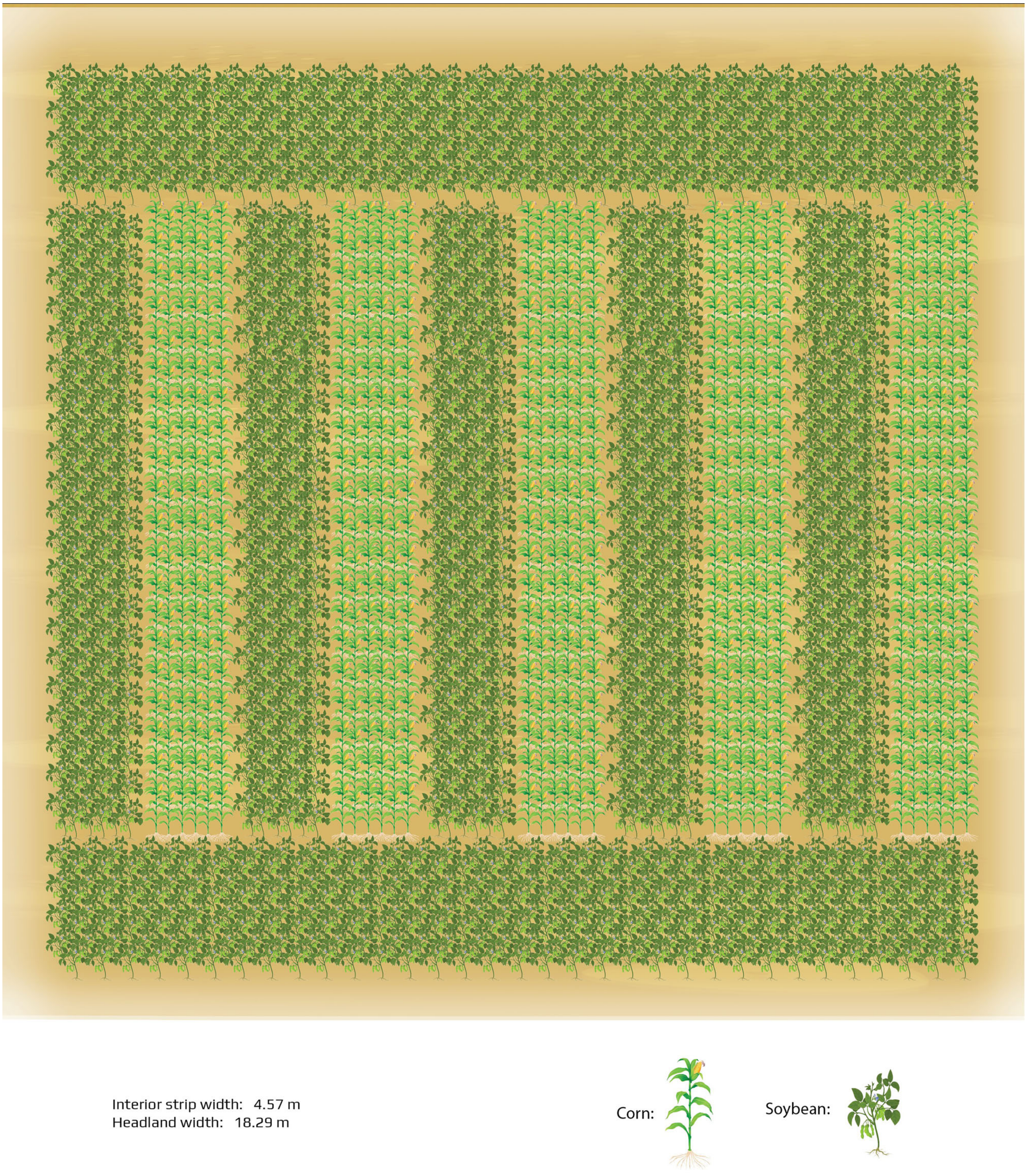

FIGURE 1 Corn–soybean strip cropping field layout planted in six, 0.76-m row strips based on Ward et al. (2016).

in arable farming with alternative crop geometries are not clear. Using constant wage rate ($16.95/h) (USDA NASS, 2021), this study examined the economic implications of different human supervision scenarios for autonomous strip cropping following 10%, 50%, and 100% supervision assumptions (Lowenberg-DeBoer, Behrendt et al., 2021) to examine the implications of binding labor constraints because human labor is scarce throughout the world. The base autonomous strip cropping model considered 10% of machine field times following the production economics study of Lowenberg-DeBoer, Franklin et al. (2021).

The third sensitivity test considered doubling field-to-field transition distance. This is important because strip cropping increases the number of times machines need to travel to

TABLE 1 Comparative labor requirements and profitability of whole field sole cropping and strip cropping practices under conventional and autonomous machine (crop robot) scenarios in the Corn Belt of central Indiana.

Equipment scenario[a]	Hired labor time (h/ha/year)	Operator time (h/ha/year)	Gross margin ($/ha/year)	Return to operator labor, management, and risk-taking ($/ha/year)
Whole field sole cropping: Conventional 228 kW^2	0.65	0.57	1503.63	185.27
Strip cropping: Conventional 37.4 kW^5[b]	2.06	0.66	1694.70	590.88
Strip cropping: Crop robot 37.4 kW^3	0.49	0.53	1769.50	753.46

[a] The superscript number indicates the number of equipment sets needed for timely operation of the 2156.974 ha farm.

[b] In the baseline modeling, the study assumed 800 h per month temporary hired labor for the whole farm, whereas the conventional strip cropping scenario required 1200 h per month temporary hired labor to optimally operate the whole farm.

the field because seeding, weed control, pest management, and harvest are at different times for the different crops. The base field-to-field transition distance was considered 2 km. The sensitivity scenarios considered 4 km field-to-field distance to model the economic implications of logistic support variation.

3 | RESULTS

3.1 | Baseline results

The baseline optimal economic solutions show that the autonomous corn and soybean strip cropping system had higher economic benefits compared to the whole field sole cropping and conventional strip cropping systems operated with human drivers (Table 1). The whole field sole cropping and autonomous strip cropping were feasible with the baseline assumptions of 800 h per month per farm temporary hired labor. The conventional strip cropping struggled, whereas it needed 1200 h per month to operate the whole farm.

The optimization model of autonomous strip cropping reveals that three sets of autonomous machines (i.e., crop robots) were required to operate the whole farm (i.e., 2157 ha) in a timely way. The autonomous machine scenario finds that per annum, 0.49 h/ha of hired temporary labor time and 0.53 h/ha of operator time were needed for optimal operations, while conventional whole field sole cropping required 0.65 h/ha and 0.57 h/ha temporary labor time and operator time. In comparison, conventional strip cropping required 2 h/ha hired temporary labor and 0.66 h/ha operator time. The conventional strip cropping would not be an economically attractive farming solution in Indiana where farm labor can be scarce. The study shows that conventional strip cropping practice required five sets of smaller conventional machines. The conventional strip cropping system faced severe labor constraints. The farm had binding operator time constraints in April to July, October, and November. In addition, tractor time was binding in April.

The findings show that at the 2022 grain prices and input costs, the gross margin was $266/ha (i.e., $17,670–$1504) higher for autonomous strip cropping compared to whole field sole cropping (Table 1). Conventional strip cropping with human equipment operators shows a slightly lower gross margin ($75/ha) than the autonomous scenario mainly because of the additional hired labor. The higher gross margin for strip cropping occurs because the value of additional corn from the edge effects in the strips more than offsets the reductions in soybean yields at 2022 prices.

Similarly, ROLMRT was $568/ha (i.e., $753–$185) higher for autonomous strip cropping than whole field sole cropping. The main factors in this difference are higher value of grain production with strip cropping, lower machinery costs with crop robots, and slightly less labor hired. The ROLMRT is somewhat lower (i.e., $753–$591 = $163/ha) for conventional strip cropping than for autonomous strip cropping because of the higher labor and machine costs in the conventional scenario.

The profitability of conventional strip cropping is not strictly comparable to whole field sole cropping and autonomous strip cropping because conventional strip cropping could not farm 2157 ha with the initial assumption of 800 h per month of temporary hired labor for the whole farm. With 800 h per month of temporary hired labor, the most profitable solutions for the conventional strip cropping scenario were to leave 45 ha farmland uncultivated because labor was a binding constraint in peak production months of April, May, October, and November. Moreover, operator time was binding in April to June and September to November. The optimal solutions for conventional strip cropping finds that 1200 h per month of temporary hired labor was required to optimally operate the whole farm. Previous research has also suggested conventional strip cropping is only possible with ample labor availability (Ward et al., 2016). However, worldwide, agricultural labor is in short supply. The COVID-19 pandemic, travel restrictions, and the political impasse over immigration reform have made the situation even more critical in the United States (Charlton & Castillo, 2021; Hamilton et al., 2022).

3.2 | Equipment investment costs

The whole field sole cropping equipment inventory and investment costs show that timely field operations required at least two units of the larger conventional equipment set with an initial equipment investment cost of $4,806,278 and an annual cost of $988,963 (Table 2). The optimal equipment needed to operate the whole farm was selected based on the LP gross margin maximization model. The larger conventional equipment inventory included two sets of 228 kW tractors, 12 m planters, 37 m self-propelled sprayers, 292 kW combines with 6 m corn heads and 11 m grain heads, and 28 t grain carts. Grain carts were included in whole field sole cropping because harvest unloaded on-the-go was assumed. Usually, corn and soybean growers have many options for machinery selection. In this study, the equipment choice was based on Ward et al. (2016) to represent the typical farming scenarios of the Midwest United States.

In strip cropping, the LP solutions show that five sets of human-operated smaller conventional machines were able to optimally operate the whole farm (Table 3). The initial investment costs were $2,456,236 for five units of smaller conventional equipment sets, which included 37 kW tractors, 18-m trailed sprayers, 5-m fertilizer applicators and planters, 151 kW combines with 5 m corn heads and grain heads. The strip cropping systems machinery inventory did not include a grain cart because the strips were not wide enough to run a combine and grain cart side-by-side. This study assumed that the combine unloads directly into the grain semi at the end of the field. The annual cost of the conventional equipment was estimated as $526,208.

The modeling of the autonomous machine scenario shows that three autonomous equipment sets were able to farm 2157 ha in a timely way. The autonomous strip cropping system used the same smaller conventional machinery but was retrofitted for autonomy for field operations. Apart from conventional equipment inventory, the autonomous machines inventory required additional hardware and software to retrofit for autonomy that needed initial investment costs of $40,871 (Table 4). The initial investment needed to equip the autonomous strip cropping farm was $859,882 less (i.e., $2,456,236 − (($491,247 + $40,871) × 3)) than for the conventional strip cropping.

3.3 | Allocation of farm expenses

Comparison of the returns and expenses of whole field sole cropping and strip cropping practices shows that total revenue was $225/ha higher (i.e., $3025–$2800) for autonomous strip cropping compared to whole field sole cropping (Figure 2), as the total value of grain produced was higher. Similarly, ROLMRT was also substantially higher (i.e., $568/ha) for strip cropping with crop robots because of higher grain value, lower machinery costs and less hired labor. Annual machinery costs and total costs were $302/ha and $343/ha lower for the autonomous scenario compared to whole field sole cropping operated with human drivers owing to the smaller number of equipment units required.

The breakdown of costs as a percentage of total costs for the three cropping systems indicates that machine costs encompassed 18% of the total costs for whole field sole cropping practice operated by humans with larger conventional machines, and the share was significantly lower for autonomous strip cropping (i.e., only 7%) (Figure 3). The conventional strip cropping practice required more hired temporary labor (1% of total costs) that made conventional strip cropping infeasible for labor-scarce arable crop sectors. The autonomous strip cropping had the advantage of reducing labor costs. In total cost percentage shares, the variable costs occupied the majority. Subsequently, fixed costs other than machinery costs (i.e., rent for farm; property and building repair; professional fees and subscriptions; water, electricity, etc.; building depreciation and miscellaneous fixed costs) encompassed the second highest share as a percentage of total costs.

3.4 | Sensitivity scenarios

Sensitivity testing over historical maximum and minimum s/c price ratios showed that autonomous strip cropping had a higher ROLMRT than conventional whole field sole cropping in each scenario. The strip cropping advantage was reduced when the price ratio was high (i.e., favored soybean production), but economics favored autonomous strip cropping in all scenarios. Detailed price sensitivity test results are given in Table S1.

The study finds that increasing supervision requirements during field operation (i.e., 50% and 100% of machine time) reduced the economic gains of strip cropping as gross margin and ROLMRT were lower compared to the baseline at 10% of machine time (Table S1). However, even with supervision at 50% and 100%, the gross margin was higher than for the whole field sole cropping. Similarly, ROLMRT was $553/ha (i.e., $738–$185) higher at 50% supervision and $516/ha higher (i.e., $702–$185) at 100% supervision.

Sensitivity tests of increasing field-to-field transition distance found that autonomous strip cropping was more profitable than whole field sole cropping and conventional strip cropping (Table S1) even though economic gains (i.e., gross margin and ROLMRT) were reduced. The findings show that

TABLE 2 Conventional larger machine inventory and costs for whole field sole cropping in $.

Inventory items	Width of the implement (m)	Initial investment	Useful life	Opportunity cost of capital	Annual depreciation	Insurance	Repair and maintenance	Annual cost (whole farm)	Annual cost (per hectare)
Tractor (228 kW)		468,183	10	23,409	46,818	4682	9364	93,636.67	43.41
Tractor (184 kW)		366,677	10	18,334	36,668	3667	7334	73,335.40	34.00
Chisel plow	7.01	97,315	10	4866	9732	243	1946	16,786.84	7.78
Field cultivator	14.326	52,500	10	2625	5250	131	1050	9056.25	4.20
Self-propelled sprayer (4542.49-L tank)	36.576	279,591	10	13,980	27,959	699	5592	48,229.45	22.36
Water tank (9084.99 L portable)	12.192	4720	10	236	472	12	94	814.20	0.38
Planter (16 row)		190,341	7	9517	27,192	476	3807	40,991.22	19.00
Combine, (292 kW)	6.096	577,680	7	28,884	82,526	5777	11,554	140,293.71	65.04
Corn head (eight Row)	10.668	94,336	10	4717	9434	236	1887	16,272.96	7.54
Grain head		100,296	10	5015	10,030	251	2006	17,301.06	8.02
Grain semi		100,000	10	5000	10,000	3000	3000	24,000.00	11.13
Grain cart (27.94 t)		71,500	10	3575	7150	179	1430	13,763.75	6.38
Total		2,403,139						494,481.51	229.25
Whole farm total[a]		4,806,278						988,963.02	458.50

[a] The study found that two sets of conventional larger machines allowed for timely operation of the whole farm (2156.974 ha).

TABLE 3 Conventional smaller machine inventory and costs for strip cropping in $.

Inventory items	Width of the implement (m)	Initial investment	Useful life	Opportunity cost of capital	Annual depreciation	Insurance	Repair and maintenance	Annual cost (whole farm)	Annual cost (per hectare)
Tractor (37.4 kW)		29,207	10	1460	2921	292	584	5841.33	2.71
Chisel plow	2.438	7334	10	367	733	18	147	1265.03	0.59
Field cultivator	3.658	14,404	10	720	1440	36	288	2484.69	1.15
Trailed sprayer (attached with 4542.49-L tank)	18.288	6894	10	345	689	17	138	1189.17	0.55
In Cab controller (four boom control sections)		4291	10	215	429	11	86	740.23	0.34
Solenoid valves (36 for four boom)		4356	10	218	436	11	87	751.41	0.35
Wiring and harness		622	10	31	62	2	12	107.31	0.05
Water tank (9084.99 L portable)		4720	10	236	472	12	94	814.20	0.38
Fertilizer applicator (urea and other granulated nitrogen)	4.572	19,180	10	959	1918	48	384	3308.55	1.53
Planter (six row)	4.572	39,462	7	1973	5637	99	789	8498.42	3.94
Combine (equivalent model to AVERO 240, 151 kW)		160,000	7	8000	22,857	1600	3200	38,857.14	18.01
Corn head (six row)	4.572	70,582	10	3529	7058	176	1412	12,175.40	5.64
Grain head	4.572	30,196	10	1510	3020	75	604	5208.81	2.41
Grain semi		100,000	10	5000	10,000	3000	3000	24,000.00	11.13
Total		491,247						105,241.70	48.79
Whole farm total[a]		2,456,236						526,208.48	243.96

[a] The study found that five sets of conventional smaller machines allowed for timely operation of the whole farm (2156.974 ha).

TABLE 4 Hardware and software needed to retrofit for autonomous system.

Equipment type	Item	HFH equipment cost[a] (£ 2016)	$ 2022[b]
	Tractor and combine		
Safety equipment	Laser	3282	5767
	Remote emergency stop	75	132
	Stop buttons—system	63	111
Control system	GPS systems	2300	4042
	Autopilot	112	197
Control adaptations	Steering motor	768	1350
	Driver control	860	1511
	Linkage control	430	756
Camera feedback	CCTV (closed circuit television) cams	340	597
Communications	WiFi	100	176
	RC (remote control) system	413	726
Consumables	Boxes/connectors and so forth	600	1054
	Total for tractor and combine	9343	16,418
	Combine only		
Safety equipment	Extra laser	3282	5767
	Three actuators	1290	2267
	Total for combine only	13,915	24,453
Total for equipment set		23,258	40,871

Abbreviation: HFH, Hands Free Hectare.

[a] Adopted from Lowenberg-DeBoer, Franklin et al. (2021).

[b] Exchange rate—£ to $—(U.S. Board of Governors of the Federal Reserve System, 2022) with inflation adjustment—(FRED, 2022).

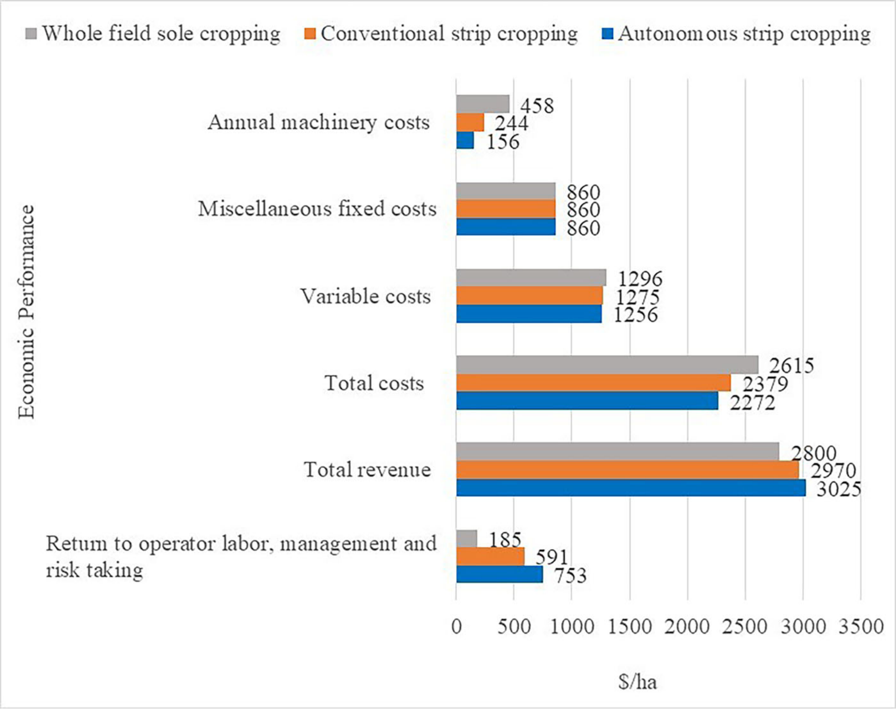

FIGURE 2 Comparative returns and expenses of whole field sole cropping and strip cropping practices.

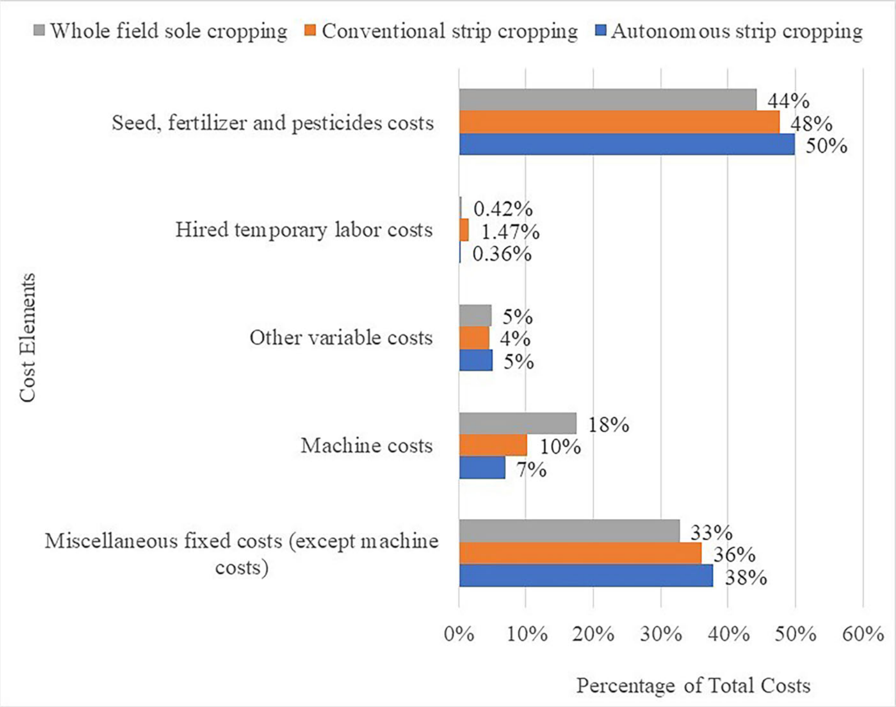

FIGURE 3 Cost elements as percentage of total costs.

with double field-to-field transition distance, strip cropping required another additional equipment set, that is the conventional strip cropping required six units of smaller conventional machines and the autonomous strip cropping required four units of crop robots to optimally operate the whole farm.

4 | DISCUSSION

The results of this study indicate an opportunity for on-farm research to optimize strip cropping with autonomous machines and enable commercialization of the practice. This study supports the hypothesis stated by Ward et al. (2016) that corn and soybean strip cropping could be profitable with autonomous machines. Sensitivity testing suggested that autonomous strip cropping was more profitable than whole field sole cropping operated under conventional machines with human operators over a wide range of s/c price ratios, even when 100% human supervision is required (e.g., as crop robots required by law or because the technology is troublesome), and extended logistic support (i.e., field-to-field transition distance).

The results indicate that at the historically high 2022 grain prices, strip cropping operated under conventional small machines with human operators would be less profitable than autonomous strip cropping, but more profitable than whole field sole cropping if temporary hired labor is reliably available. This differed from the Ward et al. (2016) results that showed that strip cropping with conventional equipment was unprofitable at 2015–2016 prices.

This study showed that strip cropping was more profitable compared to whole field sole farming even when using agronomic practices that are optimized for whole field production. It is quite possible that the optimal choice of hybrids and varieties, pest management, soil fertility management, and other agronomic practices might be somewhat different for strip cropping.

Field layout might also be optimized for strip cropping. Depending on the cost of the autonomous tractor and trailed sprayer (or autonomous sprayer unit), the time window for spray applications and other factors, it might be more profitable to use a narrow spray boom (to match strip width) and reduce headland width. Given the added machine traffic on the strip cropping headlands, grass or flower strips would be worth consideration as evidence is available for agronomic, ecological, and economic benefits (Al-Amin, Dicken et al., 2023; Quinn et al., 2017; Sapkota et al., 2022).

Farming with larger equipment is an expensive business where machinery costs occupy a significant share of total costs (Ibendahl, 2015, 2021). The cost-effective choice of small, retrofitted machines would help farmers, engineers, and agribusinesses move toward autonomous agroecological strip cropping. Small crop robots may invigorate smaller equipment manufacturers of the United States, and/or open the import opportunities, and/or promote an autonomy retrofit kit market (Karsten, 2019; Koerhuis, 2021).

One of the major uncertainties in this study is the cost of retrofitting conventional equipment for autonomy. None of the companies that now offer autonomy retrofit kits for conventional equipment have published price lists. The HFH economic study conducted by Lowenberg-DeBoer, Franklin et al. (2021) only provided estimates of the parts and software needed for retrofitting, but did not estimate a value for the labor and expertise required because the study assumed that retrofit kits would be commercially available as the kits are on the verge of commercialization processes (Future Farming, 2023). The study also did not consider machines size for retrofit kits because at this point in technology development, the retrofit hardware and software are essentially the same irrespective of machine size. However, future study focusing on wide-scale adoption and scaling up could explore the costs associated with the technical management skills of autonomous machines such as retrofitting expertise, set-up and management of field maps, and guidance and navigation, and so forth.

It is worth mentioning that HFH adapted open-source drone software to guide its equipment. That was an inexpensive solution, but not a perfect one. The HFH tramlines were a bit "wobbly." Wavey tram lines were not a major problem for the broadacre crops grown on HFH but might be more of a problem for row crops. Commercial auto-guidance is an alternative solution for autonomous machines to drive straight lines (HFH, 2021). Consequently, the retrofitting cost might be substantially more than listed in this study. However, the gain with autonomous strip cropping seems to be enough to cover the cost several multiples of the HFH estimate. The autonomous strip cropping scenario requires three autonomous machines (i.e., crop robots). With a useful life of 10 years, each robot unit adds $4087 in depreciation to whole farm costs or $2/ha. If three units are needed, then the cost is $6/ha. In case of doubling, the cost would be $11/ha and in case of quadrupling the baseline estimate would be $23/ha. With a margin of $568/ha gain with autonomous strip cropping, the autonomous option would remain the most profitable scenario even with higher retrofit costs.

Some critics have viewed autonomous machines as a blueprint for replacing human labor. But the study found that autonomous strip cropping did not substantially reduce operator labor. The whole field sole cropping required 0.57 h/ha operator time, while autonomous strip cropping needed 0.53 h/ha. Interestingly, autonomous machines reduced the problem of temporary hired labor scarcity by only requiring 0.49 h/ha temporary hired labor. Contrary to this, whole field farming operated under conventional machines with human operators needed 0.65 h/ha and conventional strip cropping needed 2 h/ha temporary hired labor.

Autonomous machines operations for arable crops production have been going through legislative issues. For instance, the EU legislations suggested a person for direct control of the machines or remote supervision (European Parliament, 2023), and the US state of California's autonomous farm equipment operations code requires readily accessible control of the machines, not necessarily in the tractor, but access could be ensured remotely (Shockley et al., 2021). The sensitivity of human supervision scenarios focused on the implications of binding labor constraints due to the labor scarcity for arable farm operations. Sensitivity tests found that even with 50% and 100% supervision, the economic returns were higher for autonomous strip cropping than for whole field farming and conventional strip cropping operated with conventional machines with human operators. The findings suggest favorable legislation would increase economic payoffs, whereas rigid regulation would be an economic barrier (Groeneveld, 2023; Maritan et al., 2023; Shockley et al., 2021). However, the economies of size achieved from individual supervision at given point of time would be interesting to explore that will answer how many hectares an individual could supervise. This is out of the scope of this study due to lack of data. Future research could address this issue considering different individual supervision percentages of multiple autonomous machines operating simultaneously.

The economic benefits of autonomous machines over whole field sole cropping and conventional strip cropping operated with human drivers signal an opportunity for the broader adoption of autonomous mixed farming. This study contributes to the state of the art of strip cropping and PA. The study only considered corn and soybean edge effects in strip cropping owing to empirical data availability of other crops typical in the United States. Future study could include other crops such as wheat, alfalfa, and oats in strips if agronomic data are available. The inclusions of several enterprises will give broader biodiversity and edge effects scenarios that will facilitate the agroecological farming and regenerative agricultural practices (Al-Amin, Dicken et al., 2023). The corn and soybean row crops and/or inclusions of other crops could be expanded to include a broader diversity of available land use options. Inclusion of "Beetle Banks" (e.g., prairie strips) in the North American context may increase biodiversity, ecosystems services (Kemmerling et al., 2022; Schulte et al., 2017), and provide yield advantages, which would help to assess the economics of precision conservation (Swinton, 2022).

This case study concentrated on central Indiana because of being a major corn and soybean growing state, and strip crop yield data were available for the Eastern Corn Belt. This optimization modeling study could be easily replicated for the other Corn Belt areas such as Illinois, Nebraska, Iowa, and Minnesota. The modeling scenarios would be quite similar because of using similar technologies; however, the agronomic responses might be quite different for soil, climate, and other associated factors. By developing retrofit prototypes or using commercially available technology, future research could conduct on-farm autonomous strip cropping demonstration for the Corn Belt regions.

Apart from the strip cropping yield advantage, the agroecological mixed farming system has the potential of reducing input use (Chen et al., 2017; Tian et al., 2022), lowering pest densities and less disease infestation (Trenbath, 1993), and increasing soil carbon and nitrogen (Cong et al., 2015). The opportunity costs of reduced fertilizer and pesticide use would increase the autonomous strip cropping payoffs. Optimizing spatiotemporal heterogeneity with strip cropping (Juventia et al., 2022) and site-specific localized input application, a potential of autonomous machines (Lowenberg-DeBoer, 2022) may reduce the variable costs of farming. These advantages were out of the scope of this study due to a lack of data. Further research to optimize autonomous strip cropping should consider input use, pest management, and soil health impacts.

The study calculated field times based on the assumptions of Ward et al. (2016) following the estimation processes of Lowenberg-DeBoer, Franklin et al. (2021). However, use of algorithms to calculate field time as followed in Al-Amin, Lowenberg DeBoer et al. (2023) or by using recorded on-field farm operations time may provide more real economic scenarios in systems analysis. To be consistent with Lowenberg-DeBoer, Franklin et al. (2021) and with the UK machinery costing practices (Redman, 2018; Witney, 1988), the study estimated fuel and lubricant costs as fixed costs irrespective of engine size because the experience of the HFH and HFF was used for the US ex ante assessment. However, future study could consider fuel and lubricant cost as variable cost as followed in the crop budget conducted by Langemeier et al. (2022) and Schnitkey and Swanson (2022).

This study addressed the crucial mechanized farm management optimization decisions associated with the binding constraints of land, labor, and equipment times. The sensitivity tests encompassed the economics of market shocks (i.e., soybean corn price ratios), regulatory obligations (i.e., human supervisions), and logistics (field-to-field transitions), whereas the risk implications that may affect farm profitability were not addressed in this study because of limited data on strip crop yield impact. Future research could address the economics of risk associated with strip cropping. The probable changes of assumptions related to equipment operating hours, good field days, and working capital and cash flows could be examined to assess the economics of farm management challenges.

5 | CONCLUSIONS

Corn and soybean strip cropping are well known to have yield and agroecological advantages, but implementation of the practice has been limited by cost disadvantages resulting from higher labor requirements in conventional human-driven mechanized systems. Noting the economic and agroecological trade-offs, this study hypothesized that autonomous machines (i.e., crop robots) might make strip cropping profitable, thereby allowing farmers to gain additional agroecological benefits. The HFH-LP optimization model, adapted to the Corn Belt of central Indiana, showed that corn and soybean strip cropping practice was more profitable with autonomous crop machines than whole field sole cropping and strip cropping system using conventional machines operated with human drivers. Sensitivity tests found that autonomous strip cropping remained more profitable over a wide range of s/c price ratios, human supervision requirements, and increased field-to-field transition distance. The profitability of autonomous strip cropping reveals that autonomous machines could be a game changer with win-win farming potential, reconciling economic, agronomic, and environmental goals of arable crop farming.

AUTHOR CONTRIBUTIONS

A. K. M. Abdullah Al-Amin: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review and editing. **James Lowenberg-DeBoer**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing—review and editing. **Bruce Erickson**: Conceptualization; data curation; investigation; methodology; project administration; resources; supervision; validation; visualization; writing—review and editing. **John Evans**: Conceptualization; investigation; methodology; resources; supervision; validation; writing—review and editing. **Michael Langemeier**: Conceptualization; investigation; methodology; validation; writing—review and editing. **Kit Franklin**: Conceptualization; investigation; methodology; project administration; software; supervision; validation; visualization; writing—review and editing. **Karl Behrendt**: Conceptualization; funding acquisition; investigation; methodology; project administration; software; supervision; validation; visualization; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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