



Techno-economic impacts of using a laser-guided variable-rate spraying system to retrofit conventional constant-rate sprayers

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Abstract

Specialty crops, such as apples, are vulnerable to insects and pathogens, and require higher pesticide input than row crops, a significant fraction of which is off-target loss, causing adverse environmental and socio-economic impacts. An advanced laser-guided variable-rate sprayer (VRS) could improve spray deposition uniformity and minimize pesticide waste, while maintaining efficacy against insects and pathogens. Despite these merits, retrofitting a conventional sprayer with laser-guided variable-rate spraying functions adds to its cost. Thus, the objective of this study was to analyze the techno-economics of a conventional pesticide sprayer retrofitted with VRS, in comparison to a conventional constant-rate sprayer (CRS) for pesticide application during apple production. A techno-economic model was developed for the apple orchards covering areas of 4 and 20 ha, which are common orchard sizes in the USA. The model incorporated cost for operation, equipment, fuel use and labor during pesticide application. The data were obtained from field tests in orchards in Ohio, USA in years 2016 and 2017, literature, and the original VRS development team at USDA-ARS and Ohio State University. The results indicated that VRS can reduce pesticide costs by 60–67%, pesticide application time by 27–32% and labor and fuel by 28% compared to CRS. For larger orchards, VRS also reduced equipment requirement. Compared to CRS, overall annual pesticide application cost savings by using VRS were between \$1420 and \$1750 ha⁻¹. The payback time for using VRS was estimated to be between 1.1 and 3.8 years for apple orchards between 4 and 20 ha, respectively, in Ohio.

Keywords Laser-guided variable-rate sprayer · Apple orchard · Techno-economic analysis · Pesticide · Insects and pathogens

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Introduction

Specialty crops refer to a wide range of agricultural products, including fruits, vegetables, tree nuts and horticulture and nursery crops. In recent years, specialty crops are grown in approximately 4.5% of the total harvested cropland and account for 30–40% of the total economic value of U.S. crops (The National Agricultural Law Center 2017). In 2012, about 5.7 Mha of land is used for specialty crop farming, engaging 1.35 million workers with total sales of \$57.6 billion in the U.S. (USDA 2012).

Most of the specialty crops are intended for fresh markets and need to be visually appealing to consumers, requiring more care and attention from growers. They also need to be transported quickly and carefully to the market. Compared to traditional row crops, specialty crops are more susceptible to pests and diseases and, thus, require intensive management practices to maintain yield and quality (Kistner et al. 2018). Thus, management of pests and diseases is of high importance for the effective maintenance of orchards and other specialty crops. The cost of pesticide application for specialty crop production is significantly higher ($> \$4695 \text{ ha}^{-1}$) compared to row crops ($< \$310 \text{ ha}^{-1}$) (Fernandez-Cornejo et al. 1998).

Pesticides are commonly applied in orchards and other specialty crops by using sprayers usually equipped with some means of air-assistance to carry small droplets deeper into the dense canopy. Using existing air blast sprayers, pesticides are usually sprayed in excess to ensure that more than adequate amount of spray reaches the target. Air blast sprayers have higher flexibility in the fluid and air delivery adjustments that allow the sprayers to be used in a wide range of orchard conditions. However, conventional air blast constant-rate sprayers (CRS) operate in continuous spray mode and do not adjust sprayer flow rate in real time in accordance with changes in canopy conditions. As a result, a significant amount of pesticide may be sprayed outside the target plant canopy, either drifting in the air or depositing on the ground and eventually leaching into the soil leading to considerable pesticide losses. This results in economic loss and environmental pollution. In addition, excessive amounts of residual pesticides on the crops (Suárez-Jacobo et al. 2017; Xu et al. 2008) can have a detrimental effect on consumer health. Research has shown that lower pesticide application rates can be effective in covering the tree canopy (Chen et al. 2013; Giles et al. 2011; Shen et al. 2017). The multi-year field experiments conducted in Ohio and other studies (Dammer et al. 2009; Sedlar et al. 2013) have shown efficacy in controlling pests and diseases even with lower pesticide application rates using a variable-rate sprayer (Stover et al. 2003; Zhu et al. 2017).

Researchers at USDA-ARS Application Technology Research team and The Ohio State University have developed a laser-guided variable-rate air-assisted sprayer (VRS) that detects the plant canopy using a laser scanning sensor and synchronizes the chemical spray output with canopy structures in real time (Chen et al. 2011; Shen et al. 2017). The sprayer system integrated an embedded computer with unique algorithm, a touch screen, a 270° radial-range laser sensor, a travel speed sensor, automatic flow rate control unit and 40 pulse-width modulated extended range flat spray nozzles operating at approximately 580 kPa pressure (Shen et al. 2017). The VRS developed for targeted pesticide applications have shown increased spray deposition efficiency with minimized pesticide losses. Initial tests have demonstrated a reduction in pesticide volume requirements by more than 50%, spray drift by up to 87% and ground loss by up to 90% while spray deposition quality on target canopies remained equivalent. It is expected that these reductions in pesticide losses ultimately have positive economic and environmental impacts. Moreover, with comparable

control of insects and diseases, VRS could lead to chemical savings of up to \$519 ha⁻¹ for ornamental nurseries in a growing season (Zhu et al. 2017).

Most of specialty crop growers use CRS to spray their crops. For wider implementation and affordability of VRS to growers, several CRS have been retrofitted with sensors and electronics to convert the CRS to VRS for variable-rate, site-specific spraying. However, retrofitting the CRS to convert them to VRS still adds to the cost of the pesticide spray equipment. Although reduced spraying cost is expected due to reduced pesticide use while maintaining effective pest control, an economic evaluation based on field tests for VRS and its comparison with CRS has not been undertaken for orchard spray applications. Thus, the objective of this study was to evaluate the techno-economic performance of VRS and compare it to CRS for effective pesticide applications in apple orchards in Ohio. Apple is one of the most widely grown specialty crops in the U.S. There are approximately 7 500 apple orchards in the U.S., covering a total area of 130 309 ha (U.S. Apple Association 2020). Apple has a high demand throughout the country with an annual wholesale market value of around \$4 billion (U.S. Apple Association 2020). Due to its high level of production in the U.S., this study considered apple orchards for comparing the techno-economics of the VRS and CRS for pesticide application.

Methodology

Systems layout and modeling overview

Orchard areas of 4 ha (representing a small commercial orchard) and 20 ha (representing a large commercial orchard) were considered for the techno-economic comparison of CRS and VRS for pesticide application in this study. Although every farm system is unique, 4-ha could be considered a minimum size for a commercial apple-growing enterprise. A 4-ha operation is large enough to use equipment efficiently and implement a continuous orchard renovation program, yet small enough that one person can take care of most orchard activities. Larger orchards can make more efficient use of machinery and equipment but require more hired labor, and thus more management skills (University of Minnesota 2018). For each size, a square layout of orchard was considered (Fig. 1). The sprayer refill station was assumed to be located at the edge of the square field layout (Fig. 1). The tree row spacing and the spacing between trees within the row were 4.3 m and 2.4 m, respectively. The tree density for the apple orchard considered for this study was 1000 trees ha⁻¹, which is based on the experimental orchard in Ohio. Average tree densities range from 350 trees ha⁻¹ in California to 825 trees ha⁻¹ in Oregon with higher average tree densities of 1100 trees ha⁻¹ in Washington state (Slattery et al. 2011). The tree density considered for this analysis falls within the range reported in the literature.

The main inputs to the techno-economic model were related to pesticide application frequency, quantity and costs of pesticides, tractor and sprayer, and logistics for pesticide application, which include tractor and sprayer speed, pesticide preparation and sprayer tank filling times, and pesticide application times. The pesticide application data was based on field tests performed in a commercial apple orchard in Wooster, Ohio (40° 42' 41.6" N 81° 58' 07.4" W) in 2016 and 2017, and was verified and supplemented with pesticide application guides and literature data, including supplier websites and personal communication with suppliers. The costs associated with retrofitting the CRS to convert it to VRS were obtained from the USDA-ARS VRS development team in Wooster, Ohio, USA.

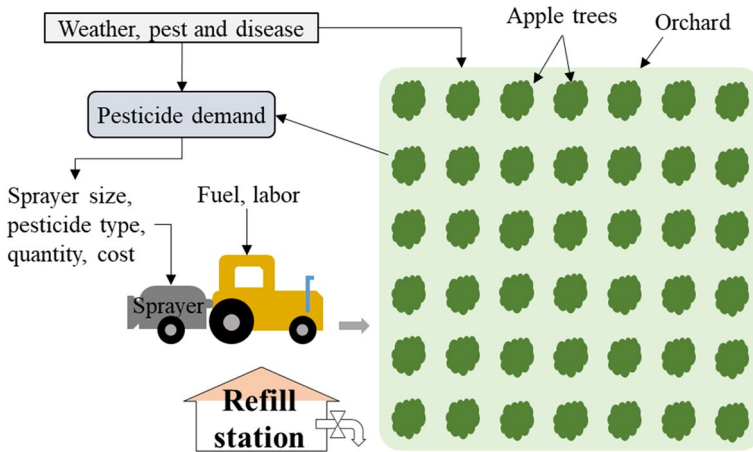


Fig. 1 Field layout and factors affecting pesticide demand in apple orchards

The information from pesticide application and field logistics were used to estimate the resource requirements (i.e., pesticides, labor time, number of tractor and sprayer units, and consumables) and fuel requirements for the operation of different types of machinery. Further, the total costs of pesticides, tractor, CRS and VRS were estimated to determine the total annual pesticide application costs per ha of orchard.

The number of trees in the orchard area, growth stages of the trees, insect incidence in the orchard and the weather patterns determine the pesticide demand of the orchard. The pesticide demand determines the requirements for pesticide, water, number of sprayer and tractor units, labor and fuel; and pesticide application costs.

Selection of sprayer capacities and estimation of sprayer and retrofit cost

Air-assisted sprayers are commonly used to apply pesticides in orchards in the U.S. Pesticides are usually mixed with water and are sprayed together with large volumes of air during application. Costs of different sizes and types of conventional air blast sprayers used in orchards ranging from 189 l to 3785 l were collected from literature (Midwest Tree Fruit Spray Guide 2012), equipment suppliers websites (Agriculture Solutions 2020; Machinio 2018; MM Sprayers USA 2017; Sprayer Depot 2017), and personal communication with equipment vendors (Midwest Grower Supply) (Fig. 2). This information was used to estimate the sprayer cost (\$) based on the sprayer capacity (l) assuming that the sprayer cost increased linearly with sprayer capacity (linear regression), and its fit is presented in Eq. 1.

$$\text{Sprayer cost} = 9.0316 \times \text{Sprayer capacity} + 4834 \quad (R^2 = 0.87) \quad (1)$$

Despite being more expensive, larger capacity sprayers help reduce the number of pesticide refills during a spraying event. This study considered CRS and VRS with 400 l capacity to be used in the 4-ha orchard and 1900 l capacity sprayer to be used in the 20-ha orchard, as these are the commonly used sprayer capacities for smaller and larger scale orchards.

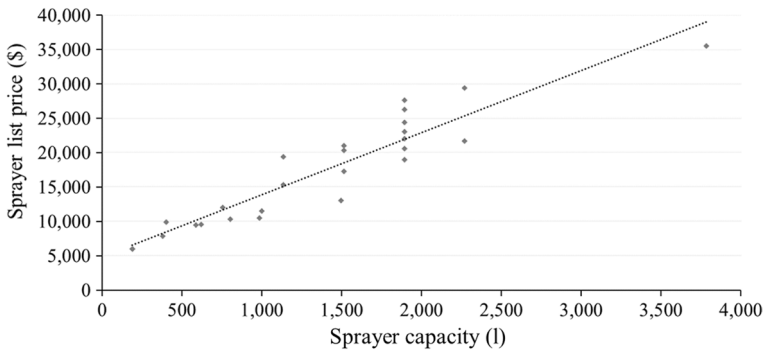


Fig. 2 Cost of conventional constant-rate sprayers of different tank capacities [collected from literature (Midwest Tree Fruit Spray Guide 2012), websites of equipment suppliers (Agriculture Solutions 2020; Machinio 2018; MM Sprayers USA 2017; Sprayer depot 2017; Tractorhouse 2018), and personal communication with equipment vendors (Midwest Grower Supply)]

The cost of retrofitting CRS to convert it to VRS was taken as \$15 200 based on the cost of materials used and estimated manufacturing costs. Different parameters related to the orchard, machinery and their economics are provided in Table 1.

Estimation of spray schedule, pesticide requirements and cost

The spray schedule for the pesticide application in the orchard depends on multiple factors such as growth stage of the trees, insect and disease incidence and weather conditions. The pesticide spray schedule was obtained from the annual spray records provided by the farm manager. Pesticide application schedule was also compared against the published spray guide for fruit trees in the U.S. Midwest region (Midwest Tree Fruit Spray Guide 2012). The actual pesticide cost for all the pesticide types used in the orchard was obtained from personal communication with orchard managers/owners. The pesticide spraying activities for the apple orchard spans from March through August of the year. Based on the two years of pesticide application data, pesticide was applied for a total of 14 times in the year 2016 and 15 times in the year 2017. The pesticide requirements of the orchard were estimated based on the spraying requirements for a 0.8-ha apple orchard sprayed with a CRS and another 0.8-ha sprayed with VRS. The spraying activity was carried out on the same day within the operating window using both CRS and VRS, while recording their pesticide consumption.

For the orchard considered in this analysis, based on the field tests, VRS reduced the pesticide requirement by 47–70% with similar pesticide efficacy level compared to the CRS. Even though the pesticide requirement was lower, the experimental results indicated that the amount of pesticide used was effective in covering the desired plant canopy and controlling pests and diseases in the orchard. Earlier similar studies for VRS have showed pesticide reductions in the range of 15–86%, depending on the type of crops and sprayer (Chen et al. 2013; Giles et al. 2011; Jeon et al. 2011; Sedlar et al. 2013; Shen et al. 2017). With a CRS, the amount of the sprayed pesticide is uniform at any given spray event regardless of the growth stage and tree canopy. However, for VRS, the spray amount and profile vary based on the growth stage of the tree and available tree canopy, which leads to decreased pesticide requirement.

Table 1 Parameters used for the techno-economic analysis of pesticide application using conventional constant-rate sprayer (CRS) and retrofitted variable-rate sprayer (VRS)

Parameter	Unit	Avg. values	Distribution*
Field parameters			
Width of tree rows ^a	m	4.3	Triangular (3, 4.3, 6.7)
Plant density in the orchard ^b	Trees ha ⁻¹	1000	Triangular (350, 1000, 1100)
Sprayer speed ^a	Km h ⁻¹	4.8	Triangular (4, 4.8, 7.2)
Preparation and wrap up time for each spraying event ^a	Min	20	Triangular (15, 20, 25)
Sprayer refilling time for 3030 l tank ^c	Min	15	Triangular (10, 15, 20)
Total hours available for each spray event ^{a,d}	h	8	Triangular (6, 8, 10)
Tractor parameters (Power unit)			
Tractor power	kW	67	
Purchase cost ^e	\$	57 402	Normal (57 402, 6097)
Tractor useful life ^f	Year	15	
Fuel cost ^g	\$ l ⁻¹	0.87	Normal (0.87, 0.17)
Labor rate ^h	\$ h ⁻¹	21.9	Triangular (14.1, 20.8, 31.5)
Interest rate ⁱ	%	5.05	Triangular (3.85, 5.05, 7.85)
Inflation rate ^j	%	2.19	Normal (2.9, 1.33)
Sprayer parameters			
Sprayer capacity for 4-ha and 20-ha orchard ^k	l	379 (for 4-ha) 1 893 (for 20-ha)	
Sprayer economic life ^f	Year	15	
Cost for retrofitting CRS to VRS (based on list price) ^l	\$	15 200	Triangular (11 425, 15 200, 19 042)
Reduction in pesticide use ^m	%	58	Triangular (47, 58, 70)

^aData obtained from the orchard owners and Parker et al. (1998)

^bData obtained from Slattery et al. (2011)

^cData obtained from Sprayers101 (2017). The variation in refilling time was for the 3030 l tank and obtained from the literature

^dDistribution in spraying window is assumed and is dependent on the weather pattern

^eData obtained from price listings for John Deere, Case IH and Massey Ferguson tractors (AGCO 2020; John Deere 2018; Tractorhouse 2018)

^fAssumed useful life for tractor

^gData obtained from U.S. Energy Information Administration (2017)—Based on diesel prices for the last 10 years in the U.S

^hData obtained from Bureau of Labor Statistics (2018)—50% of labor wage was added to cover administrative and management costs

ⁱData obtained from AgDirect (2020)—values based on the fixed interest rate for new or used equipment costing more than \$10 000

^jValues based on the inflation rate in the U.S. from 2000 to 2017

^kVariable sprayer capacity used for different orchard sizes

^lEstimated for retrofitting conventional sprayer to VRS based on the cost of materials and labor (variation is assumed as $\pm 20\%$ of the base cost)

^mData obtained from field tests of CRS and VRS in apple orchards in Ohio

*Values in parentheses for triangular distributions are minimum, most likely and maximum values, and for normal distributions are mean and standard deviation

The type and quantity of pesticides used for protection against insects and diseases in apple orchards vary widely depending on different growth stages, and insect and disease pressure. Also, specific information on the type of pesticide used was not easy to obtain because producers hesitate to share this information. Thus, the use of different pesticides is convenient to present in terms of their cost.

Estimation of field performance and logistics

Total time for each pesticide-spraying event includes the time required for preparation before spraying, during spraying pesticides, refilling sprayer tank with pesticides and traveling to and from the refilling station and wrap-up time (Fig. 3).

The preparation time during each spraying event includes time to prepare the tractor, set up and calibrate the sprayer, fill and mix the required quantity of chemicals in the sprayer tank and drive to the spraying location in the orchard. The wrap-up time considers the time to take the tractor and spray unit to the shed, and compile the data regarding machinery, labor and pesticide usage for the spraying event. The time requirements for the preparation, wrap-up and pesticide filling are included in Table 1. Based on the discussion with the orchard owner, the preparation and wrap-up time could vary depending on the field conditions and the equipment status during pesticide application and, thus, the variations in the actual times were also considered in this analysis (Table 1). The sprayer considered for this study was a pull-type sprayer pulled and powered by the tractor, which passes through each row in the orchard to spray the pesticides on to the trees. The total travel distance by the tractor and sprayer was estimated based on the considered orchard layout. The in-field spraying time was estimated based on the average operational speed of the tractor during spraying activity and the total distance covered by the sprayer in the field while spraying pesticides on to the trees. The information for the average speed of the tractor was obtained from orchard owners during different pesticide application events and is affected by field and weather conditions (Table 1). The total distance was estimated based on the area and layout of the orchard, width of tree rows and number of turns taken at the end of each row (Table 1). The spraying activity requires large volumes of pesticide to be sprayed on to the trees. Thus, the sprayer needs to be refilled multiple times to spray the entire orchard area. This study also considers the time required to refill the sprayer in the pesticide refilling station and the time required for the sprayer to travel back and forth from the refilling station to the orchard to continue the spraying activity. The refilling area/station was assumed to be situated at the edge of the orchard (Fig. 1). The sprayer refilling time depends on the

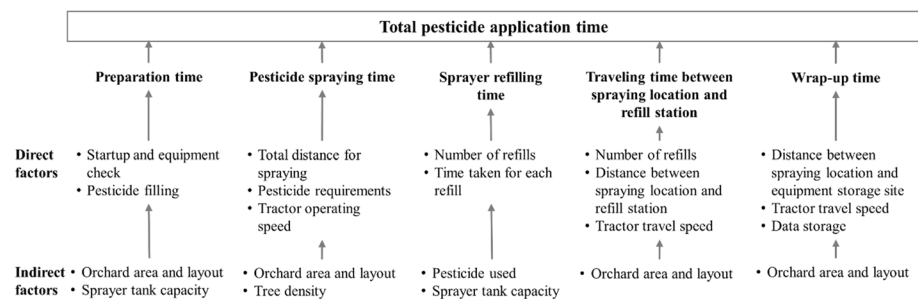


Fig. 3 Factors affecting the field performance and logistics for pesticide application in orchards

sprayer tank capacity, the type and physical properties of pesticides being used and the pesticide mixing/loading technology. The sprayer filling time was obtained from literature for a 3030 l sprayer tank capacity (Table 1). For estimation of sprayer filling time for the different sprayer capacities considered in this study, sprayer filling time was assumed to be linearly dependent on sprayer tank capacity. The variation in the sprayer filling time considered in this analysis was due to the different types of chemicals being used.

Estimation of equipment and resources

The pesticide is usually sprayed during a short operating window of 1 day/event, because spraying is significantly affected by weather conditions, such as rain and wind, and the pesticides need to be sprayed as soon as the insects and diseases are observed in order to minimize the damage. This study assumed each spraying event to be 8 h long. For safety reasons, usually, the personnel at the orchard need to wait for at least 24 h after spraying to enter the orchard again to start other activities. Thus, if possible, growers prefer to spray the whole orchard in one day. The total number of tractor and sprayer units required for each orchard was estimated based on the total time estimated for each spraying event and spraying window in which all the spraying events need to be completed.

Estimation of labor requirements

The labor requirement was based on the time required for each activity in the spraying event and the number of sprayer systems used for each spraying event. Labor cost was estimated considering one farm operator required for each spraying system and the total time for which the operator was engaged in spraying activities. Farm operator labor wage (Table 1) was based on the mean hourly wage for agricultural equipment operators (Bureau of Labor Statistics 2018), including 50% labor wage overhead for covering the benefits and health insurance.

Uncertainty and sensitivity analyses

Pesticide application activity has technical uncertainties related to pesticide requirements, spray time and fuel reduction by VRS, tractor speed and sprayer refill times, preparation and wrap up times; and market uncertainties such as labor rate, fuel cost, interest rate and inflation. Spatio-temporal uncertainties related to weather and tree growth stage affecting the disease and insect pressure determine the pesticide requirements. These different uncertainties were considered to determine the overall uncertainty in total pesticide spray application cost for both the CRS and VRS used for 4-ha and 20-ha orchards. The effect of the variabilities on the resources used and total pesticide application cost was assessed using Monte Carlo simulation with 10 000 randomized trials. For this, the distribution of values for the different parameters used in pesticide application were obtained from different sources (Table 1).

Sensitivity analysis was performed to evaluate the sensitivity of different input parameters on the overall annual pesticide application cost per ha for VRS and compared to the CRS. The values for the input parameters considered for the sensitivity analysis (Table 1) can vary considerably during the pesticide application event, and were obtained from literature, field test data and market studies. The values considered for the sensitivity analysis

were between the 10th and 90th percentile of the distribution of the different parameters (Table 1). Width between tree rows can vary for different orchards, depending on the orchard topography, tree size and equipment size used in the orchard. Tree density could vary depending on the tree size, fruit variety and their spacing requirements. Sprayer speed could depend on the tractor and sprayer conditions, pesticide application rates and desired coverage, and ambient wind speed and direction during pesticide application process. Sprayer preparation and wrap up time depends on operator efficiency, types of chemicals used and weather conditions. Sprayer filling time will depend on the efficiency of the refilling system and operator. Total hours available for each spraying event will depend on the insect and disease severity, weather conditions and potential pesticide application restrictions. The cost of pesticide, equipment and fuel will depend on the market situation.

Results and discussions

Pesticide requirements and cost

Biological control was not considered in the study. Only pesticide used was considered for controlling pest and disease. Based on the inspection of pest and disease during the two years, there were no pest or disease problem using both fixed-rate and variable-rate sprayer. These results will be published in subsequent works. With comparable insect and disease control levels reported by the grower, the reduction in pesticide usage with the VRS resulted in lower pesticide cost compared to the CRS (Fig. 4). The annual cost of pesticide used for CRS varied between \$2076 and \$2768 ha⁻¹ and was higher compared to VRS (\$865–\$907 ha⁻¹). On average, the estimated reductions in the cost of pesticides using VRS was 60–67% compared to CRS. This translated to a savings of \$4720–\$7560 for the 4-ha orchard and \$23 590–\$37 800 for the 20-ha orchard per season in pesticide cost.

Field performance and logistics estimation

Times required for different activities during each pesticide application event using CRS and VRS were estimated on a per ha basis for both 4-ha and 20-ha orchard sizes (Fig. 5). The average combined preparation and wrap-up time for both the VRS and CRS for 4-ha and 20-ha orchard was 22 and 29 min, respectively. The average combined preparation

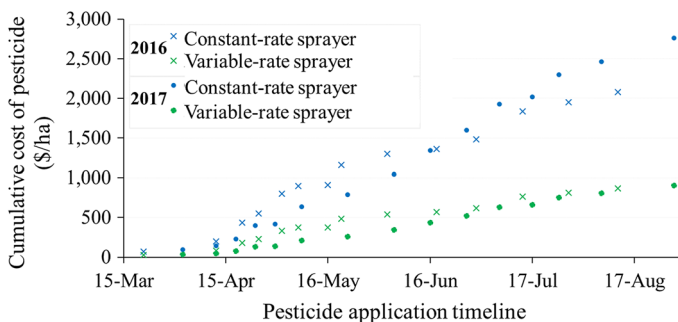


Fig. 4 Pesticide application cost and timeline for the constant-rate and variable-rate sprayers used in a commercial apple orchard (Moreland Fruit Farm) in Ohio during 2016 and 2017 growing seasons

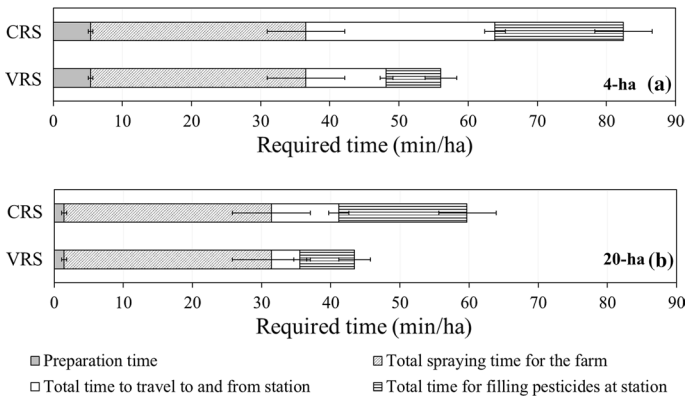


Fig. 5 Time requirement for different sub-activities during each pesticide application event using constant-rate sprayer (CRS) and variable-rate sprayer (VRS) for a) 4-ha orchard, and b) 20-ha orchard (Error bars represent 90% central range of values obtained from the Monte Carlo simulations based on 10 000 randomized trials)

and wrap-up time was approximately 5 min ha^{-1} for both types of sprayers in the 4-ha orchard. For the 20-ha orchard, preparation time per ha was reduced to 1.5 min ha^{-1} for both sprayers, as slightly higher preparation time was needed (higher initial pesticide filling time in the larger capacity tank) for a much larger orchard area. Preparation and wrap-up time could depend on the weather conditions, types of pesticides used (liquid, powder, or granular) and operator efficiency. The pesticide spraying time for both the CRS and VRS was the same as both sprayers need to travel equal distances and were considered to travel with the same tractor speed during pesticide application. However, for 20-ha orchard, the total spraying time for each sprayer was reduced slightly as less time was spent for turning the sprayers at the field edge. VRS used a significantly lower volume of pesticides compared to the CRS. Thus, the CRS needed to be refilled more frequently than the VRS. The total numbers of refills for VRS compared to CRS decreased from 40 to 17 in both 4-ha and 20-ha orchards. Although the total pesticide requirements for 20-ha was higher compared to 4-ha orchard, the capacity of sprayer considered for 20-ha orchard was also higher compared to 4-ha orchard, resulting in similar number of refills for both orchard sizes. Lower pesticide requirement for VRS reduced the time spent in refilling the sprayer tank and traveling back and forth to the refill station compared to CRS for both orchard sizes (Fig. 5). Refilling pesticides required almost 14–31% of the total pesticide application time. Technologies for faster pesticide refilling could potentially reduce the pesticide application time and cost.

For each spray event, compared to CRS, VRS reduced the total pesticide application time from 5.6 h to 3.8 h in 4-ha orchard, and 20.1 h to 14.6 h in 20-ha orchard. The reduction in pesticide application time per ha for VRS was 26 min for 4-ha orchard and 16 min for 20-ha orchard which was about 27–32% reduction in overall pesticide application time. This was equivalent to savings of almost 24 h for 4-ha orchard and 76 h for the 20-ha orchard per season. The preparation and wrap-up for pesticide application were performed once during each spray event, whereas the spraying of pesticides, traveling back and forth the refill station and refilling of pesticides occur throughout the spray event. Thus, the uncertainties (shown in Fig. 5 with error bars indicating 90% central range) in the preparation and wrap-up times were lower compared to the time taken for other activities.

Table 2 Resources used for operating constant-rate sprayer (CRS) and retrofitted variable-rate sprayer (VRS) during each growing season

Resources	Unit	4-ha orchard		20-ha orchard	
		CRS	VRS	CRS	VRS
Labor time	h	74 (64–84)	50 (43–57)	266 (228–305)	191 (161–223)
Labor*	Number	1	1	3	2
Tractor and sprayer unit*	Number	1	1	3	2
Fuel	l	1 234 (1 074–1 401)	832 (712–952)	4 436 (3 796–5 008)	3 184 (2 673–3 711)

The results are reported based on the Monte Carlo analysis, reported values in the table are mean (90% central range)

*Numbers of labor, and tractor and sprayer unit does not have distribution, thus 90% central range is not presented

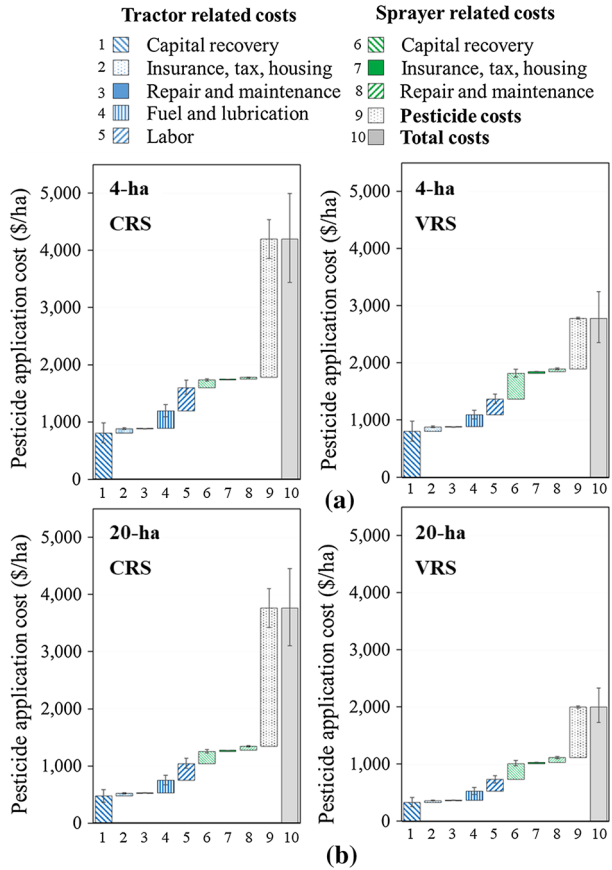
Equipment, fuel and labor requirement

The pesticide application process required a sprayer to deliver the pesticides, a tractor to pull the sprayer unit around the farm, fuel to power the tractor and sprayer unit (powered by tractor) and labor to operate the tractor and sprayer unit. The pesticide application time was lower for VRS, which reduced the number of usage hours for each equipment (sprayer and tractor) and labor necessary to spray the same orchard area. VRS reduced the labor hours and fuel consumption by approximately 28% for both cases. For 4-ha orchard area, only one CRS or VRS unit was required to spray the orchard for each spray event within the available spray window. However, for 20-ha orchard area, three CRS units were required to complete the pesticide application within the spraying window compared to two VRS units (Table 2). Delaying spray applications could result in severe crop damage and yield loss. The additional sprayer unit in the case of the CRS increased the labor, tractor and fuel requirements for spraying the same orchard area.

Annual pesticide application cost, uncertainties and payback period of VRS

The pesticide application cost includes the cost of the CRS unit, tractor used for pesticide application, labor and pesticides (Fig. 6). Total tractor related costs per year for the 4-ha orchard were approximately \$1497 ha⁻¹ (90% central range (CR): \$1250–\$1760 ha⁻¹) and \$1268 ha⁻¹ (90% CR \$1070–\$1480 ha⁻¹) for CRS and VRS, respectively. For the 20-ha orchard, the tractor related costs per year were \$987 ha⁻¹ (90% CR: \$810–\$1170 ha⁻¹) and \$692 ha⁻¹ (90% CR \$560–\$830 ha⁻¹) for CRS and VRS, respectively. The lower tractor related costs for the VRS system were due to lower hours of tractor usage for pesticide application using VRS. Sprayer related costs included the capital recovery, repair and maintenance, insurance, tax and housing costs associated with a sprayer, based on the fraction of total sprayer purchase costs and their use. Due to the added cost of retrofit of the VRS to CRS, the sprayer-related costs were higher for the VRS, and were \$180 ha⁻¹ (90% CR \$158–\$204 ha⁻¹) and \$530 ha⁻¹ (90% CR \$450–\$615 ha⁻¹) per year for the 4-ha orchard and \$300 ha⁻¹ (90% CR \$260–\$347 ha⁻¹) and \$381 ha⁻¹ (90% CR \$318–\$450 ha⁻¹) for the 20-ha orchard

Fig. 6 Overall annual pesticide application cost per ha for constant-rate sprayer (CRS) and variable-rate sprayer (VRS) for a 4-ha orchard, and b 20-ha orchard (Error bars represent 90% central range of values obtained from the Monte Carlo simulations based on 10 000 randomized trials)



for CRS and VRS, respectively. The pesticide costs included the costs of all the pesticides used for all the spray events within a season of apple production. Due to significant reductions in pesticide use by VRS, the cost of pesticide used per season was reduced from \$2420 ha⁻¹ (90% CR \$2076–\$2768 ha⁻¹) for CRS to \$886 ha⁻¹ (90% CR \$865–\$907 ha⁻¹) for VRS. The overall annual pesticide application costs were reduced by \$1420 ha⁻¹ (from \$4100 ha⁻¹ to \$2680 ha⁻¹) for the 4-ha orchard and by \$1750 ha⁻¹ (from \$3710 ha⁻¹ to \$1960 ha⁻¹) for the 20-ha orchard (Fig. 6). Even considering the uncertainties, VRS showed lower annual pesticide application costs compared to the CRS at all the times (Fig. 6). The payback period for adopting VRS for the 4-ha orchard was 3.8 years and for the 20-ha orchard was 1.1 years.

Sensitivity analysis

The sensitivity analysis indicated that the field logistics related parameter, such as tractor/spraying speed; sprayer-related parameter, such as pesticide reduction with IS; and

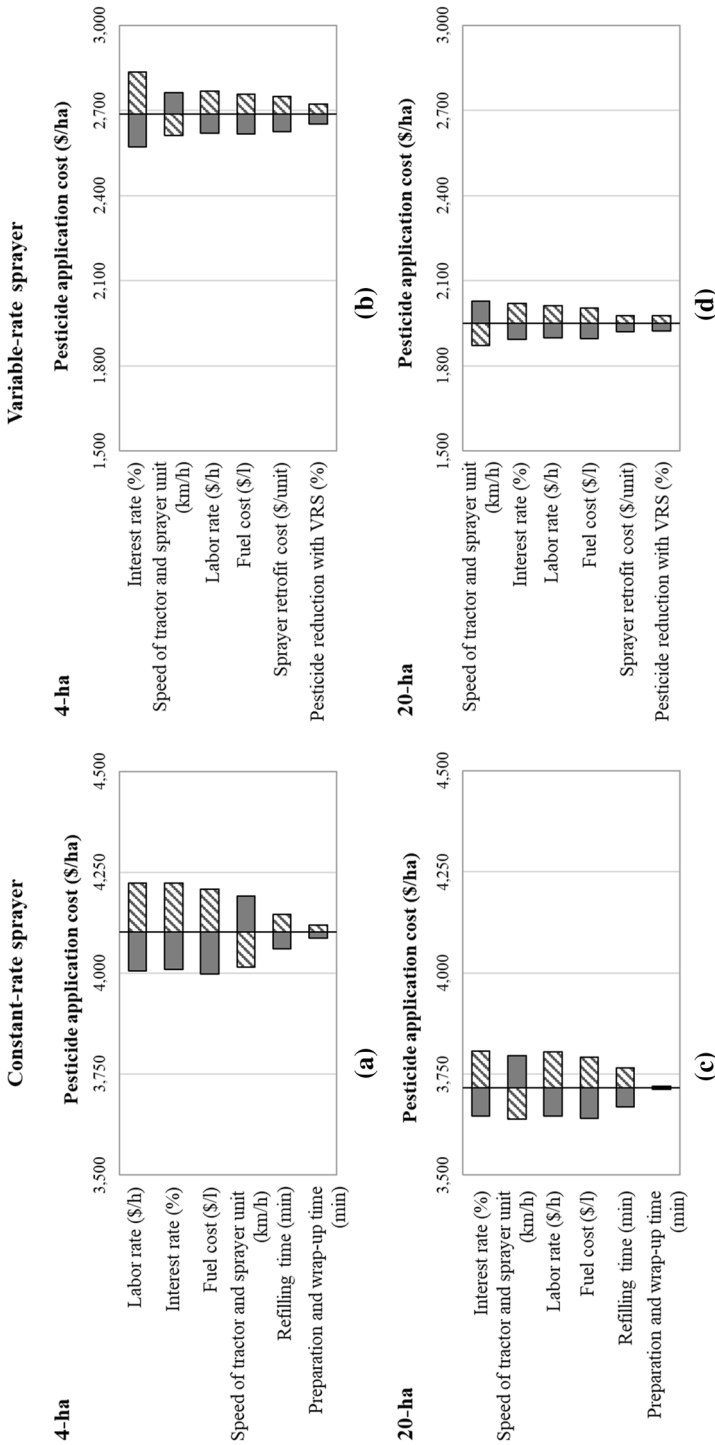
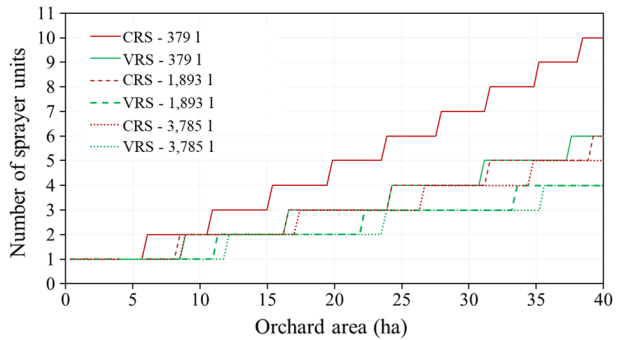


Fig. 7 Sensitivity analysis of different parameters on the overall pesticide application costs for constant-rate sprayer (CRS) and variable-rate sprayer (VRS) in 4 and 20-ha apple orchards: **a** CRS in 4-ha, **b** VRS in 4-ha, **c** CRS in 20-ha, **d** VRS in 20-ha

Fig. 8 Number of sprayer units required for various orchard sizes based on different sprayer capacities of constant-rate sprayer (CRS) and variable-rate sprayer (VRS)



labor and interest rates were the most sensitive parameters for the overall pesticide application cost (Fig. 7). Lower tractor speed increased the additional time required for traveling back and forth to the refill station and correspondingly increased the total pesticide application time, which also increased the labor hour requirement. In addition, more equipment is required if the total hours for pesticide application is higher than the pesticide application window, thus, significantly increasing the pesticide application costs. Labor rates could vary around 30% from the average rates depending on location of the orchard and availability of labor, and thus, have high impact in the total pesticide application cost. Variation in the interest rates, which depends on the status of orchard owners, loan provider and market, impacts the annual tractor and sprayer costs, thus, impacting the total pesticide application costs. Variation in the reduction in pesticide use with VRS directly impacts the quantity of pesticide requirements and, thus, shows a higher effect on the overall pesticide application costs.

Effect of orchard size on sprayer requirements

For different sprayer capacities, increasing orchard size will also increase the number of sprayer units required to spray the whole orchard within the specified spraying window. Three commonly used sprayer capacities—379 l, 1 893 l and 3 785 l, were considered to estimate the number of sprayer units required to spray different orchards up to the size of 40 ha. The number of sprayers required reduced with higher sprayer capacity (Fig. 8). Also, fewer VRS were required compared to CRS in most conditions for different orchard capacities. The VRS reduced the pesticide requirements, the number of refills for the same sprayer capacities, and the time required for spraying. Due to this, the whole orchard could be sprayed in a shorter amount of time, requiring fewer units. For both CRS and VRS, the sprayer with higher capacity reduced the number of refills and the number of times the sprayer needs to travel back and forth from the refill station. However, the spraying time and refilling time per unit sprayer capacity for a 3 785 l capacity sprayer were the same as for the sprayers with 379 and 1 893 l capacity. The advantage of the larger capacity sprayer was the reduced travel time back and forth to the refill station.

Conclusions

VRS considerably reduced pesticide consumption, spraying time, and resource requirements, when compared to CRS used in apple orchards. The overall pesticide application cost was most sensitive to field logistics-related parameters, such as tractor/spraying speed; sprayer-related parameters, such as pesticide reduction with IS; and labor and interest rates. Based on this study, annual cost savings of approx. \$1420–\$1750 ha⁻¹ can be obtained by replacing the CRS with retrofitted VRS for pesticide application in typical 4 and 20 ha apple orchards in Ohio. To put this in perspective, the total savings in annual pesticide application costs by implementing VRS in a total apple production area of 130 309 ha in the U.S. could be in between \$185 and 228 million. These benefits, however, do not consider the added environmental benefits due to reduced pesticide losses as drift in the air and ground losses to the soil and water as well as CO₂ production due to the reduced fuel consumption. Life cycle assessment could be performed in the future to assess the overall reduction in environmental impacts due to lower pesticide usage. The modeling approach used for this study can also be applied to other types of specialty crops in the future.

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