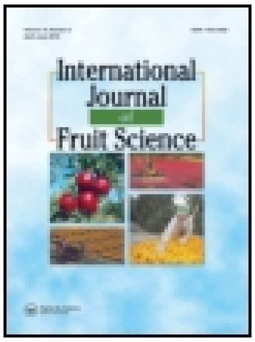

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Sprayer Type and Water Volume Influence Spatial Patterns of Pesticide Deposition and Control of Diseases and Insect Pests of Highbush Blueberries

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ABSTRACT

In highbush blueberries, *Vaccinium corymbosum* L., three sprayers and two water spray volumes were compared for spray coverage and control of key insect pests and diseases. For evaluation of coverage in 2007, sprayers applied kaolin clay to bushes and percent surface area of black cards covered by kaolin was analyzed. In 2008, bushes were sprayed with methoxyfenozide and captan, and the material deposited on leaves or fruit was measured with HPLC or MS. In general, coverage varied significantly when an airblast, tower or cannon sprayer was utilized, and significant variation in pest and disease control was observed between water volumes.

KEY WORDS

sprayer; pesticide deposition; blueberry; Integrated Pest Management

Introduction

Blueberries contribute significantly to the agricultural economy of the United States. In 2016, 313 million kilograms of cultivated blueberries (highbush and rabbiteye) worth 748 million US dollars were produced for the fresh and process blueberry markets (National Agricultural Statistics Service (NASS), 2016). Production in Michigan comprised 16% of the US total production, making it a top state for production of highbush blueberries, *Vaccinium corymbosum* L., with 50 million kilograms harvested from over 9,000 hectares, worth a farm gate value of 130 million US dollars (National Agricultural Statistics Service (NASS), 2017).

Commercial production of highbush blueberries in this region relies upon integrated pest management (IPM), including the judicious use of pesticides, to protect the crop from injury by insect pests and diseases (Cline and Schilder, 2005; Isaacs et al., 2005; Wise et al., 2016). Insect pests like Japanese beetle (*Popillia japonica* Newman), cranberry fruitworm (*Acrobasis vaccinii* Riley) and blueberry maggot (*Rhagoletis mendax* Curran) and the fungal fruit disease mummy berry (*Monilinia vaccinii-corymbosi* (J.M. Reade) Honey) are considered contaminant pests, which can jeopardize an entire fruit load at harvest (Polashock et al., 2017; Scherm and Copes, 1999). In addition, anthracnose fruit rot caused by the fungus *Colletotrichum acutatum* J.H. Simmonds, reduces fruit quality and shelf life and may also contribute to high mold counts in frozen berries leading to potential rejection of entire fruit lots by buyers (Miles and Schilder, 2008; Polashock et al., 2017; Sabaratnam et al., 2004). Another important fruit rot disease is Alternaria fruit rot which reduces yield and generally overwinters as mycelium and spores in old dried-up berries and dead peduncles (berry stems) produced the previous year. Other diseases including Phomopsis canker and twig blight (anamorph *Phomopsis vaccinii* Shear; teleomorph *Diaporthe vaccinii* Shear), and insect pests such as tussock moth (*Orgyia*

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leucostigma Smith) can weaken blueberry plants and result in yield losses over time (Polashock et al., 2017; Wise et al., 2016).

Methods of pesticide delivery range from aerial application to an array of ground air-assisted sprayers. Ground sprayers commonly used in the North Central region of the US include the rotary-fan airblast, rotary-fan tower, and cannon mist sprayer designs. Optimizing spray coverage is important for controlling pests and achieving high-quality fruit at harvest (Hanson et al., 2000). The level of coverage is influenced by the type of sprayer and operating parameters, as well as by weather conditions, crop cultivar, growth stage, and plant canopy size and structure (Pergher and Gubiani (1995); VanEe et al., (2000); Hanson et al. (2000), Cross et al., (2001); Mermer et al., 2016). The volume of water diluent to carry the pesticide to the target is one key parameter of sprayer operation that has been shown to affect coverage in some fruit crops (Landers, 2002; Wise et al., 2010). However, relatively less is known about how spray coverage is related to control of key blueberry diseases and insect pests, which may be present at different locations in the plant canopy.

In addition, it is common practice for blueberry growers to plant bushes in tightly spaced rows to maximize yields, but in turn fruit-bearing limbs can hang into drive lanes near harvest time. Because of the risk of knocking off fruit while running sprayers through planted fields, blueberry growers commonly attempt to cover multiple rows of blueberries with a single pass. Thus, there is a need to understand how spray deposition patterns and pest control change with distance from the sprayer. Due to the substantial cost of sprayers, pesticides and labor, and risk of environmental impacts, it is important to optimize spray coverage and efficiency.

To understand the spatial variation in pest control when both sprayer type and water volume are varied, we compared the deposition patterns in blueberries for three sprayers operated at two water volumes. The objectives of this study were to 1) quantify the spray deposition of three common ground sprayers used in blueberry production, 2) compare spatial patterns of performance under two spray volumes, and 3) measure the efficacy of selected pesticides against common blueberry diseases and insect pests when applied with these sprayers.

Materials and Methods

Field Plots

The study was conducted in a 1.2-hectare mature highbush blueberry, *Vaccinium corymbosum* L. (cv. Jersey), planting in Plymouth, IN in 2007 and 2008. The blueberry planting row spacing was 1.2 m within and 3.0 m between rows, rows were oriented in an east-west direction. The average bush height was approximately 2 m, with bushes filling the entire space within rows. The treatment plots were 5 bushes wide by 5 rows deep, or approximately 9.5 square meters. Treatment plots were selected to have representative canopies, and were separated by a 7.2 m minimum buffer (east-west) within rows, and 15 m (north-west) across rows.

Sprayers and Water Volumes Tested

Three sprayer designs were evaluated in 2007 and 2008; an airblast sprayer (Montana Suprema 1584, Bozeman, MT, USA) operated at 1034 kPa (300 psi) with eight Suprema 680 Poly Flipover nozzles per side (H.D. Hudson MFG, Lowell, MI, USA), a tower sprayer (Agtec 400PC VMC, Plymouth, IN, USA) operated at 1034 kPa (300 psi) with eight Mystifyer nozzles (Superb Horticulture, Plymouth, IN, USA) per side, and a cannon mist sprayer (Agtec 400PC Cannon, Plymouth, IN, USA) operated at 1034 kPa (300 psi) with eight Mystifyer nozzles (Superb Horticulture, Plymouth, IN, USA) per side. The three sprayers were calibrated to spray water volumes of 187 and 374 L/ha, at a ground speed of 5.6 km/h. In 2007, there were a total of 30 plots, comprising three sprayers and two water volumes, replicated five times in a randomized complete block design. Untreated samples were randomly collected before sprays were initiated. In 2008, there were a total of 28 plots, comprising three sprayers and two water volumes, replicated four times in a randomized complete block design, with four control plots maintained through the duration of the trial. All applications were made to the north side of the first row in each plot, and sprayers were calibrated for one-sided delivery of product to the entire plot with one pass.

Study

Compare Spatial Performance of Sprayer Type, Water Volume on Control of Japanese Beetle

The efficacy of phosmet (Imidan 70 W, Gowan Corporation, Yuma, AZ, USA) for control of *P. japonica* was compared for the three sprayers and two water volumes spatially across the five-row plots. Phosmet was applied on July 1, 2007 at a rate 1.04 kg [AI]/ha equivalent, as described above, with north winds ranging from 6.4 to 9.7 k/h during the application period. Unsprayed plots served as untreated controls. Blueberry shoots, approximately 30 cm long, were collected from each row of each treatment plot 2 h after the applications, and bioassays were set up according to Wise et al. (2007). Each shoot was pruned to have 10 ripe fruit and ten leaves, and then placed in water-soaked OASIS® floral foam (Smithers-Oasis Co., Kent, OH) in clear polypropylene 950-ml containers (Fabri-Kal, Kalamazoo, MI) with lids. The foam was covered with sealing wax (Gulf Wax, distributed by Royal Oak Sales, Inc, Roswell, GA) to preserve the integrity of the fruit and foliage. Small holes were punched in the lid to reduce condensation of water vapor inside the container. Each of these containers was considered an experimental unit in the bioassays. *P. japonica* adults collected from untreated grass fields at the Michigan State University Trevor Nichols Research Center in Fennville, MI during the prior 24-h period were placed in the bottom of each container (five beetles per container), and were held in the laboratory at approximately 21°C with a 16:8 (L:D) h photoperiod. The numbers of live beetles were recorded after 72 h of exposure for each of five replicates per treatment and used as response variable.

Percent Surface Area Covered by Kaolin

Following the Japanese beetle trial, kaolin clay (Surround® WP, Engelhard Corp., Iselin, New Jersey, USA) was used to measure spray coverage and was applied at 28 kg/ha in all treatments (Wise et al., 2010). Spray coverage was measured on 10 × 13 cm black cards, which were placed within the canopy, facing north on the north side of each bush at approximately 0.6 m (low) and at 1.8 m (high) in the outer surface of the canopy. Cards were placed in three bushes per row per plot before treatment application. Each card was scanned to create a grayscale digital image for analysis with ImageJ (Rasband WS 2019)(Schneider et al., 2012). For each spray card, the percent area covered with kaolin was measured and used for statistical testing.

2008 Study

Pesticide Deposition

Pesticide deposition was measured on June 2, 2008 by applying tank-mixes of methoxyfenozide (Intrepid® 2 F, Dow AgroSciences, Indianapolis, IN, USA) at a label rate of 210 g AI/ha and captan (Captan 50 W, Arysta Lifescience, Tokyo, Japan) at a label rate of 2.8 kg AI/ha with the same sprayer and volume combinations as mentioned above, with north north-westerly winds ranging from 5.2 to 10.3 k/h (the other application parameters were as described above). For pesticide residue analysis, approximately 30 cm long blueberry shoots were collected from the plant canopy (high and low) in all five rows per treatment plot, totaling at least six per plot row. The shoots were held in labeled zip-lock plastic bags and transported to the MSU Pesticide Analytical Laboratory in chilled coolers. A 10-g subsample (approximately 12 leaves) of leaf tissue was removed from each six-shoot sample (per row) and sonicated for 15 s in a 50:50 mix of acetonitrile:dichloromethane. Samples were then ground with a Potter-Elvehjem tissue homogenizer using a PTFE pestle (Wheaton Science Products, Millville, NJ), decanted through 10–25 g of reagent-grade anhydrous sodium sulfate (EMD Chemicals Inc, Gibbstown, NJ) to remove water and collected in a round bottom flask. Samples were then dried via rotary evaporation and 2 ml of acetonitrile (solvent) was added. Samples were passed through a 0.45 µm Acrodisc 13 mm syringe filter (Pall, East Hills, NY) to remove any particulates from the sample and were placed in 2.5-ml gas chromatography vial for high-performance liquid chromatography (HPLC) analysis. They were analyzed using a Water 2695 separator module High-performance Liquid Chromatograph (HPLC) equipped with a Water ZQ Mass Spectrometer. The column was a C18 reversed phase column with 3.0-mm bore and 50-mm column. The mass spectrometer monitored for methoxyfenozide ions 91 and 149 m/z and for captan ions 79 and 264 m/z. The mobile phase was 90:10 water:acetonitrile with 0.01% formic acid initially and changed to 70:30 water: acetonitrile with 0.01% formic acid between 12 and 13 min. The column was held at 35°C throughout the run. The resulting data were presented as concentration, as parts per million (ppm), of parent methoxyfenozide and captan residues for each treatment plot location.

Insect Control

To determine the influence of sprayer type and water volume on insecticide performance, field evaluations and insect bioassays were conducted spatially across the five-row plots after methoxyfenozide was applied in all sprayer-volume combinations.Unsprayed plots served as untreated controls.

Field assessments were used to measure insecticide performance for the control of *A. vaccinii*, by randomly sampling 25 fruit clusters within the fruiting zone (approximately 1.8 m high) for fruit infestation in each treatment row. Cluster infestation was positively identified by the presence of one or more larvae per cluster. Number of infested clusters out of 25 was used for statistical analysis.

Bioassays were used to measure insecticide performance for the control of *O. leucostigma* by randomly collecting six to eight blueberry shoots from both low (approximately 0.6 m) and high (approximately 1.8 m) locations in the bushes from each row in each treatment plot. Samples were placed into labeled zip-lock bags and transported in chilled coolers to the MSU laboratory. Shoots were refrigerated overnight until bioassays were initiated. Bioassays were conducted using clear polypropylene 950-ml containers, as described above, and two to three trimmed treated shoots from the field were placed in each chamber. Five first-to-second instar *O. leucostigma* larvae, hatched from recently field-collected egg masses, were added to each chamber. Larval mortality was measured after 7 days. Due to limited larva availability, bioassay chambers for only replicates 1 and 2 (all 5 rows) were loaded and assessed for each treatment. Count of larva found alive after 7 days was used as a response variable.

Control of Fungal Diseases

To determine the influence of sprayer type and water volume on fungicide performance, field evaluations and laboratory assays were conducted spatially across the five-row plots after captan was applied in all sprayer-volume combinations.

Laboratory incubation assessments were made of infection incidence of green and ripe fruit by fungal fruit rot pathogens in rows 1 to 5, at increasing distance from the point of sprayer applications. Unsprayed plots served as untreated controls. On June 24, 2008, 10 green berries from each row of each plot were surface-sterilized for 2 min using a 1:4 dilution of bleach (6.15% sodium hypochlorite [NaClO]). Before cutting the berries in half with a sterile blade, they were washed three times with sterile-distilled water to remove NaClO residues. Half-berries (cut longitudinally) were plated separately with the cut surface down on Petri dishes (VWR International, Radnor, PA) containing 20 ml of ¼-strength potato dextrose agar (PDA) and were incubated at 22–23°C. The presence or absence of fungal growth (*Alternaria* spp., *Botrytis* spp., *Colletotrichum* spp., *Pestalotia* spp. and *Phomopsis* spp. as well as total saprophytic fungi) out of the fruit tissue was visually assessed at days 5 and 9 (total incidence summer across both assessment days) and fungi were identified based on culture appearance and morphology of the spores and spore-bearing structures. In addition, on July 29, 2008, 50 non-sterilized ripe berries per sample were placed on metal screens in a humid chamber for approximately 10–14 days at room temperature to allow fungal emergence and sporulation from the fruit tissue. Berries were rated for evidence of sporulation (*Alternaria* spp., *Botrytis* spp., *Colletotrichum* spp., *Pestalotia* spp. and *Phomopsis* spp. as well as total saprophytic fungi) to determine infection incidence.

Statistical Analysis

Statistical software SAS 9.3 (SAS Institute Inc., Cary, NC, USA) was used in testing the entire data sets from 2007 to 2008.

2007 Study

Number of *P. japonica*, found live after 72 h on highbush blueberry fruit clusters across 5 rows, treated with phosmet was subjected to logarithmic transformation and tested using three-way ANOVA in the PROC MIXED procedure.

Data set kaolin deposition in highbush blueberry crop canopies, expressed as percentage on surface of black cards across five rows was logarithmically transformed and analyzed using four-was ANOVA with PROC MIXED statement.

2008 Study

Data sets captan (ppm) and methoxyfenozide (ppm) deposition were found to follow normal distribution and then tested in four-way ANOVA using the REPEATED statement function in PROC MIXED.

Number of *A. vaccinii* infested fruit clusters and number of live *O. leucostigma* larva were analyzed using the REPEATED statement function in PROC MIXED as three-way ANOVA. Distribution of residuals in data set number of live *O. leucostigma* larvae was found to significantly diverge from the normal distribution and thus square root transformed.

Count of fungal colonies on green berries and incidence of *Alternaria* sp. on green and ripe fruit were analyzed using three-way ANOVA. Data sets were analyzed using the REPEATED statement function in PROC MIXED and all-pairwise comparisons were conducted using Tukey's HSD at $\alpha = 0.05$.

Results

2007 Study

The percentage of the card surface covered by kaolin was significantly affected by sprayer and row (Table 1). The two-way interactions sprayer × bush, sprayer × row and row × bush, as well as three-way interaction sprayer × volume × row were significant at $\alpha = 0.05$. The best coverage was provided by the Airblast sprayer in row 1, especially low in the bush, while the Cannon sprayer had the best performance in rows 2 to 5. In relation to location on bush, lower portions of the bush were better covered in row 1, while the upper parts of bushes were better covered in rows 3 to 5.

In the bioassay, where blueberry shoots treated with phosmet were used for testing mortality of *P. japonica*, significant effects of volume, row, and the interaction of sprayer × row were found (Table 2). Use of the Airblast sprayer resulted in highest mortality in row 1, whereas the Cannon and Tower sprayers showed superior performance in row 3. The higher water volume, 374 L/ha, was more effective in the control of *P. japonica* in rows 2 to 4.

2008 Study

Insect Control and Insecticide Residues

Residues of methoxyfenozide were affected by sprayer and row and their interaction (sprayer × row) was significant (Table 3). The highest residue levels were observed with the Cannon sprayer

Table 1. Effect of sprayer, water volume and height in bush on kaolin deposition in highbush blueberry crop canopies, measured as percentage on surface of black cards across five rows in 2007.

Source of variation	Row				
Sprayer	1	2	3	4	5
Airblast	53.68a	0.66 c	0.08 c	0.01b	0.00 c
Cannon	33.10b	13.27a	7.21a	3.32a	0.92a
Tower	15.50 c	2.32b	0.41b	0.03b	0.00b
Volume (L/ha)					
187	30.64a	6.55a	2.31a	1.26a	0.11a
374	37.55a	4.28b	2.82a	0.98a	0.50a
Height in Bush					
High	24.03b	6.92a	4.58a	2.08a	0.56a
Low	44.16a	3.90a	0.55b	0.15b	0.05a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	<.0001	<.0001	<.0001	<.0001	0.0419
Volume	0.3541	0.0293	0.1425	0.5958	0.6483
Height in Bush	0.0002	0.8087	0.0017	0.0194	0.2605
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		<0.0001			
Volume		0.0624			
Sprayer*Volume		0.4878			
Height		0.2204			
Sprayer* Height		<0.0001			
Volume* Height		0.5289			
Sprayer*Volume* Height		0.9884			
Row		<0.0001			
Sprayer*Row		<0.0001			
Volume*Row		0.4351			
Sprayer*Volume*Row		0.018			
Row* Height		<0.0001			
Sprayer*Row* Height		0.1097			
Volume*Row* Height		0.7014			
Spray*Volume*Row* Height		0.9745			

Mean values were based on five replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

in rows 2 to 5, whereas the two other sprayers showed higher deposition in row one. Treatments with 374 L/ha of water provided better methoxyfenozide deposition in rows 1 and 4. Also, greater levels of methoxyfenozide deposition were found in the lower canopy of blueberries in row 3. Sprayer and row had significant effects on the number of *A. vaccinii* infestations of blueberry fruit clusters (Table 4). The Cannon sprayer showed superior performance in row 3 over the other two types of sprayers. There was no effect of water volume on control of *A. vaccinii*.

All three types of sprayers were highly effective for *O. leucostigma* control in the first two rows resulting in mean values of zero; therefore, only rows 3 to 5 were taken into further consideration for statistical analysis (Table 5). Three-way (treatment × row × bush) and two-way (treatment × row) interactions were significant and all three main factors affected the number of live *O. leucostigma* larvae. Across the rows, the lowest survival of *O. leucostigma* was observed when the Cannon sprayer was used at 187 L/ha of water, suggesting high sensitivity to methoxyfenozide, even with small droplets and far distances. Also, higher water volumes improved performance of the Airblast sprayer at the furthest distance from the point of application. Lastly, the shoots collected from the upper canopy generally showed higher survival of *O. leucostigma* larvae in the bioassays.

Disease Control and Fungicide Residues

The deposition pattern of captan residues was affected by the type of sprayer, volume of water, row and the interactions sprayer × row, volume × row, and sprayer × volume × row (Table 6).

Table 2. Effect of sprayer and water volume on the number of Japanese beetles, *P. japonica*, found alive out of 5 after 72 h on highbush blueberry fruit clusters across five rows, treated with phosmet in 2007.

Source of variation	Row				
Sprayer	1	2	3	4	5
Airblast	0.00a	1.10a	3.96a	3.90a	4.55a
Cannon	0.40a	0.30a	1.58b	3.13a	3.10a
Tower	0.10a	0.00a	1.48b	4.29a	4.00a
Volume (L/ha)					
187	0.27a	0.93a	3.35a	4.62a	4.50a
374	0.07a	0.00b	1.32b	2.93b	3.27a
*Interaction (Sprayer*Volume)*					
Airblast187	0.00a	2.20a	4.91a	5.00	4.91a
Airblast374	0.00a	0.00b	3.00ab	2.80	4.20a
Cannon187	0.60a	0.60ab	2.75ab	4.05	3.80a
Cannon374	0.20a	0.00b	0.40b	2.20	2.40a
Tower187	0.20a	0.00b	2.40ab	4.80	4.80a
Tower374	0.00a	0.00b	0.56b	3.78	3.20a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.3343	0.1094	0.0231	0.7217	0.2505
Volume	0.4525	0.0136	0.0148	0.0253	0.0578
Sprayer*Volume	0.671	0.0195	0.0232	0.2454	0.1851
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		0.1638			
Volume		0.0016			
Sprayer*Volume		0.8564			
Row		<0.0001			
Sprayer*Row		0.0142			
Volume*Row		0.1898			
Sprayer*Volume*Row		0.5072			

Mean values were based on five replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

The highest deposition of captan in row 1 was found with the Tower sprayer, with similar levels from the Airblast sprayer. However, Cannon left higher captan residues in rows 3 to 5. The Airblast and Tower sprayers showed generally declining captan residues with distance from the application point, whereas the Cannon sprayer showed a comparatively uniform deposition pattern across the 5 rows. Significant differences caused by volume of water were found in rows 1 and 4, where 374 L/ha resulted in higher captan deposition. Captan residues were also greater in the lower parts of bush canopies in rows 3 to 5.

Overall rot incidence on green and ripe fruit was primarily affected by the row (*P*-values for Type 3 Tests of Fixed Effects are <0.0001 and 0.0039, respectively)(data not shown). The incidence of *Alternaria sp*. (%) on green fruit in 2008 was significantly influenced by row and the interaction of sprayer × row (Table 7). While all sprayers demonstrated similarly good control across rows 1 to 3, the Cannon sprayer showed significantly better performance in row 4, and the Airblast sprayer in row 5.

A significant reduction of *Alternaria* infection of green fruit was achieved with a higher water volume, 374 L/ha, in row 3. Row location also influenced the incidence of *Alternaria* on ripe fruit. Higher water volume similarly improved *Alternaria* control in ripe fruit, with significantly lower incidence in row 1 with 374 L/ha (Table 8). There were no significant differences in the incidence of *Pestalotia* sp. and *Phomopsis vaccinii* on green and ripe fruit nor in the incidence of *Botrytis cinerea* and *C. acutatum* on ripe fruit in 2008 (data not shown).

Sprayer, row, and the interaction sprayer × row had an impact on the total number of fungal colonies recovered from green fruit in 2008 (Table 9). Fewer colonies developed after using the Airblast sprayer in row 2 and Cannon sprayer in row 4. Also, a higher water volume, 374 L/ha, reduced the total number of colonies in row 3.

Table 3. Effect of sprayer, water volume and height in highbush blueberry bushes on methoxyfenozide (ppm) deposition across five rows in 2008.

Source of variation	Row				
Sprayer	1	2	3	4	5
Airblast	25.6a	14.6b	5.2b	2.0b	1.4b
Cannon	16.7b	31.4a	24.0a	16.9a	6.3a
Tower	29.5a	30.3ab	5.9b	1.6b	0.8b
Volume (L/ha)					
187	21.3b	27.4a	10.9a	5.8b	2.8a
374	26.6a	23.5a	12.5a	7.9a	2.9a
Height in Bush					
High	23.2a	25.9a	10.0b	5.7a	3.0a
Low	24.7a	24.9a	13.4a	7.9a	2.7a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.0028	0.0004	<.0001	<.0001	<.0001
Volume	0.0447	0.6939	0.2969	0.0254	0.5062
Bush	0.5683	0.9933	0.0165	0.3634	0.6751
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		<0.0001			
Volume		0.0781			
Sprayer*Volume		0.4199			
Height		0.2254			
Sprayer* Height		0.282			
Volume* Height		0.6748			
Sprayer*Volume* Height		0.8749			
Row		<0.0001			
Sprayer*Row		<0.0001			
Volume*Row		0.332			
Sprayer*Volume*Row		0.8529			
Row* Height		0.2116			
Sprayer*Row* Height		0.5298			
Volume*Row* Height		0.7946			
Spray*Volume*Row* Height		0.8389			

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

Discussion

This study demonstrates the influence of sprayer type and water volume on the spatial deposition and pesticide performance of pesticides used to manage blueberry diseases and insect pests. In general, the Airblast and Tower sprayers performed best against diseases and insect pests on rows nearest to the point of application (row 1), whereas the Cannon sprayer performed best in mid-distances (rows 2 to 4). Higher water volume generally improved deposition and performance, especially with greater distances from the application point. The exception was with the Cannon sprayer, for which lower water volume was generally sufficient to achieve optimum performance. The Cannon sprayer was able to cover > 10% with spray residue on black cards, other studies have noted that optimal coverage is typically between 10 and 20% (Holland et al., 2014).

A closer examination of sprayer performance across the spectrum of target insect pests we tested reveals some distinctive patterns. The *P. japonica* data indicate that as distance from the application point increases, and surface area coverage diminishes, the higher water volumes provide better control. This makes sense for a highly mobile adult-stage coleopteran pest, which

Table 4. Effect of sprayer and water volume on number of cranberry fruitworm, *A. vaccinii*, infested highbush blueberry fruit clusters out of 25, across 5 rows, treated with methoxyfenozide in 2008.

Source of variation	Row				
Sprayer	1	2	3	4	5
Airblast	1.38a	1.63a	2.50a	2.88a	3.00a
Cannon	0.88a	1.25a	0.50 c	2.00a	2.75a
Tower	1.25a	1.50a	2.38ab	1.88a	3.75a
Volume (L/ha)					
187	1.17a	1.25a	1.83a	2.00a	3.25a
374	1.17a	1.67a	1.75a	2.50a	3.08a
*Interaction (Sprayer*Volume)*					
Airblast187	1.50a	0.75a	1.75abc	2.50a	3.00a
Airblast374	1.25a	2.50a	3.25ab	3.25a	3.00a
Cannon187	1.00a	1.25a	0.25 c	1.50a	3.00a
Cannon374	0.75a	1.25a	0.75bc	2.50a	2.50a
Tower187	1.00a	1.75a	3.50a	2.00a	3.75a
Tower374	1.50a	1.25a	1.25abc	1.75a	3.75a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.6833	0.8154	0.0019	0.2964	0.3249
Volume	1	0.4495	0.8796	0.3646	0.7619
Sprayer*Volume	0.949	0.6044	0.0029	0.4316	0.7395
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		0.0275			
Volume		0.6366			
Sprayer*Volume		0.2839			
Row		<0.0001			
Sprayer*Row		0.1759			
Volume*Row		0.7934			
Sprayer*Volume*Row		0.4902			

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

is more likely to eventually encounter the poison. In contrast, the target life-stage of the other two insect pests (*A. vaccinii* and *O. leucostigma*) being lepidopteran eggs and larvae, are more dependent on coverage to insure lethal exposure to the insecticide. Similar results were documented by Wise et al. (2010) for the Airblast sprayer, where higher water volumes resulted in better control of grape berry moth, *Paralobesia viteana* (Clemens), in grapes. This is supported by the significant negative correlations between methoxyfenozide residues and *O. leucostigma* survival in bioassays. The methoxyfenozide residue data for the Airblast and Tower sprayers, however, showed poor uniformity across the five rows, compared to the Cannon sprayer. The fact that control of *O. leucostigma* larvae was relatively good for all sprayers across all rows indicates that product may have been over-applied to rows 1 to 2 by the Airblast and Tower sprayers.

The disease control results indicate that the Airblast and Tower sprayers perform best in the rows nearest the point of application, whereas the Cannon sprayer effectively reaches further out across the rows. Although Airblast and Tower sprayers showed significant correlations between captan residues and disease incidence, the Cannon sprayer provided a more uniform distribution across the plot rows. This again suggests product deposition inefficiencies for Airblast and Tower sprayers in those further rows. The influence of water volume on blueberry disease control in this study was similar to that seen in Wise et al. (2010) in grapes, where higher water volumes improved fungicide performance against foliar powdery mildew and *Phomopsis* fruit infections. In general, *Alternaria* fruit rot was the most common in this study in both green and ripe fruit (incidence ranged between ~10 and 40%) and fruit rot control on green fruit was more effective than on ripe fruit. This difference may be due to the length of time between the single fungicide application and date of harvest of the fruit. Captan is a protectant fungicide, which can be washed off by rain (Xu et al., 2008). A single fungicide

Table 5. Number of live tussock moth, *O. leucostigma*, larvae out of five in bioassays after 7 days on highbush blueberry shoots collected from field plots treated with methoxyfenozide in 2008.

Source of variation	Row		
Treatment	3	4	5
Airblast187	0.13b	1.50b	2.00b
Airblast374	0.13b	1.25b	4.24a
Cannon187	0.00b	0.00b	1.38 c
Tower187	1.88a	3.88a	2.75ab
Tower374	0.75b	1.00ab	2.88ab
Height in Bush			
High	0.75a	1.85a	3.15a
Low	0.40a	1.20b	2.15b
*Interaction (Treatment*Bush)*			
Airblast187*High	0.25ab	2.25ab	3.50abc
Airblast187*Low	0.00b	0.75bc	0.50d
Airblast374*High	0.25ab	2.50ab	3.50abc
Airblast374*Low	0.00b	0.00 c	4.98a
Cannon187*High	0.00b	0.00 c	1.75bcd
Cannon187*Low	0.00b	0.00 c	1.00 cd
Tower187*High	1.75ab	4.25a	3.25abc
Tower187*Low	2.00a	3.50a	2.25abcd
Tower374*High	1.50ab	0.25 c	3.75ab
Tower374*Low	0.00b	1.75abc	2.00abcd
F Test for Least Squares Means Slice (*P*-value)			
Treatment	<.0001	<.0001	<.0001
Height in Bush	0.1829	0.0214	0.0114
Treatment * Height	<.0001	<.0001	<.0001
Type 3 Tests of Fixed Effects (*P*-value)			
Treatment	<0.0001		
Height	0.0011		
Treatment * Height	0.0616		
Row	<0.0001		
Treatment *Row	0.0003		
Row* Height	0.6359		
Treatment *Row* Height	0.0005		

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

* note that data from Rows 1 and 2 were "zero values" for all treatments, thus only rows 3–5 were analyzed and displayed. Cannon347 data were excluded from analysis because of all "zero values" across 5 rows.

application was aimed at a critical time for infection to make the correlation between spray coverage and disease less challenging to assess. However, it is quite uncommon in the Midwest to use a single fungicide application to manage fruit rots in blueberries. Favorable environmental conditions for multiple secondary infection events occur normally all the way until harvest for pathogens like *C. acutatum*, which may also explain these differences (Miles et al., 2013).

For efficiency and to reduce loss of harvestable fruit, blueberry growers often try to cover multiple rows of bushes with one pass of the sprayer. The results of this study provide important insights into the factors that should be considered to ensure optimal disease and insect pest control. Clearly the deposition limitations of each type of sprayer should guide the spatial dimensions of pest control attempted with each pass. For some sprayers, like the Tower and Airblast sprayers, optimal plant protection is limited to two rows, while increasing water volume may extend the effective reach of the sprayer. A Cannon sprayer can be expected to provide uniform coverage for up to four or five rows, with disease and insect pest control best in the upper canopy. The nature of pesticide and pest are also factors to consider, where insect mobility and the inherent sensitivity of the target organisms to the toxicant can impede or expand the area that can be protected with a given spray application event.

Table 6. Effect of sprayer, row and water volume on captan (ppm) deposition in highbush blueberry crop canopies in 2008.

Source of variation	Row				
Sprayer	1	2	3	4	5
Airblast	2254.6ab	1471.5a	417.1b	126.0b	12.6b
Cannon	1177.0b	3553.8a	3538.5a	1700.6a	261.8a
Tower	3599.3a	2487.3a	254.8b	70.5b	27.6b
Volume					
187	1739.4b	2549.1a	1741.0a	295.9b	90.9a
374	2947.8a	2459.3a	1066.0a	968.9a	110.5a
Height in Bush					
High	2519.6a	2573.3a	1118.5b	358.0b	65.0b
Low	2167.6a	2435.1a	1688.4a	906.7a	136.4a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.0426	0.1789	<.0001	<.0001	<.0001
Volume	0.0455	0.8994	0.1662	0.0001	0.3446
Height	0.7155	0.4225	0.0309	0.044	0.0436
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer	<0.0001				
Volume	0.0138				
Sprayer*Volume	0.4589				
Height	0.2861				
Sprayer* Height	0.3297				
Volume* Height	0.6078				
Sprayer*Volume* Height	0.5977				
Row	<0.0001				
Sprayer*Row	<0.0001				
Volume*Row	0.0147				
Sprayer*Volume*Row	0.0113				
Row* Height	0.2047				
Sprayer*Row* Height	0.245				
Volume*Row* Height	0.0853				
Spray*Volume*Row* Height	0.4324				

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

Table 7. Effect of sprayer, row and water volume on incidence of *Alternaria* (%) on green highbush blueberry fruit treated with captan in 2008.

Source of variation	Row				
Sprayer	1	2	3	4	5
Airblast	8.7a	7.5a	23.7a	45.0a	25.0b
Cannon	10.0a	20.0a	25.0a	18.7b	41.2a
Tower	8.7a	16.2a	22.5a	40.0a	40.0a
Volume (L/ha)					
187	10.8a	16.7a	29.2a	37.5a	35.8a
374	7.5a	12.5a	18.3b	31.7a	35.0a
*Interaction (Sprayer*Volume)*					
Airblast187	15.0a	7.5a	37.5a	50.0a	25.0a
Airblast374	2.5a	7.5a	10.0b	40.0ab	25.0a
Cannon187	12.5a	22.5a	27.5ab	17.5b	45.0a
Cannon374	7.5a	17.5a	22.5ab	20.0b	37.5a
Tower187	5.0a	20.0a	22.5ab	45.0a	37.5a
Tower374	12.5a	12.5a	22.5ab	35.0ab	42.5a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.9713	0.1072	0.9163	<.0001	0.0135
Volume	0.4966	0.3959	0.0296	0.2358	0.8648
Sprayer*Volume	0.6422	0.3426	0.0613	0.0006	0.0806
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		0.6478			
Volume		0.1265			
Sprayer*Volume		0.5009			
Row		<0.0001			
Sprayer*Row		<0.0001			
Volume*Row		0.5351			
Sprayer*Volume*Row		0.1696			

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

Table 8. Effect of sprayer, row and water volume on incidence of *Alternaria* (%) on ripe highbush blueberry fruit, treated with captan in 2008.

Source of variation	*Row*				
Sprayer	1	2	3	4	5
Airblast	19.0a	21.8a	16.8a	33.3a	38.5a
Cannon	24.5a	31.7a	16.2a	26.5a	38.1a
Tower	23.0a	23.3a	24.0a	28.0a	30.5a
Volume					
187	26.2a	22.3a	22.2a	33.3a	38.3a
374	18.2b	28.9a	15.8a	25.2a	33.1a
*Interaction (Sprayer*Volume)*					
Airblast187	18.5a	16.1a	17.1a	36.0a	44.5a
Airblast374	19.5a	27.6a	16.5a	30.5a	32.6a
Cannon187	34.5a	31.6a	23.3a	37.5a	46.0a
Cannon374	14.5a	31.9a	9.2a	15.5a	30.2a
Tower187	25.5a	19.3a	26.3a	26.5a	24.5a
Tower374	20.5a	27.2a	21.7a	29.5a	36.5a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.4998	0.1921	0.5571	0.6705	0.5936
Volume	0.0526	0.168	0.332	0.2189	0.4701
Sprayer*Volume	0.0988	0.2919	0.704	0.4387	0.4898
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		0.8852			
Volume		0.1867			
Sprayer*Volume		0.0935			
Row		0.0085			
Sprayer*Row		0.5657			
Volume*Row		0.1097			
Sprayer*Volume*Row		0.8811			

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

Table 9. Effect of sprayer, row and water volume on total number of fungal colonies on green highbush blueberry fruit, treated with captan in 2008.

Source of variation	*Row*				
Sprayer	1	2	3	4	5
Airblast	2.8a	2.4b	10.3a	12.3a	11.5a
Cannon	4.0a	5.1ab	7.9a	5.3b	11.5a
Tower	4.4a	6.8a	8.4a	11.8ab	13.4a
Volume					
187	3.5a	5.3a	10.0a	10.6a	11.7a
374	3.9a	4.2a	7.7b	8.9a	12.6a
*Interaction (Sprayer*Volume)*					
Airblast187	3.8a	3.0ab	11.5a	12.5a	10.5a
Airblast374	1.8a	1.8b	9.0ab	12.0a	12.5a
Cannon187	3.3a	5.0ab	9.8ab	6.5bc	12.5a
Cannon374	4.8a	5.3ab	6.0b	4.0 c	10.5a
Tower187	3.5a	8.0a	8.8ab	12.8a	12.0a
Tower374	5.3a	5.5ab	8.0ab	10.8ab	14.8a
F Test for Least Squares Means Slice (*P*-value)					
Sprayer	0.3766	0.002	0.1239	<.0001	0.208
Volume	0.6745	0.2412	0.0205	0.0954	0.3564
Sprayer*Volume	0.405	0.0104	0.0534	<.0001	0.1427
Type 3 Tests of Fixed Effects (*P*-value)					
Sprayer		0.0045			
Volume		0.1138			
Sprayer*Volume		0.5997			
Row		<0.0001			
Sprayer*Row		<0.0001			
Volume*Row		0.1033			
Sprayer*Volume*Row		0.2767			

Mean values were based on four replicates. Means within the column followed by the same letter are not significantly different by Tukey's honest significant difference test, at $P < 0.05$.

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