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The Economic Feasibility of Autonomous Equipment for Biopesticide Application

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Abstract

Since the European Union (EU) ban on neonicotinoid seed treatments in 2013, Cabbage Stem Flea Beetle (CSFB) is a pest with no effective control in the UK and the area sown to OSR has been cut in half. Biopesticides offer one promising approach, but most biopesticides have little residual effect, and consequently must be applied frequently. For a bulk commodity crop like OSR, the margins are tight and the cost of frequent application may make the crop unprofitable. Autonomous equipment could reduce application costs. If farmers own the equipment, the main cost of autonomous application is the original purchase of the machines, the marginal cost of additional applications is small. The objective of this study is to determine under what circumstances use of autonomous equipment for application of biopesticides would be profitable for farmers. The main hypothesis is that biopesticide application with autonomous equipment would be more profitable on farms that already use autonomous equipment for other field operations than on farms with conventional mechanisation. The study adapts the Hands Free Hectare (HFH) farm linear programming model by updating OSR yields and production practices for current CSFB challenges, adding alternative break crops like field beans and linseed, and includes biopesticide application with conventional or autonomous equipment. Initial results suggest that a low cost biopesticide might be profitable for farmers with either conventional or autonomous equipment, the cost of the biopesticide product is a key constraint, and HFH type retrofitted autonomous equipment still requires too much human labour. This study will be of interest to pest management researchers, agri-tech economists, OSR producers, and entrepreneurs developing autonomous farm equipment businesses.

Keywords

biopesticides, oilseed rape, cabbage stem flea beetle, autonomous equipment, robot, profit

Presenters Profile

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Introduction

In recent decades oilseed rape (OSR) has been the most profitable "break crop" in many arable rotations in the United Kingdom, but farmers are being forced to seek alternatives because of Cabbage Stem Flea Beetle (CSFB - *Psylliodes chrysocephala*). Since the European Union (EU) ban on neonicotinoid seed treatments in 2013, CSFB has become a pest for which there is no effective conventional insecticide control and the area sown to OSR in the UK has been cut in half. Biopesticide products offer one promising approach with which to control CSFB, but most biopesticides have little residual effect, and consequently must be applied frequently. For a bulk commodity crop like OSR, the margins are tight and the cost of frequent application may make the crop unprofitable. Autonomous equipment could reduce application costs. For example, if farmers own the equipment then the marginal cost of autonomous application is small. The objective of this study is to determine under what circumstances use of autonomous equipment for application of biopesticides would be profitable for farmers. The main hypothesis is that biopesticide application with autonomous equipment would be more profitable on farms that already use autonomous equipment for other field operations than on farms using conventional mechanisation. The study adapts the Hands Free Hectare (HFH) farm linear programming model by updating OSR yields and production practices for current CSFB challenges, adding alternative break crops like field beans and linseed, and includes biopesticide applications with conventional or autonomous equipment. This study will be of interest to pest management researchers, agri-tech economists, OSR producers, and entrepreneurs developing autonomous farm equipment businesses.

OSR was a minor crop in the UK until plant breeding in the 1970s created OSR varieties that were low in both erucic acid and glucosinolates, which allow greater use of OSR oil for cooking and OSR meal for animal feed (Canola Council of Canada, undated). High erucic acid in cooking oil can lead to heart health problems. Glucosinolates create palatability and nutritional problems from OSR meal used in animal feed. Until the late 1970s, OSR oil was mainly used as an industrial lubricant and the meal was a minor livestock feed ingredient. In the late 1960s, harvested OSR area in the UK was a few thousand hectares annually (FAOSTAT, 2020). That rose to 755,717 ha by 2012. Approximately 361,000 ha of OSR are expected to be harvested in the UK in 2020 (AHDB, 2020).

Chandler et al. (2011) define biopesticides as mass-produced agents manufactured from living microorganisms or natural products and sold for the control of plant pests. Biopesticide products typically fall into one of three types according to the active substance: (i) microorganisms, such as bacteria, fungi, viruses and protozoa (this group is often extended to include some species of nematode); (ii) biochemicals, such as secondary metabolites produced by plants and micro-organisms; and (iii) semiochemicals, which are defined as chemical signals produced by one organism that causes a behavioural change in an individual of the same or a different species. Biopesticides that target insect pests currently account for approximately one fifth of all products currently registered for professional use in the UK. These product registrations are, however, almost exclusively for use on high value horticultural crops and are priced accordingly (e.g. £100-£300/ha per application) for these markets. The cost of using biopesticides is further increased by the fact that most of these products have little or no residual effect and consequently must be applied repeatedly during the period in which the crop is vulnerable to a particular pest. While biopesticides can often be applied using conventional spray equipment, applications typically require large volumes of water (e.g. up to 1500 L/ha) in order to achieve the good crop coverage required to optimise the efficacy of these products. In addition, environmental conditions at the time of application may also be an important factor in determining the efficacy of these products. This may mean that applications must be made during periods when rain is not forecast or that the application is made in the evening when humidity is higher and UV radiation is lower. To date there has been comparatively little research investigating the potential of biopesticides for the management of insect pests affecting most arable crops. The product price, the frequency of application and the volume of water applied all would create obstacles to application in broadacre crops.

Several terms are used to describe farm machines that are mobile and have some autonomy (e.g. robot, autonomous machine, automated equipment). Based on the arguments in Kyrakopoulos and Loizou (2006) for this study the word “Robot” is reserved for machines with substantial decision-making capacity, while “autonomous equipment (or machines)” is used when the technology has autonomy of operation with a predetermined path or itinerary. This study focuses on levels 4 and 5 of the widely used driving automation level scale (SAE, 2018). It should be noted that this definition, the popular terms “milking robot” and “industrial robot” are largely honorific because those machines are not mobile, and often have minimal decision-making capacity.

Autonomous equipment for crop production is being trialled throughout Europe, mainly for mechanical weeding of vegetable crops and sugar beets. The only European country with quantitative data on crop robotics and autonomous equipment is France, with over 100 autonomous machines in use in crop production (Digital Agriculture Observatory, 2018). In the USA 3% of agricultural input dealers report using robots in their businesses (Erickson and Lowenberg-DeBoer, 2020). Several companies are preparing to market retrofit kits that would convert conventional farm equipment for autonomous use. For example, the Smart Ag company in the USA is marketing a hardware and software kit that converts a conventional tractor and chaser bin for autonomous use (SmartAg, 2020).

Publicly available economic analysis of crop robotics and autonomous equipment is rare. This is because commercial farm experience with this technology is limited and many crop robot/autonomous machine technologies are in the prototype or beta test stages protected by non-disclosure agreements. Lowenberg-DeBoer et al. (2019) found 18 published studies of the economics of crop robotics all of which find that the current robotics technology is potentially profitable for producers in certain circumstances. Most of those studies use partial budgeting to examine the potential profitability of automation of a single crop operation (e.g. weeding, harvesting). The most systematic analyses are for grains and oilseeds because those technologies present fewer engineering challenges and are closer to commercialisation than robotics for horticulture. Shockley et al. (2019) employed farm linear programming to analyse the economics of using autonomous equipment for maize and soybean production in Kentucky USA based on experience with robot prototypes. The analysis suggested that relatively small autonomous equipment would have economic advantages for a wide range of farm sizes, but especially for small farms. With the availability of data from HFH and using linear programming to model a UK arable farm, Lowenberg-DeBoer et al. (2019) went beyond Shockley et al. (2019) to show that the economic benefits of robotic technology potentially go beyond labour saving to include changes in economies of scale, reduction in investment required for farm, and environmental benefits. No study on the economics of use of autonomous equipment or robotics for biopesticide application is available.

Given the urgency of the OSR pest management issues and the lack of economic analysis of autonomous equipment for pesticide application, the objective of this study is to determine under what circumstances use of autonomous equipment for application of biopesticides would be profitable for farmers. The main hypothesis is that biopesticide application with autonomous equipment would be more profitable on farms that already use autonomous equipment for other field operations than it would be on farms with conventional mechanisation. Other pesticide application hypotheses were not tested because they seem less likely to be profitable. For example, in the UK contractors typically charge £12-£16/ha for pesticide application (ABC, 2019). With repeated applications the cost would quickly outstrip any benefit. Some researchers have envisioned a small, light autonomous sprayer for targeted micro application of synthetic pesticides (e.g. a few drops of herbicide on a weed leaf). Given the volume of water recommended for many biopesticides, a substantial machine is needed just to transport the required volume of spray mixture. A small, light, cheap autonomous sprayer is unlikely for this type of biopesticide.

Methods

The hypothesis was tested using the Hands Free Hectare linear programming (HFH-LP) model of an arable farm in the English West Midlands. The HFH-LP model was based on a well tested and particularly flexible system for modelling farming operations known as the Purdue Crop/ Livestock Linear Program (PC/LP) (Preckel *et al.*, 1992; Dobbins *et al.*, 1990; Dobbins *et al.*, 1992; Dobbins *et al.*, 1994). This system was used from the mid-1990s through to 2010 as an analytical tool for Purdue's Top Crop Farmer Workshop. Farmers from across the Midwestern United States came to Purdue University each summer and developed linear programming models for their farms to evaluate alternative technologies and resource investments. Many of those farmers attributed their subsequent success in part to insights gained from the PC/LP analysis. The model has also been used in Brazil, Colombia, Thailand and several African countries. An updated version of the PC/LP system has been developed in the General Algebraic Modelling System (GAMS, 2019) modelling language (Preckel et al., 2019). The HFH-LP model is a modified version of the PC/LP model using the GAMS, software. In many ways the HFH-LP is similar to the Audsley (1981) UK farm LP, but takes advantage of more recent software.

The HFH-LP model can be expressed in the standard summation notation used by Boehlje and Eidman (1982) as:

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

subject to:

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

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

where:
X_j = the level of the *j*th production process or activity,
c_j = the per unit return (gross margin) to fix resources (b_i's) for the *j*th activity,
a_{ij} = the amount of the *i*th resource required per unit of the *j*th activity
b_i = the amount of the *i*th resource available.

The gross margin (c_j's) is total crop sales revenue minus total direct costs, and can be considered returns to fixed costs. In other words, net returns from the operation equals gross margin minus fixed costs excluding any government subsidies. In the HFH-LP analysis, the objective function was to maximize gross margin for each set of land, operator labour, and equipment. Fixed costs are land, farm facilities, equipment, and compensation for management, risk taking, and labour provided by the operator.

To focus on the essentials the initial HFH-LP is specified with a straightforward crop rotation and using standard cost estimates from the Nix Pocketbook (Redman, 2018) and The Agricultural Budgeting & Costing Book (Agro Business Consultants, 2018). The initial HFH-LP focused on the short term (two year) autumn sown winter wheat-OSR rotation which was for many UK farmers the most profitable arable cropping option in recent decades. That rotation was modelled with a range of timeliness of planting and harvesting with associated yield differences. A similar short-term, spring barley-autumn OSR, rotation was modelled with several timeliness alternatives. The barley-OSR rotations were included to give the model some flexibility in the timing of field operations. Field operation timing is drawn from Finch *et al.* (2014) and Outsider's Guide (1999). Equipment timeliness estimates and other machine relationships are from Witney (1988). All crops are assumed to be direct drill. Additional information on the HFH-LP model is available in Lowenberg-DeBoer et al. (2019).

The production costs, output prices, yields and human and machine work times from the HFH economic analysis were used. To avoid the complications of scale issues, the initial focus of the biopesticide application analysis was on a 500 ha farm with 450 ha arable. Equipment investment and cost estimates were updated with new information from the set-up of Hands Free Farm (www.handsfree.farm) on cost of a small combine (£28,000 compared to £20,000 in the initial analysis) and retrofitting non-hydrostatic drive equipment for autonomous use (£23,262 compared to £4,850 in the initial analysis). Previous research identified an equipment set with a 300 hp tractor and a trailed 36 m boom sprayer with a 3000-5000 L tank as profit maximizing for this 500 ha farm (Lowenberg-DeBoer et al. 2019). The optimal equipment set for the autonomous farm was three autonomous units each with a 38 hp tractor and associated equipment. The sprayer for the autonomous unit was a trailed 4 m boom and 200 L tank. Especially important for this analysis is the assumption that this is a farm on which there is one operator and that operator is available 100% of their work time for farm work. This means that the main cash cost of additional biopesticide applications is the biopesticide product. Temporary labour can be hired on a daily basis if needed.

The HFH-LP model was adapted in three ways: 1) including the impact of the neonicotinoid ban on CSFB damage to OSR in the short rotations, 2) introducing a longer rotation including other break-crops and 3) developing a winter wheat-OSR short rotation with biopesticides for CSFB control. Based on the research literature, CSFB damage to OSR is modelled both through land sown to OSR that is abandoned (and resown to another crop in the spring) and yield loss on the OSR harvested. CSFB damage as measured in research studies varies widely geographically and from year to year (Alves et al. 2015; Hughes et al. 2015 & 2017; Nicholls 2015 & 2016; Scott and Bilsburrow 2015 & 2017; White 2015; White and Cowlrick 2016; Wynn et al 2014 & 2017). There is not enough research to allow estimation of reliable average OSR abandonment or OSR yield loss. Consequently, this study used the 5% of OSR area abandoned and 10% yield loss as representative loss levels.

One alternative to the two year cereal/OSR rotation is a longer rotation including additional non-cereal break crops (EPPO, 2017; Bell, undated). The focus is on non-cereal break-crops because of the substantial yield penalty for second and subsequent year cereal production. That longer rotation can still include OSR if the overall presence of OSR in the agricultural landscape is reduced enough to break the CSFB cycle. For this study a six year rotation with winter wheat every other year, with the break crops being OSR, field bean, and linseed. The field bean and linseed can be either autumn or spring sown. Parameters for this longer rotation are taken from standard UK farm budgeting references (e.g. ABC, 2019; Finch et al, 2014; Redman, 2019). It is assumed for the model that the OSR in this rotation is not damaged significantly by the CSFB. If it is found that CSFB continues to damage OSR even in the longer rotation, OSR could be dropped entirely from that rotation. Without high yielding OSR, the long rotation would be slightly less profitable than the estimates in the model, but labour, equipment time, and investment levels would be similar.

A winter wheat/OSR short rotation was modelled with biopesticide application the first four months after sowing OSR with at least 2 applications per month. The model is solved for a range of biopesticide product costs and application frequencies. It would be possible to model a similar spring barley/autumn sown OSR short rotation with biopesticide; this was not done in order to reduce model complexity. While there is uncertainty about the cost of the biopesticide product for broadacre crop application, the initial focus was on low cost biopesticide products (<£15/ha/application) such as those formulated from plant derived fatty acids. Higher biopesticide product costs are not economically feasible with current OSR prices. In the model OSR can be sown in September or October.

Results

The LP results show the importance of resolving the CSFB problem. Conventional short rotation winter wheat/OSR without neonicotinoid seed treatment, has the lowest return to operator labour, management, and risk taking, among the alternatives considered for both conventional mechanisation and autonomous equipment (Table 1). Introduction of the long rotation with field beans and linseed increases whole farm returns by £26,000 to £32,000. With low cost biopesticides and twice per month application, returns can be increased another £21,000 to £27,000. Individual farmers with opportunities for other higher profit rotation crops (e.g. potatoes, sugar beets, vegetables) might not see this CSFB effect, but it illustrates why OSR area is dropping rapidly in the UK.

Solutions for biopesticide product costs from £0 to £15/application for two applications per month, show the sensitivity of returns to biopesticide costs. At £15/application the biopesticide OSR activities have completely disappeared from the conventional mechanisation solution and occupy only a portion of the area on the autonomous farm. At a cost greater than £15/application, the biopesticide activities disappear from the autonomous farm as well. The gain for both conventional and autonomous farms from introduction of a biopesticide option for management of CSFB is almost identical for all levels of biopesticide product cost tested (Fig. 1). The “gain” is calculated over the baseline of winter wheat/OSR without neonicotinoid seed treatments, but before introducing the longer rotation or the biopesticide options. The gain for the autonomous farm at the £15/application cost is slightly lower than for the conventional farm because tractor time becomes a binding constraint.

Table 1 - Biopesticide on OSR analysis for a 450 ha arable farm in the UK with conventional and autonomous equipment over a range of biopesticide product costs and application frequencies.

Biopesticide Activity Available	Long Rotation Available	Apply per month	Product Cost per Biopesticide Application, £/ha	Labour Hired days	Operator Time days	Wheat Ha	OSR Ha	Bean Ha	Linseed Ha	Gross Margin £/farm	Return to Operator Labour, Management and Risk Taking, £/farm
Conventional Mechanisation with Human Operators:											
Yes	Yes	2	£15.00	34	88	225	75	75	75	332035	69101
Yes	Yes	2	£10.00	35	97	225	225	0	0	335677	72743
Yes	Yes	2	£5.00	35	97	225	225	0	0	344677	81743
Yes	Yes	2	£0.00	35	97	225	225	0	0	353677	90743
Yes	Yes	4	£0.00	37	105	225	225	0	0	353514	90580
Yes	Yes	8	£0.00	35	107	225	225	0	0	347468	84534
No	Yes	NA	NA	34	88	225	75	75	75	332035	69101
No	No	NA	NA	35	90	225	225	NA	NA	299939	37005
HFH autonomous farm:											
Yes	Yes	2	£15.00	95	92	225	96	65	65	324707	123116
Yes	Yes	2	£10.00	107	86	225	225	0	0	330085	128494
Yes	Yes	2	£5.00	107	86	225	225	0	0	339085	137494
Yes	Yes	2	£0.00	107	86	225	225	0	0	348085	146494
Yes	Yes	4	£0.00	107	97	225	225	0	0	348085	146494
Yes	Yes	8	£0.00	97	103	225	127	49	49	332731	131140
No	Yes	NA	NA	96	90	225	96	65	65	320977	119386
No	No	NA	NA	107	77	225	225	NA	NA	294347	92756

NA = not applicable

Fig. 1 - Gain from biopesticide on OSR compared to the HFH solution without neonicotinoids for conventional and robotic farms over a range of biopesticide product cost for twice per month application.

Solutions for the negligible cost biopesticide (£0/application) over a range of application frequencies show that the retrofitted equipment of the type used on the HFH farm does not resolve the problem (Fig. 2). The gain for the conventional and autonomous farms is similar (Fig. 2), except for the twice weekly application (i.e. 8 times per month), in which tractor time is a binding constraint for both the conventional and autonomous farms. The conventional farm switches some land to the late planted winter wheat and OSR with biopesticides to deal with tractor time constraints. The autonomous farm switches some land to the long rotation in this case. Autonomous tractor time becomes binding with 8 applications per month because smaller equipment (4 m boom) requires about 10 times longer to cover the same area compared to the 36 m boom used with large conventional equipment set. So even though the autonomous equipment can operate 22 hours per day, it still has difficulty making the 8 applications per month.

For the autonomous farm, one solution to the tractor time constraint would be to invest in a 4th autonomous tractor and sprayer (i.e. £19,900). With the 4th tractor, the solution for the negligible biopesticide cost scenario switches back to all winter wheat/OSR rotation with biopesticide and the gain (i.e. £50,915) is slightly greater than that of the conventional farm in spite of the extra equipment cost. For the conventional farm sprayer capacity is lumpier. Acquiring another tractor and sprayer unit to deal with the tractor time constraint is more costly (i.e. £320,000).

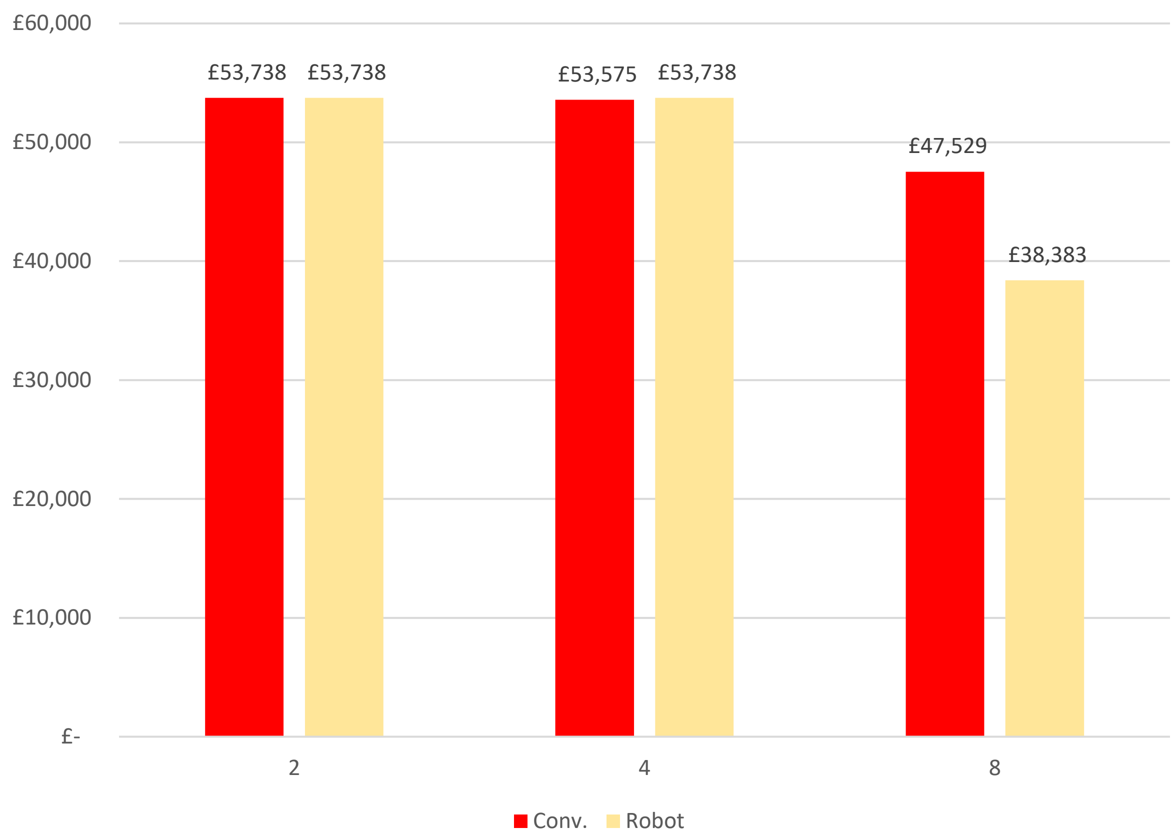

Fig. 2 - Gain from Biopesticides on OSR for Conventional and Robotic Farms over a range of application frequencies per month and with very low cost product

With 8 biopesticide applications per month, operator time also becomes a constraint for the autonomous farm because of the 10% human supervision time assumed. The 10% human supervision time is based on the HFH experience, but it is at the lower end of the range of human supervision time assumptions in the autonomous equipment economics literature. Dewitte (2019) assumes a 50% human supervision time. Many European countries and the US state of California require an on-site human supervisor 100% of the time for autonomous farm equipment. Even if regulation of autonomous equipment allowed less than 10% human supervision time, technical changes would probably be required including artificial intelligence for problem solving to reduce the need for human intervention and automated refilling of the sprayer tanks. The HFH economic analysis assumes that the human supervisors assist with input resupply for autonomous equipment.

Discussion

The primary hypothesis of this study was not supported. At low biopesticide product prices the gain from introduction of the biopesticide option is very similar on conventional and autonomous 500 ha farms with the previously Identified optimal equipment sets. This occurs for the twice per month and once per week biopesticide applications because they can be accomplished mainly with operator labour that would otherwise be unused. The October to January period is not a peak labour or tractor time demand period for the winter wheat/OSR short rotation previously identified as optimal. With twice per week biopesticide applications (8 times per month) the gain is reduced because of October tractor time constraints for both the conventional and autonomous farms.

The October tractor time constraint can be resolved quite inexpensively for the autonomous farm by acquiring another tractor and sprayer. For the conventional farm, equipment capacity comes in bigger, more expensive steps, and is consequently not a profitable option for the scenarios considered.

Conclusions

This study has identified several constraints to use of autonomous equipment for application of low residual biopesticides on OSR, including:

- The volume of water required is a major constraint to use of autonomous equipment. The logistics of transporting and applying that volume of water means that a substantial machine is required. The small, light, inexpensive robots envisioned by some researchers for micro-spraying cannot be used. Research is needed on applications methods and alternative biopesticides that would reduce the water requirement.
- The human supervision time is an important constraint for the autonomous farm when then spray frequency increases. Reducing human supervision time has regulatory and engineering aspects. In some countries autonomous farm equipment must have 100% of the time with human on-site supervision. The engineering aspect is related to AI for problem solving in the field to avoid the need for human attention and to automatic resupply of the biopesticide water mixture without human assistance.
- For both the conventional and autonomous farms the price of the biopesticide product is an important factor. With frequent application the overall cost of the biopesticide quickly becomes burdensome even if the cost per application is relatively low.

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