Can a LiDAR-enhanced Air-blast Sprayer Improve Coverage on Tough Targets like Tree Trunks and Emerging Shoots?

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ABSTRACT. Eastern filbert blight (EFB) and pacific flatheaded borer (PFB) are two problems of Pacific Northwest orchard and nursery production. Fungicides and insecticides used to manage these issues are typically applied to plant tissues with minimal foliage present that can result in considerable spray waste or drift. The Intelligent Spray System (ISS) is a laser-guided, variable-rate sprayer that detects objects in the target zone and releases spray volumes proportional to the density of plant tissues, thereby increasing application efficiency and reducing waste. However, the ISS has not been tested when targeting low-foliage plant tissues such as emerging shoots and trunks. Three experiments were conducted from 2018 to 2021 to evaluate the potential use of the ISS for EFB and PFB management by assessing spray coverage on emerging hazelnut shoot tips, hazelnut tree trunks, and maple tree trunks. On hazelnut shoot tips, coverage was <10% of the shoot on both adaxial and abaxial sides, with the highest coverage on the adaxial side (9.5%) resulting from spraying in standard mode (no sensors) at 3.1 kph. On hazelnut trunks, application at the slowest tested speed (3.1 kph) in intelligent mode resulted in spray coverage greater than or equal to that applied in standard mode at 5.1 kph. In addition, coverage was significantly higher on cards placed on the ground between trees when the sprayer was used in standard mode, indicating higher amounts of wasted spray and drift over intelligent mode. On maple trunks, the slowest speed tested (3.1 kph) resulted in the highest coverage of tree trunks facing the sprayer that were two and three rows away from the sprayer, with the highest coverage levels on the row of trees closest to the sprayer occurring at the highest tested speed of 6.4 kph. On cards placed on trunk sides not facing the sprayer, the slowest tested speed of 3.2 kph resulted in significantly higher coverage than both treatments at 6.4 kph and intelligent mode at 4.8 kph in the tree row closest to the sprayer. This work has demonstrated a baseline of coverage that hazelnut buds receive when spraying for EFB, illustrates that the ISS was able to effectively target trunks, and could be an alternative to drenches for PFB control.

Air blast sprayers are the most common sprayer type used for specialty crops around the world (Fox et al. 2008; Warneke et al. 2020) but are not known for their efficiency, with spray losses as ground deposits or drift commonly amounting to 20% to 50% of total applied volume (Jensen and Olesen 2014). Despite their inefficient characteristics, the flexibility of air blast sprayers to fit down a variety of row sizes and spray a wide range of plant sizes, makes them relevant today even though their design has not changed much since the 1950s (Fox et al. 2008). An air blast sprayer functions by using high-velocity, spray-laden, turbulent air to displace the stagnant air in plant canopies. The turbulence in the air rotates plant leaves and improves spray penetration and coverage into irregular shaped structures compared with laminar flow air. Air blast sprayers are commonly used for spraying crops with high-density foliage such as fruit trees and vines; however, they are also used in so-called delayed dormant applications when there is little to no foliage present on trees (Giles et al. 2011; Warneke et al. 2019, 2020). In addition, air blast sprayers are also used in nurseries and young orchards, where the target of the spray is a slender trunk-like object with minimal canopy (Chen et al. 2019; Fessler et al. 2021; Nackley et al. 2021). These low-foliage applications are necessary to maintain tree health but have a high likelihood of large amounts of pesticide waste. EFB (*Anisogramma anomala* Peck) and PFB (*Chrysobothris mali* Horn) are two important horticultural pests in the Willamette Valley of Oregon that require low-foliage applications.

EFB is a longstanding issue in Pacific Northwest (PNW) hazelnut production regions, first discovered in southern Washington in 1973, and in the northern Willamette Valley in 1986 (Johnson et al. 1996). EFB has a 2-year life cycle, where infection happens in the spring of year 1 when ascospores from overwintering stromata infect emerging apical shoot tips (Johnson et al. 1996). After filbert blight infection has occurred, *A. anomala* colonizes the phloem, cambium, and the outermost layer of xylem; however, visual symptoms of the disease in the form of sunken cankers with stromata are not visible until the spring of year 2 (Johnson et al. 1996). EFB is managed with regular applications of fungicides starting at budbreak and continuing for ≈8 weeks (Pscheidt et al. 2018). In late 2023, orchards planted with EFB-resistant cultivars were found to be infected with a new strain of EFB (Perkowski 2024). This emerging concern has renewed the importance of spraying fungicides for EFB management among all age classes of orchards, even in those with EFB-resistant cultivars. Most hazelnut growers use air blast sprayers for these applications, and recommended application volumes of 100 to 200-gal/acre (935 to 1870 L/ha) are standard to ensure good coverage on susceptible emerging tissue (Wiman et al. 2023). EFB applications begin when there is little to no foliage on the trees and finish before the canopy is fully developed, and as such, there can be substantial pesticide waste due to drift and blow through.

PFB (*C. mali* Horn) is another emerging issue in PNW nursery and orchard production, especially Oregon's Willamette Valley (Wiman et al. 2019). In the Willamette Valley, the threat from PFB is in part due to a shift from large acreages devoted to forage and grass seed crops to large plantings of higher value hazelnuts. As of 2023, more than half of the total ∼90,000 acres of hazelnut orchards are trees that are less than 10 years old (Wiman et al. 2019). Young trees are the most susceptible to severe damage from PFB, as larvae tunneling can more easily girdle and kill them (Addesso et al. 2020). As the acreage of hazelnuts has expanded, orchards have been planted in areas where there are alternate hosts for PFB, and losses of up to 35% of planted trees have been observed (Wiman et al. 2019). Many newly planted hazelnut orchards are in areas that are suboptimal for hazelnut tree growth, with problems such as excessive water retention, or limited access to irrigation water (Pscheidt and Ocamb 2021; Wiman et al. 2019). These factors can lead to plant stress among newly planted orchard trees, which is attractive to PFB and other buprestid borers (Crook et al. 2008). Although PFB attacks can be devastating, infestations are typically sporadic both in time and space (Wiman et al. 2019). Because of these uncertainties, drench application of systemic insecticides has been singled out as the most effective pesticide application tactic, as the effects of a single systemic insecticide application can be active for up to 4 years, depending on the product used (Oliver et al. 2010). However, applications of systemic insecticides are expensive compared with trunk sprays, which are comparable to the efficacy of systemic insecticides in a single year (Oliver et al. 2010). However, using conventional air blast sprayers to apply to young orchards with large gaps between trees leads to excessive pesticide waste. Using sensor-controlled sprayers to only apply pesticide when a tree is directly in line with the sprayer nozzles has the potential to save large quantities of pesticide in young orchards when applying PFB targeted sprays.

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The ISS is a sensor sprayer retrofit kit that can be fitted on almost any standard air blast sprayer (Warneke et al. 2022). The ISS consists of a LiDAR sensor, GPS sensor, pulse width modulation valves at each nozzle, and a graphical user interface (Shen et al. 2017). The ISS goes beyond standard on/off sensor sprayers that only turn nozzles fully on or off depending on object presence or absence, to being fully variable rate, whereby the sprayer modulates output volume in real time based on the canopy density (Warneke et al. 2019). The ISS has been demonstrated to be as effective as a standard air blast sprayer on a wide variety of pests and diseases across a range of crops, with reductions in spray volume used ranging from ∼30% to 70% (Chen et al. 2019, 2020; Nackley et al. 2021; Warneke et al. 2022). Most of the studies evaluating spray application volume savings have occurred at application timings when the spray target was plant foliage and fruit. However, the ISS has had limited testing for viability in targeting plant structures that have little foliage, such as to tree trunks or apical shoot tips. The goal of the research presented here was to evaluate the feasibility of using the ISS to spray hazelnut shoot tips and hazelnut and maple tree trunks.

Materials and methods

Shoot tip coverage

Hazelnut experiments used a 50-gallon air blast sprayer (Pak-blast Rears Mfg., Coburg, OR, USA) retrofitted with the ISS and operated using a tractor (M5N-111; Kubota Tractor Corp., Grapevine, TX, USA). The spray volume between the different speeds used was kept consistent at 100 GPA (935 L/ha) using nozzles and spray pressure, which meant that as the application driving speed increased, so too did the application volume rate. This change in flow rate was large enough to require different sets of hollow-cone nozzles for each spraying speed (Table 1). The spray coverage trial was conducted on 25 Apr 2019 in an orchard of 5-year-old Jefferson hazelnut trees in Corvallis, OR, USA (lat. 44.568, long. −123.243). Trees in the orchard were planted at "double density," with 10-ft (3-m) spacing within rows and 20-ft (6.1-m) spacing between rows and at this growth stage there was a gap of ∼4 to 5 ft (1.2–1.5 m) between the canopies of adjacent in-row trees. Plots consisted of single trees separated from adjacent plots by at least one nontreated tree, with a total of 24 plots. Surround WP (Kaolin clay) was used to visualize the spray applied to the trees and was mixed in the spray tank at the rate of 0.5 lb Surround/1 gallon (227 g/3.8 L) water.

On each tree two water-sensitive cards were placed near the center of the canopy, one facing east, and one facing west. Shoots were sampled from three areas of the sprayed trees, the leading edge of the canopy, midcanopy, and the lagging edge of the canopy based on the travel direction of the sprayer. The leading edge of the canopy was where the sprayer first passed as it traveled down the row, the midcanopy was roughly in line with the trunk perpendicular to the hazelnut row, and the lagging edge was where the sprayer last passed the tree as it traveled down the row. After allowing 30 min of drying time, water-sensitive cards were collected, and shoot tips were sampled by clipping several small lateral branches 5 ft (1.5 m) off the ground that contained at least three tips total at a similar growth stage from within each zone. Sampled branches and shoots were placed into plastic bags then into Styrofoam coolers, and finally a refrigerator. In this experiment and hereafter, after allowing time to dry, water-sensitive cards were collected and placed into paper envelopes and subsequently scanned and analyzed for percent coverage and droplet density using DepositScan (Zhu et al. 2011).

Once in the laboratory, three shoot tips of similar growth stage (BBCH 13, Taghavi et al. 2022) per sampling zone were removed from the small branches using forceps, for a total of 216 excised shoot tips. Excised shoot tips were placed in a custom light box designed for taking photos of plant samples that used four 565-lumen halogen light bulbs. Tree shoot tips were photographed (Canon Powershot A2500; Canon Inc., Ota-ku, Tokyo, Japan) by taking a photo of one side of the shoot, then flipping the shoot over and taking an image of the other side with a background of white paperboard using auto white balance and an ISO of 100. Images were subsequently analyzed for percent coverage and other spray parameters

Table 1. Sprayer settings used in the 2019 hazelnut shoot tip coverage trial and observed volumes per acre from the trial.

Tractor speed (mph)	Nozzle set	Sprayer mode[i,ii]	Mean observed spray rates from trial (GPA)[iii]
1.9	TeeJet D5, DC46-HSS	Standard	112 (±4)
		Intelligent	42 (±6)
3.2	TeeJet D10, DC45-HSS	Standard	97 (±3)
		Intelligent	50 (±0.6)
4.7	Teejet D10, DC46-HSS	Standard	116 (±3)
		Intelligent	63 (±5)

[i] All standard treatments were calibrated to apply 100 gal/acre at tractor PTO-rated speed.
[ii] Treatments in intelligent mode applied at a spray volume setting of 0.06 fl oz/ft^3 of canopy.
[iii] Rates calculated from an assumed spray area of 300 ft^2 per replicate, actual sprayed areas varied in size, means followed by standard error in parentheses.

using a custom, automated macro in the open source program ImageJ. The macro first detected the plant shoot and the background of the photo, then removed the background (Fig. 1). Subsequently a threshold was applied to the image and was used to differentiate the kaolin clay from the leaf tissue, which was then used to calculate spray coverage (Fig. 1).

Trunk coverage

A first trunk coverage trial was conducted on 26 Sep 2018 in an orchard of 4-year-old Jefferson hazelnut trees located in Corvallis, OR, USA (lat. 44.568, long. 123.243) using only water as the spray mixture. Individual plots consisted of six hazelnut trees, three in one row, and three in an adjacent row. Eight water-sensitive cards were placed in four areas in each individual row, with cards replicated in a mirror image in the adjacent row, altogether making a plot (Fig. 2). Cards were attached to trunks 6 inches off the ground, horizontal the ground midway between the first and second trees in the plot, 6 inches (15 cm) and 30 inches (76 cm) off the ground on three-fourths-inch (1.9-cm) PVC tubes staked into the ground (Fig. 2). The 6-inch cards were meant to illustrate sprays targeted at trunks, whereas the cards 30 inches (76 cm) off the ground were meant to catch any off-target application. The lowest three nozzles of the sprayer were used in the study, with the top four nozzles capped off. Cards were attached with duct tape onto trunks and PVC pipes and ground cards were staked into the ground with a single carpentry nail. These groups of cards will hereafter respectively be referred to their position as trunk, ground, PVC low, and PVC high. Duct tape about covered the outside 5 mm of each 76 × 51-mm card. Rows in the orchard were north-south oriented, so in the east row of the plot cards were facing west on the trunks and PVC pipes and on the west row cards were facing east, so that they were facing the sprayer as it traveled between rows (Fig. 2). Ground speeds tested included 1.9 mph, 3.2 mph, and 6.7 mph (3.1 kph, 5.1 kph, and 10.8 kph, respectively) in intelligent mode and 3.2 mph (5.1 kph) in standard mode as a reference treatment. The trial was arranged in a randomized complete block with four replications.

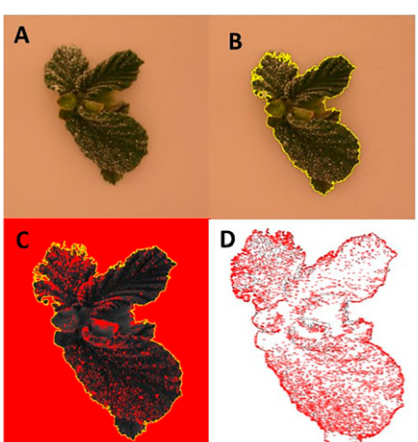

Fig. 1. Workflow for measuring coverage on hazelnut shoot tips. (A) Placement of shoot tip on even-colored background to allow for detection. (B) Identification of the shoot tip, and drawing a border around it. (C) Removal of the image background and identification of spray deposits depicted as red dots on leaf surface. (D) Identification and quantification of spray deposits (now red) on green leaf tissue.

A second trial was conducted to evaluate spray coverage on the trunks of maple trees using three different driving speeds and at three different distances from the sprayer. The spray coverage trial was conducted on 13 Aug 2021 at a commercial tree nursery in Clackamas Co., OR, USA in a block of *Acer ×freemanii* 'Jeffersred' maples, also known as Autumn Blaze maples. The spray application was performed with 120-gal (454 L) tower air blast sprayer (Pul-blast, Rears Mfg.) retrofitted with the commercially available ISS (Smart Apply, Indianapolis, IN, USA). The sprayer was powered with a tractor (5075 GV; John Deere, Moline, IL, USA) and water was used as the spray mixture. The trial was organized as a completely randomized design with four replicates. Treatments included 2 mph, 3 mph, and 4 mph (3.2 kph, 4.8 kph, and 6.4 kph, respectively) in both standard spray mode and intelligent spray mode with four replicates. Each plot consisted of three rows of maples with cards duct taped on a single tree in each of the three rows, with another card placed on the ground in the opposite row using a small nail to anchor it directly to the soil surface (Fig. 3). Cards were placed on tree trunks 12 inches (30 cm) off the soil surface with duct tape. Two cards were placed on each trunk. The two cards were oriented perpendicular to each other, with one card directly facing the sprayer, and one card perpendicular to the plane of the spray and toward the sprayer as it drove through the row (Fig. 3). In addition to the cards on tree trunks, there was a single card attached directly to the soil surface with a small carpentry nail between the sprayer in the row and the first tree, to detect any spray deposited on the ground before the first tree (Fig. 3).

Statistical analysis

Shoot tip coverage. Spray coverage data were divided into three separate analyses. Coverage on the adaxial side of shoots was analyzed using a generalized linear model with a binomial distribution, to account for the percentage nature of the data. Spray coverage on the abaxial side of shoots could not be analyzed using a generalized linear model because the data all contained small values that when rounded to integers for the binomial analysis, depleted all the variation in the data, therefore a linear model was used to analyze the percent coverage on the abaxial side of shoots.

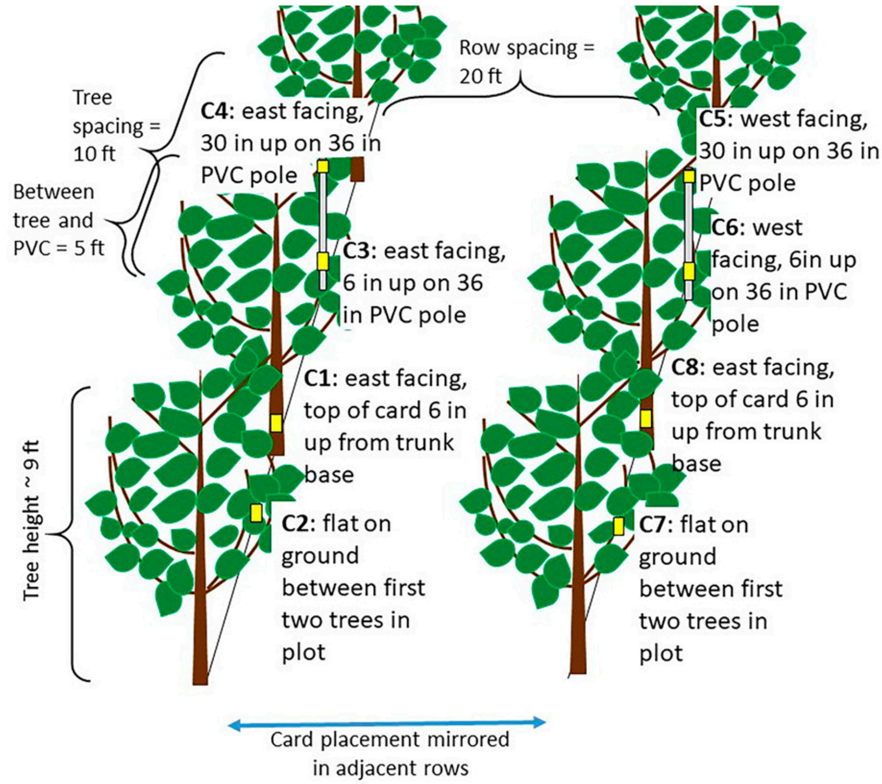

Fig. 2. A schematic of a single plot setup of water-sensitive cards in the 2018 hazelnut trunk coverage experiment, looking north. The schematic is not to scale and is meant for illustration only.

A final analysis on the shoot tip spray coverage data was done where the total coverage (adaxial + abaxial coverage) was analyzed using a generalized linear model with a binomial distribution. Water-sensitive cards were analyzed to examine the effect of sprayer speed, sprayer setting, and card orientation on both the percent coverage on cards, and the volume median diameter (DV 0.5) values. To examine spray coverage on water-sensitive cards, a generalized linear model with a quasibinomial distribution was fit to the percent coverage data, due to overdispersion. To examine DV 0.5 values, due to heteroscedasticity, the values were natural log transformed then a linear model was fit to the data. Contrasts were conducted using least squared means (marginal means) using the emmeans package, all data were analyzed in R version 3.5.1.

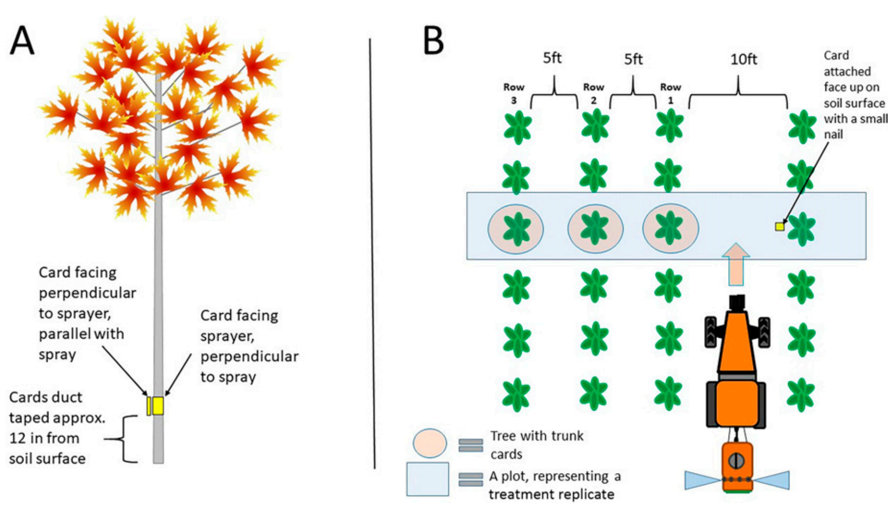

Fig. 3. Schematic of a single tree (A) and an overhead view of a single plot setup (B) of water-sensitive cards in the 2021 maple tree trunk coverage experiment. The schematic is not to scale and is meant for illustration only.

Trunk coverage. For analysis, cards were analyzed in the groups that corresponded to the location of their placement in plots and percent spray coverage was examined for the different tractor/sprayer settings within those locations. Spray coverage percentages were modeled using a generalized linear model in R version 3.5.1. Treatment contrasts were conducted using the emmeans package. Uncertainty was estimated using asymptotic 95% confidence intervals.

Coverage data were analyzed using a generalized linear model, and deposit density data were analyzed using a linear model. Treatment contrasts were conducted using the emmeans package and *P* values were adjusted using the Tukey method (Lenth 2020). All data were analyzed in R version 4.2.2 (R Core Team 2020).

Results

Shoot tip coverage. On both sides of shoots when all settings and speeds were compared, the standard sprayer mode applied at 1.9 mph (3.1 kph) resulted in the highest coverage, while intelligent mode at 3.2 mph (5.1 kph) resulted in the lowest coverage (Table 2). On the adaxial side of shoots, the 1.9 mph (3.1 kph) and 4.7 mph treatments applied in standard mode had the highest coverage levels that were not significantly different from each other, while the 1.9 mph (3.1 kph) treatment resulted in coverage levels significantly higher than all other speed and setting combinations. In addition, when spray was applied in intelligent mode at 3.2 mph (5.1 kph) it resulted in the lowest coverage level observed that was not significantly different from intelligent mode applied at 4.7 mph. Also, on the adaxial side of shoots, spray applied in intelligent mode at 1.9 mph (3.1 kph) resulted in 5.3% coverage, near the middle of those observed and not significantly different from standard mode at 3.2 mph (5.1 kph) or intelligent mode at 4.7 mph. On the abaxial side of shoot tips, the spray applied in standard mode at 1.9 mph (3.1 kph) had significantly higher coverage than the treatment applied in intelligent mode at 3.2 mph (5.1 kph), whereas all

Table 2. Percent coverage on hazelnut shoot tips when averaged over sampling location.

Tractor speed	Sprayer setting[i,ii]	Percent coverage adaxial[iii]	Percent coverage abaxial[iii]
1.9	Intelligent	5.3 (4.4–6.4) C	1.2 (0.9–1.4) AB
	Standard	9.5 (8.1–11.1) A	1.4 (1.2–1.6) A
3.2	Intelligent	3.3 (2.7–4.1) D	0.9 (0.7–1.1) B
	Standard	6.1 (5.0–7.4) BC	1.2 (0.9–1.4) AB
4.7	Intelligent	4.7 (3.9–5.7) DC	1.0 (0.8–1.2) AB
	Standard	8.5 (7.2–10.0) AB	1.3 (1.0–1.5) AB

[i] All treatments were applied at 100 gal/acre at tractor PTO-rated speed.
[ii] Treatments in intelligent mode applied at a spray volume setting of 0.06 fl oz/ft^3 of canopy.
[iii] Means followed by 95% confidence intervals in parentheses, means within columns followed by different letters are significantly different at $P < 0.05$.

other treatments were not significantly different from either of those treatments (Table 2).

Coverage was not significantly different among all sprayer settings and speed groups on water-sensitive cards when intelligent mode was compared with standard mode (Table 3). In addition, cards in the 1.9 mph (3.1 kph) group had significantly larger DV 0.5 s than all other settings except for 4.7 mph standard which was not significantly different from 1.9 mph (3.1 kph) intelligent (Table 4).

Trunk coverage. In the hazelnut trunk study, the 3.2 mph (5.1 kph) standard and 1.9 mph (3.1 kph) intelligent settings resulted in similar and significantly higher coverage than the other settings tested on trunks (Table 5). In the ground group, 3.2 mph (5.1 kph) standard resulted in significantly higher coverage than all other settings tested and the 1.9 mph (3.1 kph) intelligent treatment resulted in significantly higher coverage than the 3.2 mph (5.1 kph) intelligent treatment (Table 5). For cards placed on the ground in the intelligent treatment, all speeds (1.9 mph, 3.2 mph, 6.7 mph) resulted in similar coverage. In the PVC low group, the 3.2 mph (5.1 kph) standard treatment resulted in the highest coverage, followed by 1.9 mph (3.1 kph) intelligent and 3.2 mph (5.1 kph), with 6.7 mph (10.8 kph) intelligent resulting in the least. There was statistical similarity among adjacent treatments in that order, except for 6.7 mph (10.8 kph) intelligent that resulted in significantly lower coverage than 3.2 mph (5.1 kph) intelligent (Table 5). In the PVC high group, all sprayer settings resulted in similar and low average percent coverage of less than 1% (Table 5). The spray volume applied in intelligent mode at 1.9 mph (3.1 kph), 3.2 mph (5.1 kph), and 6.7 mph (10.8 kph) was 75%, 84%, and 89% lower than that applied in standard mode at 3.2 mph (5.1 kph), respectively.

In the maple tree trunk study, for cards facing the sprayer in first row of trees, coverage in both intelligent and standard mode was significantly higher when the sprayer was traveling at 4 mph (6.4 kph) than when the sprayer was traveling at 2 mph (3.2 kph) or intelligent mode at 3 mph (4.8 kph) (Fig. 4). However, this trend reversed for the second and third rows of trees where coverage was significantly higher than all other speeds and settings when the sprayer was traveling at 2 mph (3.2 kph) in both standard and intelligent modes (Fig. 4). In row two, standard mode at 3 mph (4.8 kph) had significantly higher coverage than intelligent mode at 4 mph (6.4 kph), which was the only significant difference in coverage among 3 mph (4.8 kph) and 4 mph (6.4 kph) treatment groups. In row three there were no significant differences in coverage among the 3 mph (4.8 kph) and 4 mph (6.4 kph) groups (Fig. 4). For deposit density, values were largely reciprocal to the coverage values, where deposit densities were lowest among 4 mph (6.4 kph) treatments in row 1, and among 2 mph (3.2 kph) treatments in rows two and three (Fig. 5). In row one, deposit densities among treatments applied at 4 mph (6.4 kph) were significantly different from both settings at 2 mph (3.2 kph), but not from those applied at 3 mph (4.8 kph, Fig. 5). In row two, deposit densities among treatments applied at 2 mph (3.2 kph) were significantly lower than those applied at both 3 mph (4.8 kph) and 4 mph (6.4 kph). In row three, deposit densities were significantly lower for treatments applied at 2 mph (3.2 kph) than those applied at 3 mph (4.8 kph) and 4 mph (6.4 kph) except for intelligent mode 4 mph (6.4 kph).

Coverage on the trunk-side cards followed the same pattern in rows one, two, and three where the highest average coverage occurred when the sprayer was traveling 2 mph (3.2 kph), with incremental drops in coverage as the speed increased to 3 mph (4.8 kph) and 4 mph (6.4 kph, Fig. 4). However, there were only two significant differences among all three rows of trees: in row one and row two standard mode

Table 3. Percent coverage on water-sensitive cards in the 2019 hazelnut shoot tip trial.

Card facing direction	Tractor speed (mph)	Sprayer setting[i,ii]	Percent coverage[iii]
East	1.9	Intelligent	35 (22–50)
		Standard	46 (32–61)
	3.2	Intelligent	14 (6–27)
		Standard	28 (17–44)
	4.7	Intelligent	18 (9–32)
		Standard	22 (12–37)
West	1.9	Intelligent	15 (7–29)
		Standard	21 (11–36)
	3.2	Intelligent	3 (0.3–15)
		Standard	7 (2–19)
	4.7	Intelligent	3 (1–15)
		Standard	9 (3–22)

[i] All treatments were applied at 100 gal/acre at tractor PTO-rated speed.
[ii] Treatments in intelligent mode applied at a spray volume setting of 0.06 fl oz/ft^3 of canopy.
[iii] Means followed by 95% confidence intervals in parentheses, asterisk indicates significantly lower coverage at $P < 0.05$. Comparisons were conducted between sprayer settings, within speed groups. If there are no asterisks, there are no significant differences.

Table 4. Median droplet diameter on water-sensitive cards from the 2019 hazelnut shoot tip coverage trial.

Tractor speed	Sprayer setting[i,ii]	Median droplet diam (DV 0.5, μm)[iii]
1.9	Intelligent	1872 (1358–2580) AB
	Standard	2573 (1867–3547) A
3.2	Intelligent	572 (415–788) C
	Standard	786 (570–1083) C
4.7	Intelligent	795 (577–1096) C
	Standard	1093 (793–1507) BC

[i] All treatments were applied at 100 gal/acre at tractor PTO-rated speed.

[ii] Treatments in intelligent mode applied at a spray volume setting of 0.06 fl oz/ft^3 of canopy.

[iii] Means followed by 95% confidence intervals in parentheses, means followed by different letters are significantly different at $P < 0.05$.

applied at 2 mph (3.2 kph) had significantly higher coverage than both sprayer settings at 4 mph (6.4 kph) and intelligent mode at 3 mph (4.8 kph) in their respective rows. For deposit density, similar to coverage, the quantity of deposits was highest in row one, and lowest in row three, with row two falling in-between (Fig. 5). There was only one significant difference within the row on trunk sides, where standard mode in row two resulted in significantly higher deposits than both sprayer settings at 4 mph (6.4 kph) and intelligent mode at 3 mph (4.8 kph).

Coverage on soil cards in standard mode applied at 3 mph (4.8 kph) was significantly higher than intelligent mode at 4 mph (6.4 kph) and standard mode at 2 mph (3.2 kph), but not from the rest of the speeds and settings (Table 6). For deposit density, however, standard mode at 2 mph (3.2 kph) resulted in significantly higher deposits than both settings at 3 mph (4.8 kph) and standard mode at 4 mph (6.4 kph), but not intelligent mode at 4 mph (6.4 kph) or 2 mph (3.2 kph, Table 6).

Discussion

The results of all three trials indicated that spray coverage was highest at the slowest driving speed. With all air blast sprayers, the airflow a sprayer emits is the primary carrier of the spray droplets to their point of deposition (Cross et al. 2013; Deveau et al. 2021). Air penetration into a crop canopy is a function of fan output and dwell time at a given location, with canopy density as the largest plant-based factor on ease of spray penetration (Cross et al. 2013; Deveau et al. 2021). In all three of the studies conducted here, the density of plant tissues was low given there was little to no foliage present, and as such, treatments at slower speeds generally resulted in deeper penetration of spray, such as on maple trunks, and better coverage, as seen on hazelnut shoots. However, the opposite was observed on maple trunks where coverage at 2 mph (3.2 kph) was lowest on trunks closest to the sprayer, as opposed to 3 mph (4.8 kph) and 4 mph (6.4 kph) treatments. These results may have been observed because at the higher driving speeds there would have been less dwell time at each given tree as the sprayer passed by, resulting in a larger proportion of sprayer air not penetrating into the tree rows. This sprayer air, with spray droplets entrained, likely billowed around behind the sprayer and came to rest closer to the sprayer than if the air and spray emitted were released at slower speeds. Thus, at 2 mph (3.2 kph), a larger proportion of spray penetrated into the plot of trees, while at 3 mph (4.8 kph) and 4 mph (6.4 kph) a larger proportion of spray came to rest closer to the sprayer, resulting in less spray penetration, but greater coverage on row one. Air from the sprayer is the primary carrier of the spray to its point of deposition on the plant, so as the sprayer sped up, spray penetration into the plot of trees would have gone down.

In these studies, across nearly every speed and nozzle combination tested, the intelligent mode consistently yielded lower coverage compared with the standard mode under identical settings, speeds, and conditions, whether on emerging shoots, trunks, or water-sensitive papers. While conventional wisdom suggests that achieving 100% coverage of tissue for maximum efficacy

Table 5. Mean percent coverage of water-sensitive cards in the 2018 Jefferson hazelnut trunk coverage trial comparing a regional commercial standard practice (standard spray setting and 3.2 mph) against three different speeds in the intelligent sprayer mode.

Tractor speed and sprayer mode	Mean percent coverage of water-sensitive cards (%) Trunk cards[i]	PVC low cards[i]	PVC high cards[i]	Ground cards[i]	Average spray volume applied per plot (gal)	Average spray savings (%) compared with 3.2 standard
3.2 mph Standard	45.8 (37.6–54.2) A	44.0 (36.2–52.1) A	0.88 (0.41–1.8) A	25.4 (20.7–30.7) A	0.36 ± 0.02	—
1.9 mph Intelligent	56.6 (48.2–64.7) A	30.8 (23.9–38.6) AB	0.75 (0.34–1.7)A	8.4 (5.6–12.6) B	0.092 ± 0.008	75
3.2 mph Intelligent	26.5 (19.8–34.5) B	18.4 (12.9–25.4) B	0.75 (0.34–1.7) A	2.1 (0.96–4.6) C	0.060 ± 0.007	84
6.7 mph Intelligent	5.9 (3.0–11.3) C	6.8 (3.7–12.1) C	0.38 (0.12–1.2) A	3.6 (2.0–6.5) BC	0.040 ± 0.0	89

[i] Mean percent coverage followed by asymptotic 95% confidence interval in parentheses. Means within a column with the same letters do not differ significantly, meaning $P > 0.05$.

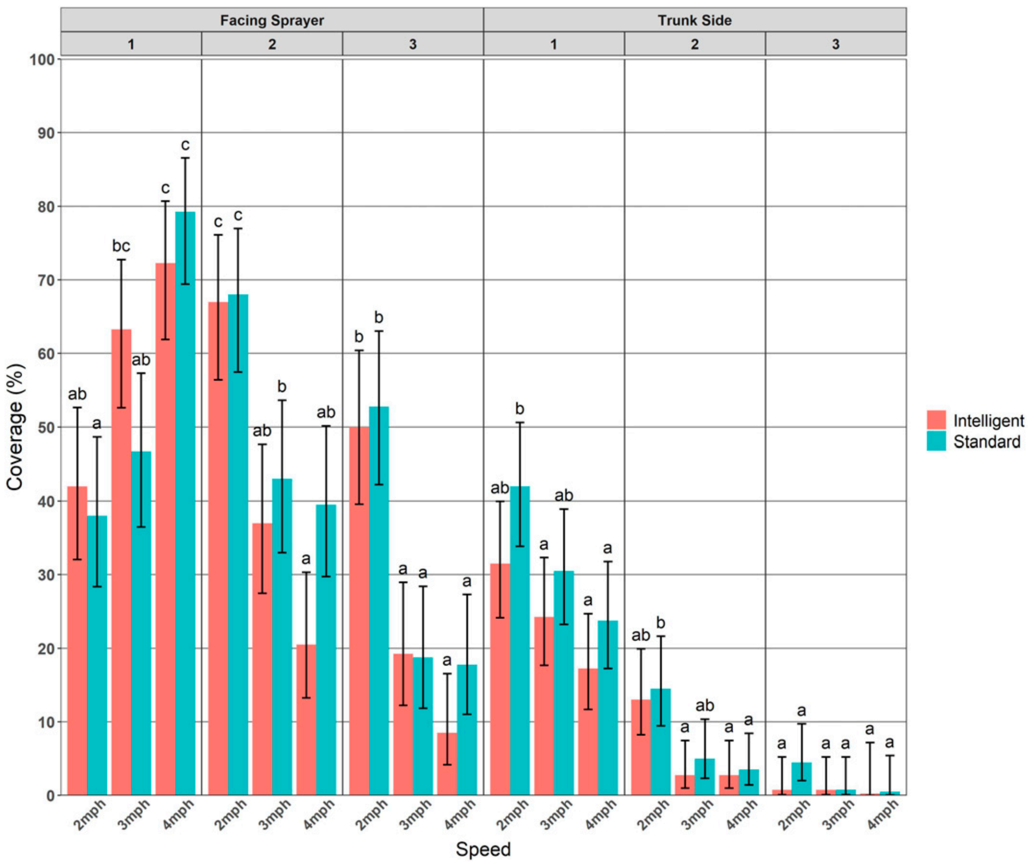

Fig. 4. Percent coverage on cards placed on Autumn Blaze maple trunks 12 inches above the soil surface. Letters above error bars within tree row number columns indicate significant differences at *P* < 0.05.

is ideal, this is often not the case in practice. For most pesticides, ~10% to 15% coverage with ≥85 droplets/cm^2 is considered adequate for efficacy, with values above this considered excessive (Deveau et al. 2021; Syngenta Crop Protection A. G. n.d.). However other agricultural spray practitioners have set the threshold for excessive coverage more conservatively at >30% (Chen et al. 2013; Fessler et al. 2020). The ideal coverage profile of a given pesticide for maximum efficacy and minimal waste is likely within the aforementioned parameters, but different for every active ingredient and/or product and disease or pest system. There were many values of coverage recorded among cards in both trunk trials that were >30%, which can be considered overspray, and therefore, waste (Fessler et al. 2020). Coverage values <30% may seem to farmers like it will not achieve the desired outcome; however, lower coverage indicates less runoff and therefore lower waste (Fessler et al. 2021).

Overall, the coverage values observed in the trunk coverage trials indicate that the ISS was able to effectively target trunks and could provide a cost-effective alternative to drenches for PFB control. In the 2018 hazelnut trunk coverage trial, 75%, 84%, and 89% of spray savings were observed for 1.9 mph, 3.2 mph, and 6.7 mph (10.8 kph) intelligent mode treatments compared with the 3.2 mph (5.1 kph) standard mode treatment. Over the acreage of an orchard, these spray savings would represent substantial reductions in costs to spray for PFB compared with using a standard sprayer, and could result in multiple trunk sprays being cheaper on a per area basis when compared with drenches (Oliver et al. 2010). Lowering the cost of trunk sprays by reducing the pesticide volume required would make them more appealing for farms that do not have perennial problems with the pest or have recently planted plant material in need of periodic protection.

Despite the widespread use of air-blast sprayers for EFB management, little is known about the amount of coverage hazelnut buds receive from a given spray event. Spraying for EFB management is categorized by regular interval sprays (usually 2 weeks) in spring when the buds emerge, continuing until the weather is no longer favorable for primary infection for a total of about four to six applications (Wiman et al. 2023). This work has shown that coverage received by hazelnut shoot tips was below the generally accepted threshold of 10% to 15% coverage for both standard and intelligent modes, although deposits per area were not quantified. Besides the use of resistant cultivars, fungicide applications are the primary means of EFB management, and have been effective at managing the disease for decades (Johnson et al. 1996; Wiman et al. 2023). Therefore for all the years of spraying to manage the disease, the amount of spray material applied to developing hazelnut shoots appears to have been enough to protect the vast majority from EFB infection. This may indicate that the sprayer used in this study is not powerful enough and/or did not use high enough spray volume to effectively cover the hazelnut shoot tips, or that less than 10% coverage is required for efficacy using fungicides currently on the market.

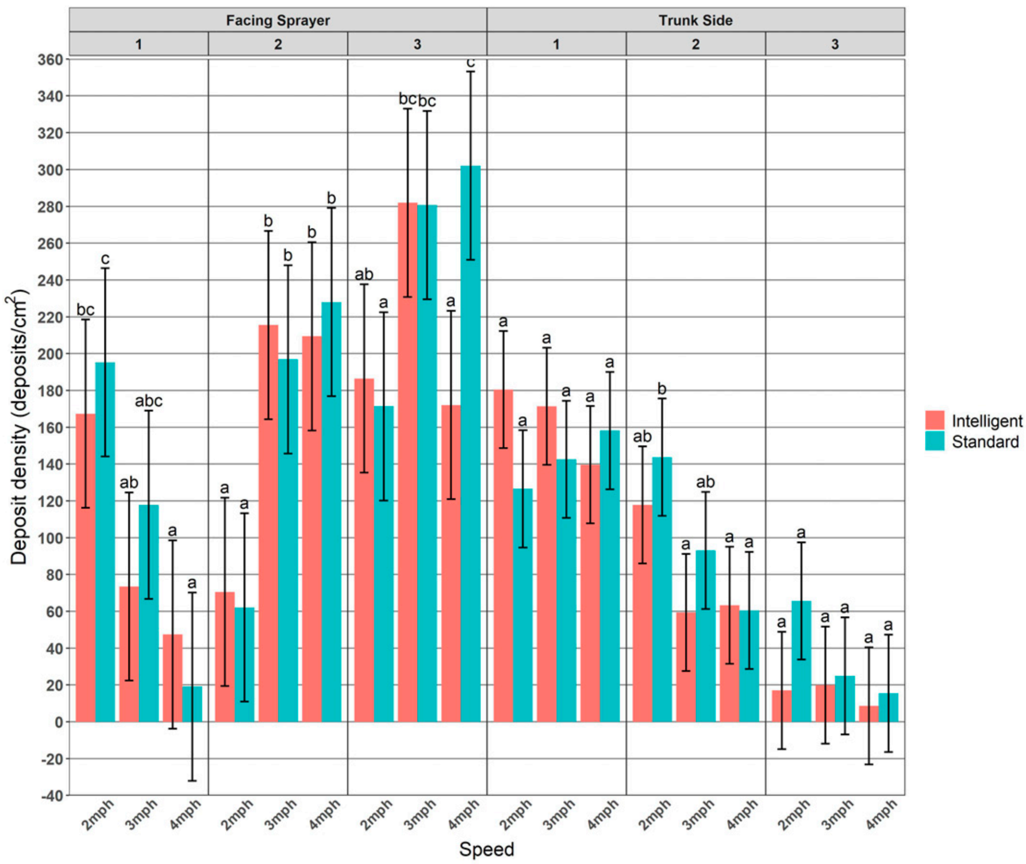

Fig. 5. Deposit density on cards placed on Autumn Blaze maple trunks 12 inches above the soil surface. Letters above error bars within tree row number columns indicate significant differences at $P < 0.05$.

Coverage is especially important for contact mode-of-action fungicides that are commonly used to manage EFB (Warneke et al. 2022; Wiman et al. 2023). There are several reasons that low coverage levels were observed on shoot tips. The sprayer that was used in the study had a 24-inch (61 cm) axial fan, which is more commonly used on sprayers designed for small fruits (e.g., grapevines) rather than orchards. The fan may have been too small to produce adequate airflow to effectively project the spray into the canopy of the 20-ft (6-m)-wide rows. Decreased coverage was more pronounced at faster speeds, where there was less dwell time for the sprayer air to penetrate the stagnant air in the canopy of the trees (Deveau et al. 2021). In addition, the spray volume between the different speeds used was attempted to be kept consistent at 100 GPA (935 L/ha) using nozzles and spray pressure, which meant that as the application driving speed increased, so too did the application volume rate (gallons per minute), and droplet size (DV 0.5). A larger droplet spectrum will result in droplets that would fall out of the sprayer air stream more quickly on the way to the tree than smaller droplets, and thus the smaller DV 0.5 observed on 3.2 mph and 4.7 mph treatment cards (Felsot et al. 2011). Synthetic fungicides with redistribution properties are also used to manage EFB (Wiman et al. 2023). Despite the lower coverage levels observed on hazelnut shoot tips, spray coverage of less than 10% may be enough to result in adequate redistribution and thus efficacy against EFB when using synthetic fungicides.

Spray coverage is important but does not always provide a good indication of pesticide efficacy. Numerous studies have found the intelligent sprayer to manage a wide range of diseases and pests similarly to a standard sprayer using programs containing synthetic pesticides that redistribute throughout the plant (Boatwright et al. 2020; Chen et al. 2019, 2020). However, in another study using the intelligent sprayer for grape powdery mildew (GPM) management with sulfur, coverage between intelligent and standard mode treatments was not significantly

Table 6. Percent coverage and deposit density on water-sensitive cards placed on the ground in front of maple trunks in the 2021 study.

Tractor speed mph (kph)	Sprayer setting	Percent coverage[i]	Deposit density[i]
2 (3.2)	Intelligent	59.0 (47.4–70.0) AB	118.0 (64.5–171.5) AB
	Standard	45.3 (34.2–56.8) A	183.1 (129.5–236.6) B
3 (4.8)	Intelligent	64.0 (52.4–74.2) AB	61.0 (7.5–114.5) A
	Standard	69.0 (57.5–78.6) B	56.6 (3.1–110.2) A
4 (6.4)	Intelligent	45.0 (34.0–56.5) A	100.7 (47.1–154.2) AB
	Standard	68.2 (56.7–77.9) AB	44.8 (−8.7 to 98.3) A

[i] Means followed by 95% confidence intervals in parentheses, means within columns followed by different letters are significantly different at $P < 0.05$.

different for most speeds and settings tested; however, efficacy against GPM was lower in intelligent mode when using the same concentration of sulfur as standard mode (Warneke et al. 2022). Sulfur is a contact fungicide that functions most effectively when plant tissues are evenly covered, forming a barrier the target pathogens must penetrate to infect the plant (Tweedy 1981). Similar GPM management in intelligent mode compared with standard mode was achieved by increasing the concentration of sulfur in the spray mix, or increasing the spray volume output per-unit-canopy (i.e., for a given amount of foliage, Warneke et al. 2022), indicating that there was a threshold amount of sulfur required to be applied to vines for efficacy. Several fungicides that are commonly used to manage EFB (e.g., chlorothalonil and ziram) and insecticides that are used to target buprestid borers (e.g., chlorpyrifos and cyfluthrin) are nonsystemic products. Applications of these contact-based products may require adjustments to achieve similar efficacy as to when they would be applied in standard mode. Efficacy trials on tree trunks and hazelnut shoot tips should be conducted with the intelligent sprayer to more clearly elucidate EFB and buprestid borer management potential when using the intelligent sprayer (Oliver et al. 2010).

In conclusion, our studies underscore the complexities and practical implications of spray coverage when targeting diffuse plant tissues. The conventional wisdom of slower application speed and higher application volume led to improved coverage in some cases, but our findings reveal that lower application volumes, such as those applied by the ISS, can result in comparable coverage. Although the ISS showed promise in reducing spray volumes and thus costs for managing pests like the PFB on tree trunks, its application efficacy varied, necessitating further investigation to ensure performance in different crop scenarios. Moving forward, optimizing spray parameters such as speed, nozzle configuration, and spray volume remains crucial for maximizing both efficacy and cost-efficiency in agricultural spray applications.

References cited

Addesso KM, Oliver JB, Youssef NN, Fare DC. 2020. Evaluation of systemic imidacloprid and herbicide treatments on flatheaded borer (Coleoptera: Buprestidae) management in field nursery production. J Econ Entomol. 113(6):2808–2819. https://doi.org/10.1093/jee/toaa228.

Boatwright H, Zhu H, Clark A, Schnabel G. 2020. Evaluation of the intelligent sprayer system in peach production. Plant Dis. 104(12):3207–3212. https://doi.org/10.1094/PDIS-04-20-0696-RE.

Chen L, Wallhead M, Reding M, Horst L, Zhu H. 2020. Control of insect pests and diseases in an Ohio fruit farm with a laser-guided intelligent sprayer. HortTechnology. 30(2):168–175. https://doi.org/10.21273/HORTTECH04497-19.

Chen L, Wallhead M, Zhu H, Fulcher A. 2019. Control of insects and diseases with intelligent variable-rate sprayers in ornamental nurseries. J Environ Hortic. 37(3): 90–100. https://doi.org/10.24266/0738-2898-37.3.90.

Chen Y, Ozkan HE, Zhu H, Derksen RC, Krause CR. 2013. Spray deposition inside tree canopies from a newly developed variable-rate air-assisted sprayer. Transactions of the ASABE. 56(6):1263–1272. https://doi.org/10.13031/trans.56.9839.

Crook DJ, Khrimian A, Francese JA, Fraser I, Poland TM, Sawyer AJ, Mastro VC. 2008. Development of a host-based semiochemical lure for trapping emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae). Environ Entomol. 37(2):356–365.

Cross J, Balsari P, Doruchowski G, Douzals JP, Herbst A, Marucco P, Nuyttens D, Walklate P. 2013. Orchard spray application in Europe - state of the art and research challenges. Integrated Protection of Fruit Crops IOBC-WPRS Bulletin. 91:465–475.

Deveau J, Ledebuhr M, Manketelow D. 2021. Airblast 101. In: Sprayers101.com (2nd ed). Ontario Ministry of Agriculture, Food and Rural Affairs. https://sprayers101.com/airblast101/.

Felsot AS, Unsworth JB, BHJ, Linders J, Roberts G, Rautman D, Harris C, Carazo E. 2011. Agrochemical spray drift; assessment and mitigation-a review. J Environ Sci Health B. 46(1):1–23. https://doi.org/10.1080/03601234.2010.515161.

Fessler L, Fulcher A, Lockwood D, Wright W, Zhu H. 2020. Advancing sustainability in tree crop pest management: refining spray application rate with a laser-guided variable-rate sprayer in apple orchards. HortScience. 55(9):1522–1530. https://doi.org/10.21273/HORTSCI15056-20.

Fessler L, Fulcher A, Schneider L, Wright WC, Zhu H. 2021. Reducing the nursery pesticide footprint with laser-guided, variable-rate spray application technology. HortScience. 56(12):1572–1584. https://doi.org/10.21273/HORTSCI16157-21.

Fox RD, Derksen RC, Zhu H, Brazee RD, Svensson SA. 2008. A history of airblast sprayer development and future prospects. Transactions of the ASABE. 51(2):405–410. https://doi.org/10.13031/2013.24375.

Giles DK, Klassen P, Niederholzer FJA, Downey D. 2011. “Smart” sprayer technology provides environmental and economic benefits in California orchards. Calif Agr. 65(2):85–89. https://doi.org/10.3733/ca.v065n02p85.

Jensen PK, Olesen MH. 2014. Spray mass balance in pesticide application: A review. Crop Prot. 61:23–31. https://doi.org/10.1016/j.cropro.2014.03.006.

Johnson KB, Mehlenbacher SA, Stone JK, Pscheidt JW, Pinkerton JN. 1996. Eastern filbert blight of european hazelnut: it’s becoming a manageable disease. Plant Dis. 80(12):1308–1316. https://doi.org/10.1094/PD-80-1308.

Lenth R. 2020. emmeans: Estimated Marginal Means, aka Least-Squares Means (1.5.2-1). https://cran.r-project.org/package=emmeans.

Nackley LL, Warneke B, Fessler L, Pscheidt JW, Lockwood D, Wright WC, Sun X, Fulcher A. 2021. Variable-rate spray technology optimizes pesticide application by adjusting for seasonal shifts in deciduous perennial crops. HortTechnology. 31(4):479–489. https://doi.org/10.21273/HORTTECH04794-21.

Oliver JB, Fare DC, Youssef N, Scholl SS, Reding ME, Ranger CM, Moyseenko JJ, Halcomb MA. 2010. Evaluation of a single application of neonicotinoid and multi-application contact insecticides for flatheaded borer management in field grown red maple cultivars. J Environ Hort. 28(3):135–149. https://doi.org/10.24266/0738-2898-28.3.135.

Perkowski M. 2024. Resurgent pathogen overcomes Oregon hazelnut tree defenses. Capital Press. https://www.capitalpress.com/state/oregon/resurgent-efb-pathogen-overcomes-oregon-hazelnut-tree-defenses/article_d3a2c1e4-bb23-11ee-80e1-436e9afb58ce.html.

Pscheidt JW, Heckert S, Cluskey SA. 2018. Tank mixing fungicides for effectiveness against eastern filbert blight of hazelnut. Plant Dis. 102(5):919–924. https://doi.org/10.1094/PDIS-08-17-1298-RE.

Pscheidt JW, Ocamb CM (eds). 2021. Pacific Northwest plant disease management handbook. Oregon State University. https://pnwhandbooks.org/plantdisease.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing. https://www.r-project.org/.

Shen Y, Zhu H, Liu H, Chen Y, Ozkan E. 2017. Development of a laser-guided, embedded-computer-controlled, air-assisted precision sprayer. Transactions of the ASABE. 60(6):1827–1838. https://doi.org/10.13031/trans.12455.

Syngenta Crop Protection A. G. n.d. Water-sensitive paper for monitoring spray distribution.

Taghavi T, Rahemi A, Suarez E. 2022. Development of a uniform phenology scale (BBCH) in hazelnuts. Sci Hortic. 296: 110837. https://doi.org/10.1016/j.scienta.2021.110837.

Tweedy BG. 1981. Inorganic sulfur as a fungicide. Residue Reviews. 43–68. https://doi.org/10.1007/978-1-4612-5910-7_3.

Warneke B, Thiessen LD, Mahaffee WF. 2020. Effect of fungicide mobility and application timing on the management of grape powdery mildew. Plant Dis. 104(4): 1167–1174. https://doi.org/10.1094/PDIS-06-19-1285-RE.

Warneke BW, Nackley LL, Pscheidt JW. 2022. Management of grape powdery mildew with an intelligent sprayer and sulfur. Plant Dis. 106(7):1837–1844. https://doi.org/10.1094/PDIS-06-21-1164-RE.

Warneke BW, Pscheidt JW, Rosetta RR, Nackley LL. 2019. Sensor sprayers for specialty crop production. Oregon State Extension Service, PNW. 727.

Warneke BW, Zhu H, Pscheidt JW, Nackley LL. 2020. Canopy spray application technology in specialty crops: A slowly evolving landscape. Pest Manag Sci. 77(5):2157–2164. https://doi.org/10.1002/ps.6167.

Wiman N, Andrews H, Mugica A, Rudolph E, Chase T. 2019. Pacific flatheaded borer ecology and knowledge gaps in Western Oregon orchard crops. Proceedings of the Flatheaded Borer Workshop, p 28–30. https://bugwoodcloud.org/CMS/mura/sipmc/assets/File/UPDATED Proceedings of the Flatheaded Borer Workshop.pdf.

Wiman NG, Pscheidt JW, Moretti M. 2023. 2023 Willamette Valley Pest Management Guide for Hazelnuts. Oregon State Extension Service.

Zhu H, Salyani M, Fox RD. 2011. A portable scanning system for evaluation of spray deposit distribution. Comput Electron Agric. 76(1):38–43. https://doi.org/10.1016/j.compag.2011.01.003.