

## Sprayer type and water volume influence pesticide deposition and control of insect pests and diseases in juice grapes

John C. Wise<sup>a,c,\*</sup>, Paul E. Jenkins<sup>a</sup>, Annemiek M.C. Schilder<sup>b</sup>, Christine Vandervoort<sup>b</sup>, Rufus Isaacs<sup>a</sup>

<sup>a</sup> Department of Entomology, Michigan State University, East Lansing, MI 48824, USA

<sup>b</sup> Department of Plant Pathology, Michigan State University, East Lansing, MI 48824, USA

<sup>c</sup> Trevor Nichols Research Complex, Michigan State University, Fennville, MI 49408, USA

### ARTICLE INFO

#### Article history:

Received 26 May 2009

Received in revised form

21 November 2009

Accepted 23 November 2009

#### Keywords:

*Paralobesia viteana*

*Guignardia bidwellii*

*Phomopsis viticola*

*Uncinula necator*

*Plasmopara viticola*

Airblast sprayer

Air-assisted rotary atomizer

Proptec

Pesticide deposition

### ABSTRACT

In a mature *Vitis labrusca* L. “Niagara” vineyard, we compared an airblast sprayer and an air-assisted rotary atomizer (AARA) low-volume sprayer for coverage of grape clusters and control of grape berry moth, *Paralobesia viteana*. In addition, the effect of spray volume on control of fungal diseases was evaluated using the fungicides ziram and azoxystrobin applied with an airblast sprayer. For evaluation of coverage, sprayers applied kaolin clay at 28 kg/ha to grapevines while operating at low, medium and high water volumes. Kaolin residues on grape clusters were analyzed to compare the total amount of spray material deposited, percent of fruit surface covered, number of deposits, size of deposits and distance between deposits. There were no significant differences between sprayers or water volumes in the total amount of kaolin deposited on clusters, but the percent surface coverage was much greater on outside-facing berry surfaces (facing the sprayer) than inside-facing surfaces (facing the rachis). On the outside-facing berry surfaces, the airblast sprayer at 468 L/ha of water (medium volume) provided the highest percent coverage, the greatest density of deposits, the largest deposit diameter, and the smallest distance between deposits. On the inside-facing berry surfaces, the same sprayer–volume combination provided the highest percent coverage and greatest deposit diameter, but deposits from the airblast sprayer operating at 935 L/ha (high volume) had the smallest distance between deposits. No significant differences between sprayers or among water volumes were detected in the deposit density on the inside-facing berry surfaces. Bioassays of grape clusters sprayed with fenpropathrin or methoxyfenozide using the airblast or AARA sprayers at two water volumes revealed the greatest fruit protection from *P. viteana* at the higher volume for the airblast sprayer, but at the lower volume for the AARA sprayer. Spray volume of the airblast sprayer also affected disease control by the protectant fungicide ziram more than by the systemic fungicide azoxystrobin, with 468 L/ha providing better control than 187 L/ha. However, for most diseases, fungicide type was more influential than spray volume in determining the disease control outcome. The results of this study emphasize the need for appropriate water volumes relative to the sprayer and pesticide being used to optimize pest and disease control in juice grape vineyards.

© 2009 Elsevier Ltd. All rights reserved.

### 1. Introduction

Commercial production of grapes in the eastern United States utilizes Integrated Pest Management (IPM) and an array of pesticide offerings to protect the crop from injury or infestation by insect pests and fungal diseases (Isaacs et al., 2005; Wise et al., 2008). A key insect pest in this region is the grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), which has three or

more generations per year (Biever and Hostetter, 1989; Tobin et al., 2003) and requires management actions throughout the growing season to minimize infestation. Vineyards at high risk from *P. viteana* infestation receive three or more prophylactic insecticide sprays each season (Dennehy et al., 1990). Achieving coverage of grape clusters with spray applications is critical to prevent larval infestation of berries, where they are relatively safe from chemical insecticides. Important fungal diseases of grapes in this region include powdery mildew caused by *Uncinula necator* (Schwein.) Burrill, black rot caused by *Guignardia bidwellii* (Ellis) Viala & Ravaz, and *Phomopsis* fruit rot and rachis infection caused by *Phomopsis viticola* (Sacc.) Sacc., all of which require management actions in a typical growing season to minimize damage (Dami et al., 2005).

\* Corresponding author at: Department of Entomology, Michigan State University, 206 Center for Integrated Plant Systems, East Lansing, MI 48824-1311, USA. Tel.: +1 517 432 2668; fax: +1 517 353 5598.

E-mail address: [wisejohn@msu.edu](mailto:wisejohn@msu.edu) (J.C. Wise).

Mid-summer juice grape (*Vitis labrusca* L.) vineyards in the eastern United States typically have thick canopies with multiple layers of leaves covering the grape clusters. This makes reaching the fruit with pesticide applications very challenging. For applications made from the side of the target, as is typical in these vineyards, the horizontal distribution of spray deposits can be strongly influenced by canopy density (Walklate et al., 2002). To control direct pests such as *P. viteana*, pesticides are typically applied with the use of air-assisted ground sprayers, for which various models and operating parameters are used. The most common vineyard sprayer used in Michigan is an airblast design (FMC Corp., Jonesboro, AR, USA), originally developed for spraying tree fruit. In recent years, a high speed air-assisted rotary atomizer (AARA) sprayer has been developed (Proptec<sup>®</sup>, Ledebuhr Industries, Bath, MI, USA), that combines atomization of spray liquid with hydraulic-driven fans to provide pesticide delivery at lower water volumes. This type of sprayer technology has been shown to provide superior control of fruit rots in blueberries compared to an airblast sprayer (Hanson et al., 2000). It has also provided similar control of insects and diseases in peach orchards, while significantly reducing off-target drift of pesticides (Reilly et al., 2004). As the spectrum of spray droplet size decreases, as is the case with atomization technology, the deposition and efficacy of pesticides may be enhanced (Smith et al., 2000; Giles et al., 2002). In laboratory trials, small spray droplets have been shown to be more efficient than large droplets at controlling *P. viteana* (Alm et al., 1989).

The level of coverage achieved in grape canopies may be affected by the type of sprayer and operating parameters, as well as by the weather conditions, crop cultivar, growth stage, and training system of the vineyard (Pergher and Gubiani, 1995; Van Ee et al., 2000; Balsari and Marucco, 2005; Hewitt, 2005;). The volume of water used to carry the pesticide to the target is one key parameter of sprayer operation that can be varied by the grower to improve the level of coverage of the target crop (Landers, 2002). Landers (2004), and Landers and Farooq (2005) described the role of air speed, nozzles and canopy on the spray penetration in grapevine canopies. However, relatively little is known about how variation in water volume affects target coverage in grape canopies, and even less is known about how this coverage affects control of key vineyard insect and disease pests with different pesticides. Under vineyard conditions, spray deposits on the targeted vegetation can be variable and the relationship between spray deposit and pest control is not well understood (Smith et al., 2000). Viret et al. (2003) tested the influence of sprayer technology on the deposition of fungicides on grape canopies, showing that sprayers delivering uniform leaf coverage provided superior control of powdery mildew. For fruit cluster-infesting insects and diseases, coverage of the target with pesticide is more difficult due to the three-dimensional configuration of clusters, their position within the leaf canopy, and the tight spaces within the cluster.

Increases in the cost of fuel and labor are expected to lead to interest in sprayer designs that can achieve fruit cluster coverage with reduced volumes of water, such as the high speed AARA designs (USDA NASS, 2008). These factors have also forced some growers to cut water volumes of pesticide applications when using airblast sprayers (R. Isaacs, unpublished data). A recent survey of Michigan grape growers revealed that the average volume of water applied was 97.6 (range 37.8–189.3) L/ha, with few growers adjusting volumes as the vine canopy size increases during the growing season (R. Isaacs, unpublished data). While these low volumes may have been sufficient for use with neurotoxic insecticides, many of the conventional pesticides historically relied upon by grape growers for pest control have been eliminated or labeled uses restricted as a result of the Food Quality Protection Act (USEPA, 1996). Even though many of the new reduced-risk pesticides

(USEPA, 1997) being registered to control vineyard pests have shown promising results in recent field research and efficacy trials (Schilder et al., 2002; Isaacs et al., 2004, 2005; Wise et al., 2005; Schilder et al., 2006; Jenkins and Isaacs, 2007), the mode of action and performance characteristics are in many cases different (Ware and Whitecre, 2004; Wise et al., 2008). For example, the ecdysone agonist insect growth regulator (IGR), methoxyfenozide, has little to no contact toxicity, but instead relies upon ingestion for control of Lepidopteran insect pests (Carlson et al., 2001). In the case of reduced risk fungicide, azoxystrobin has plant-systemic attributes, whereas conventional compounds are generally plant protectant compounds that remain on the surface of the crop (Wong and Wilcox, 2001). It is not well understood how sprayer design and water volume affect the performance of these new compounds.

To understand the variation in pesticide deposition when both sprayer type and water volume are varied, we compared the deposition patterns of kaolin on grape clusters in a mature juice-grape vineyard canopy for two sprayers operated at three water volumes. Additionally, a neurotoxic insecticide and an IGR insecticide were compared for their ability to control *P. viteana* when applied by the same sprayers at two representative water volumes used in Michigan vineyards. Thirdly, both a protectant and a systemic fungicide were compared for their ability to control multiple fungal diseases when applied with an airblast sprayer at two representative water volumes.

## 2. Materials and methods

### 2.1. Field plots

All studies were conducted in a mature *V. labrusca* var. “Niagara” grape vineyard at the Trevor Nichols Research Complex of Michigan State University in Fennville, Michigan, USA (latitude 42.5951°: longitude –86.1561°). Grapevines were planted in 2000 and trained to a bilateral cordon (Hudson River Umbrella) system (Reynold and Vanden Heuvel, 2009), with vines planted in separate 7-vine rows to enable separate treatments to be applied to separate plots in a completely randomized design. Vine spacing was 1.83 m within and 3.05 m between rows. Treatment plots were selected to display representative canopies of leaves, and were separated by a minimum of 12 m buffer.

### 2.2. Sprayers and water volumes tested

Two sprayer designs were evaluated in these studies; an airblast sprayer (model 1029, FMC Corp., Jonesboro, AR, USA), and an AARA Proptec sprayer (Ledebuhr Industries Inc., Bath, MI, USA). The airblast sprayer was operated at 4 km/h with three nozzles on a side, and tested at three industry representative water volumes; 187 (nozzle disc #2<sup>1</sup>/<sub>2</sub>, 1-hole ceramic whirl plate, and 1104 kPa), 468 (nozzle disc #3, 3-hole ceramic whirl plate, and 1104 kPa), and 935 L/ha (nozzle disc #4, 3-hole ceramic whirl plate, and 1242 kPa) (Durand-Wayland Inc., LaGrange, GA, USA). The AARA Proptec sprayer was operated at 7.2 km/h with three high-speed fans, one positioned below and two above the canopy at opposing 45° positions, tested at three industry representative water volumes; 47 (CP #4916-35 orphice plate, and 207 kPa), 93 (CP #4916-46 orphice plate, and 207 kPa), and 187 L/ha (CP #4916-63 orphice plate, and 221 kPa) (Spray Solutions Inc., Wheaton, IL, USA). Untreated plots served as controls in all studies.

Applications were made to both sides of each treated row; the airblast sprayer making two passes in the same direction to complete the application, while the AARA sprayer treated both sides of a row with one pass. Prior to application with each sprayer and water volume combination, ten uniformly sized, untreated

clusters were picked randomly from within in the same vineyard and placed into the row to be treated at ten predetermined positions. In each case, clusters were hung on the trellis wire on an opened paper clip in the fruiting zone, and these positions were marked to allow cluster placement in the same position for each treatment. After each application, grape clusters were allowed to air dry for approximately 10 min, and then were carefully retrieved and brought back to the laboratory for further analysis (see below). Kaolin clay (Surround® WP, Engelhard Corp., Iselin, NJ, USA) was used to represent the spray deposition of a pesticide active ingredient, when measuring cluster coverage using the sprayer technologies and volumes described above. Kaolin was applied at 22.4 kg/ha in all treatments.

### 2.3. Characterization of spray deposition on fruit clusters

#### 2.3.1. Total spray deposition

The total amount of kaolin deposited on clusters was determined using an optical method modified from [Puterka et al. \(2000\)](#). Treatments described above were applied on 18 August, 2004 and five of the ten clusters (odd positions) placed within each treatment plot were assigned to this analysis. In the laboratory, all berries were removed from each of the five clusters for each treatment series and placed into individual 237-ml glass bottles filled with 75 ml of methanol. To dislodge the kaolin particles, the bottles were sonicated with an ultrasonic cleaner (Branson, Danbury, CT, USA) for 2 min. Using forceps, berries were removed from each bottle one at a time and allowed to drip (3–5 s), ensuring excess methanol remained in the bottle. Samples were held at  $-20^{\circ}\text{C}$  until analysis was performed at the MSU Pesticide Analytical Laboratory in East Lansing, Michigan, USA.

Total kaolin deposition on clusters was measured by UV-VIS spectroscopy using a dual wavelength absorbance spectrometer (model 2487, Waters, Milford, MA, USA). The extracted methanol was placed in the spectrometer for determination of kaolin absorbance at 400 nm.

The extracted methanol sample was placed in the spectrometer for determination of kaolin absorbance at 400 nm. A standard curve for kaolin clay concentration was determined using four standards to create a linear regression equation ( $r^2 = 0.9999$  of regression line). The standard concentrations ranged from 1  $\mu\text{g}/\text{ml}$  to 1000  $\mu\text{g}/\text{ml}$ . The sample absorbance values were placed in the regression line to determine concentration. To determine the absorbance due to kaolin only, the mean absorbance of untreated control samples in methanol was subtracted from the treated samples. Data were compared across all sprayer–water volume combinations and for each sprayer separately using analysis of variance (ANOVA) (PROC MIXED, [SAS Institute, 2003](#)). Data were analyzed both for normality using the Shapiro–Wilk test, and for equality of variance across the six treatments and five replicates using Levene's test. Absorbance data were normally distributed and a transformation wasn't necessary prior to analysis. Tukey's HSD test was used for multiple comparisons and the significance level was  $\alpha = 0.05$ .

#### 2.3.2. Spray coverage

The remaining five clusters (even positions) in each treatment were collected as described above and returned to the laboratory to quantify the remaining cluster coverage parameters. Individual berries were selected from one of three positions (top, middle, and bottom) within each cluster in a plane perpendicular to the sprayer, and from each of two locations (inside-facing and outside-facing) of the cluster. Berries to be used for analysis were selected prior to treatment applications by marking individual berries with a fine-point Sharpie® permanent marker (Sanford Corp., Oak Brook, IL,

USA). This ensured that berries facing the sprayer were consistently used for spray deposition analysis.

Spray deposition analysis was performed by digital photography using the QCapture Imaging program within Adobe® Photoshop® (Adobe Systems Inc., San Jose, CA, USA). Standardized digital photographs were taken of individual berries through a microscope (Olympus SZ-ST, Olympus America Inc., Center Valley, PA, USA) using a 1.2 $\times$  objective and two gooseneck lights (Ace LR92240, Schott North America Inc., Auburn, NY, USA) with EKE lamps set at 80% illumination and positioned so that light was directed from the lower left and upper left corner of the preparation. The microscope stage was surrounded by a 5-cm-high ring of white paper to diffuse the incident light, and was directed from outside the paper ring. A cylinder of vellum sheets was placed over each berry (six sheets thick; three sheets wrapped around two times), with a 1-cm<sup>2</sup> square frame to outline the area of the berry to be photographed. Photographs were taken in a dark room to decrease glare, with a 3.2-megapixel Q-Color3™ camera (Olympus America Inc., Center Valley, PA, USA). Exposure time was set to 865 ms, binning was set to 2, and we used the File Import Twain Imaging Cam through Adobe Photoshop.

From the images, a 0.635-cm<sup>2</sup> circular area was used to measure the spray deposition on each berry, termed the region of interest (ROI). This allowed quantification on a standard area and also minimized potential error due to the curvature of the berry surface. Within the ROI, the percent surface area covered with kaolin, the density of spray deposits (area of discrete kaolin deposition), the size of deposits, and the distance between deposits were measured. This was done automatically using a customized macroinstruction within the image-processing program (Scion Corp., Frederick, MD, USA). To distinguish the deposition of kaolin from background deposits, the mean values from untreated control samples was subtracted from the values of the treated samples. The percentage surface area covered, number of deposits, size of deposits, and distance between deposits for the inside-facing surface (facing the rachis) and outside-facing surface (facing the sprayer) of berries were averaged for each treatment plot and compared among water volumes using ANOVA (PROC MIXED, [SAS Institute, 2003](#)) for each sprayer separately. Data were analyzed for normality using the Shapiro–Wilk test and for equal variance across six treatments and five replicates using Levene's test. Percentage data were arcsine square root ( $p^{1/2}$ ) transformed and all other data were  $\log(x + 1)$  transformed prior to analysis to meet normality assumptions. Tukey's HSD test was used for multiple comparisons and the significance level was  $\alpha = 0.05$ .

### 2.4. Control of *P. viteana* infestation

To determine the influence of sprayer design and water volume on insecticide performance, both sprayers were tested at two representative water volumes to compare control of *P. viteana* with fenprothrin (Danitol® 2.4EC, Valent USA, Walnut Hills, CA, USA) and methoxyfenozide (Intrepid® 2F, Dow AgroSciences, Indianapolis, IN, USA). The airblast sprayer was tested at 187 and 468 L/ha and the AARA sprayer was tested at 47 and 187 L/ha. These volumes were chosen to represent the typical range of application volumes used in Michigan vineyards and to provide one equivalent volume to compare sprayers directly. Treatments were applied as described above on 2 August, 2005.

For each sprayer and volume combination, fenprothrin was applied at 224 g AI/ha and methoxyfenozide was applied at 210 g AI/ha to randomly selected treatment plots and an untreated control, each separated by at least 15 m. Twenty untreated clusters were placed in each treatment plot prior to the applications as described above, and were allowed to air dry for approximately

10 min after being sprayed. The clusters were carefully transported to the laboratory and placed inside 473-ml polypropylene containers (Fabri-Kal, Kalamazoo, MI), and small holes were punched into the lids to allow gas exchange. One day after treatment application (DAT), approximately 10 eggs of *P. viteana* on 1–2 untreated berries from a colony maintained in the MSU Small Fruit Entomology Laboratory were added to each container. The berries were placed in contact with treated clusters so that the neonate larvae could move onto these treated clusters. This experiment was repeated by removing the remaining ten clusters from the grape canopy 6 DAT, and repeating the application of *P. viteana* eggs to the containers. One week after eggs were placed on the berries, the clusters were examined under a microscope, and the number of entrance holes from *P. viteana* larvae were counted in each container. From these values, the number of infested berries within each sample was calculated. At the end of 4 weeks, samples were placed at  $-20^{\circ}\text{C}$  for 24 h to ensure mortality of specimens. The containers were then opened and the number of *P. viteana* adults, pupae, and fourth-instar larvae were enumerated. From these values, the percentage of *P. viteana* surviving within each sample was calculated.

To test the effect of water volume and sprayer type on insecticide performance, each water volume and sprayer combination was compared within each insecticide treatment and against the untreated control using ANOVA (PROC MIXED, SAS Institute, 2003). Additionally, all water volumes were compared within each sprayer using ANOVA. Data were analyzed for normality using the Shapiro–Wilk test and for equal variance across the six treatments and five replicates using Levene's test. The proportion of *P. viteana* surviving was arcsine square root ( $p^{1/2}$ ) transformed with number of infested berries was  $\log(x + 1)$  transformed prior to analysis. Tukey's HSD test was used for multiple comparisons and the significance level was  $\alpha = 0.05$ .

## 2.5. Control of fungal diseases

To determine the effect of water volume on fungicide performance, the airblast sprayer described above was used to apply the protectant fungicide Ziram<sup>®</sup> (76% ziram, United Phosphorus Inc., King of Prussia, PA, USA) and the systemic fungicide Abound<sup>®</sup> (22.9% azoxystrobin, Syngenta, Raleigh, NC, USA) at 187 and 468 L/ha. Ziram was applied at 2.58 kg AI/ha, and azoxystrobin was applied at 0.22 kg AI/ha, regardless of spray volume. Treatments were applied to both sides of 7-vine rows bordered by a buffer row of vines on each side and replicated three times in a randomized complete block design. Untreated rows served as controls. The trial was conducted twice: in 2005 and 2007. In 2005, spray dates were as follows: 9 June (pre-bloom), 21 June (first post-bloom), 15 July (second post-bloom), 29 July (third post-bloom), and 12 August (fourth post-bloom). Rainfall totals between sprays were 8.1, 19.8, 29.5, and 16.8 mm, respectively. On 13 September, powdery mildew (*Uncinula necator*) incidence (% leaves infected) and severity (% leaf area infected on diseased leaves only) were visually estimated on 25 randomly selected leaves in each plot. On 27 September, black rot (*Guignardia bidwellii*) and *Phomopsis* fruit rot and rachis infection (*Phomopsis viticola*) were visually assessed on 25 randomly selected clusters per plot. Disease incidence was rated as % clusters or % rachises with disease symptoms and disease severity was rated as % infected berries or % infected rachis area on diseased clusters only. Overall severity was calculated as incidence  $\times$  severity/100.

In 2007, spray dates were as follows: 1 June (pre-bloom), 18 June (first post-bloom), 2 July (second post-bloom), 21 July (third post-bloom), and 8 August (fourth post-bloom). Rainfall totals between sprays were 13.2, 11.4, 11.4, and 71.4 mm, respectively. On 2 October,

downy mildew incidence (% leaves infected) and severity (% leaf area infected on diseased leaves only) were visually estimated on 25 randomly selected leaves in each plot. Powdery mildew was not present and therefore not rated. Black rot and *Phomopsis* fruit rot incidence and severity were assessed as described above. Overall severity data were analyzed with one- and two-way ANOVA using the StatGraphics Plus 4.1 program (Statistical Graphics Corp., Herndon, VA, USA) and Fisher's Protected LSD for mean separation. In the two-way ANOVA to assess the effects of fungicide, spray volume, and their interaction, the untreated check was left out, whereas in the one-way ANOVA, all treatments were compared. Data were square-root,  $\log(x)$  or  $\log(x + 1)$  transformed to equalize variances as needed.

## 3. Results

### 3.1. Characterization of spray deposition on fruit clusters

#### 3.1.1. Total spray deposition

Despite a 52% difference in kaolin deposition on clusters between the highest and lowest average values, there were no significant differences among treatments in absorbance values ( $F = 1.13$ ;  $df = 5,20$ ;  $P = 0.38$ ). Additionally, when comparing the three water volumes separately for each sprayer, no significant differences in total kaolin deposition on clusters were observed for either the AARA sprayer ( $F = 1.88$ ;  $df = 2,8$ ;  $P = 0.21$ ) or the airblast sprayer ( $F = 1.68$ ;  $df = 2,8$ ;  $P = 0.25$ ). However, run-off of solution from the grape clusters was observed at the highest volume tested (935 L/ha) with the airblast sprayer, which may be due in part to separation of larger droplets or deflection after contact with the target (Hartley and Brunskill, 1958; Tadros, 1987).

#### 3.1.2. Spray coverage

The combinations of sprayer and water volume significantly affected the percent surface area covered for both the inside-facing and the outside-facing surfaces of berries (Table 1). The percent of the inside-facing surface covered ranged from 0.02 to 0.78%. The coverage achieved by the airblast sprayer at 468 L/ha was significantly greater than with 187 L/ha, and also greater than the AARA at all sprayer volumes tested. Intermediate coverage was achieved with the airblast sprayer with the 935 L/ha water volume treatment. On the outside-facing berries, the percent surface area covered was an order of magnitude higher than for the inside-facing berries. The percent coverage was highest with the airblast at 468 L/ha, and when combined the airblast sprayer at 935 L/ha provided greater surface coverage than all of the AARA treatments. When the data were analyzed separately for each sprayer, the percent surface area covered varied significantly among water volumes when measured on the inside- ( $F = 4.09$ ;  $df = 2,21$ ;  $P = 0.032$ ) and outside-facing surface of the berries ( $F = 17.34$ ;  $df = 2,27$ ;  $P < 0.0001$ ), with the airblast 468 L/ha volume providing the highest values. For the AARA sprayer, there were no significant differences among water volumes in the percent surface area covered for the inside- ( $F = 1.11$ ;  $df = 2,9$ ;  $P = 0.37$ ) or outside-facing surface ( $F = 0.44$ ;  $df = 2,22$ ;  $P = 0.65$ ) of the berries.

Inside-facing surfaces of the berries received far fewer spray deposits than the outside surfaces (Table 1). The density of spray deposits per unit area did not vary with sprayer or volume on the inside-facing surface of the berries (Table 1), but the treatments had a significant effect on deposit density of the outside-facing surfaces. Deposit densities were highest on the outside of berries treated with the airblast sprayer at low and medium water volumes. In the case of the airblast sprayer, water volume did not affect the density of spray deposits on either the inside-facing ( $F = 3.06$ ;  $df = 2,21$ ;  $P = 0.068$ ) or outside-facing ( $F = 2.77$ ;

**Table 1**  
Mean (SE) values of coverage parameters for deposits of kaolin on grape clusters within a mature juice grape (var. "Niagara") canopy. Measurements were taken from the inside-facing (A) and outside-facing (B) surface of berries positioned on the sprayer side of canopy, and collected after application of kaolin from airblast or air-assisted rotary atomizer (AARA) sprayers, each tested at three appropriate water volumes. Means within a column followed by the same letter are not significantly different at  $\alpha < 0.05$ .

Sprayer	Volume (L/ha)	Coverage (% of area)	Deposit density (No./cm <sup>2</sup> )	Deposit diameter ( $\mu$ m)	Between-deposit distance ( $\mu$ m)
<b>A. Inside-face of berries</b>					
AARA	47	0.13 (0.11) b	18.6 (12.0) a	21.1 (4.5) bc	650.2 (229.5) ab
	93	0.02 (0.01) b	5.8 (1.9) a	12.7 (1.5) c	500.6 (181.1) ab
	187	0.03 (0.01) b	8.0 (2.8) a	15.6 (2.3) bc	681.7 (111.4) a
Airblast	187	0.10 (0.04) b	10.4 (2.7) a	23.7 (2.2) abc	628.1 (105.7) a
	468	0.78 (0.32) a	18.9 (5.0) a	44.1 (7.7) a	440.5 (120.2) ab
	935	0.49 (0.18) ab	26.1 (6.9) a	30.5 (5.5) ab	228.5 (59.2) b
		$F = 5.06$ $P = 0.001$	$F = 2.05$ $P = 0.091$	$F = 7.23$ $P < 0.0001$	$F = 2.95$ $P = 0.023$
<b>B. Outside-face of berries</b>					
AARA	47	1.1 (0.4) c	61.9 (11.2) ab	24.7 (1.7) d	196.0 (29.8) ab
	93	0.8 (0.6) c	56.9 (29.9) b	24.1 (2.3) d	404.2 (95.2) a
	187	1.7 (0.8) c	90.2 (29.8) ab	30.3 (2.7) cd	258.1 (75.2) ab
Airblast	187	3.5 (0.8) bc	124.3 (20.9) a	39.9 (2.5) bc	129.2 (10.3) b
	468	12.9 (2.5) a	135.6 (23.5) a	58.1 (4.5) a	107.5 (10.2) b
	935	4.9 (0.9) b	82.2 (17.0) ab	55.7 (7.1) ab	153.1 (34.2) b
		$F = 20.50$ $P < 0.0001$	$F = 4.28$ $P = 0.002$	$F = 20.14$ $P < 0.0001$	$F = 5.31$ $P = 0.0004$

df = 2,28;  $P = 0.080$ ) surfaces of berries. Water volume also had no effect on the density of spray deposits for the AARA sprayer at either position (inside-facing:  $F = 0.43$ ; df = 2,8;  $P = 0.67$ ; outside-facing:  $F = 1.83$ ; df = 2,24;  $P = 0.18$ ).

The largest individual spray deposits were achieved using the airblast sprayer at 468 L/ha, for both the inside-facing and outside-facing surfaces of the berries (Table 1). The airblast sprayer operating at 468 L/ha volume produced significantly larger diameter deposits on the outside-facing surfaces of berries than the airblast sprayer at 187 L/ha, and was larger than all AARA treatments in both berry surface positions. For the AARA sprayer, when analyzed separately, there was no significant difference in the size of spray deposits for either the inside- ( $F = 1.87$ ; df = 2,17;  $P = 0.18$ ) or outside-facing ( $F = 2.51$ ; df = 2,24;  $P = 0.10$ ) surface of berries.

Distances between deposits on the inside-facing surfaces of berries were not significantly different among water volumes for the AARA sprayer ( $F = 0.69$ ; df = 2,8;  $P = 0.53$ ) (Table 1). The distance between deposits decreased as the water volume increased in the airblast treatments ( $F = 6.31$ ; df = 2,21;  $P = 0.0072$ ). The distance between deposits for the highest airblast sprayer volume was one third of that for the highest volume applied through the AARA sprayer, and deposits were closer together on the outside-facing surfaces of berries than on the inside-facing, reflecting the difficulty in penetrating the interior surfaces of grape clusters.

### 3.2. Control of *P. viteana*

The different combinations of sprayer and water volume provided varying levels of control of *P. viteana* with both fenprothrin and methoxyfenozide, although the relationship between level of control and the amount of water applied was not the same between the two sprayers. Superior insect control was found at the lower water volume applied with the AARA sprayer and at the higher volume applied in the airblast sprayer (Table 2). For 1-day-old methoxyfenozide and fenprothrin-treated clusters, applications with the AARA sprayer at 47 L/ha and the airblast sprayer at 468 L/ha were the only combinations that provided significant fruit protection, compared to the untreated clusters. Once the residues had aged under vineyard climatic conditions for six days, a similar pattern was observed, except that methoxyfenozide applied with the AARA no longer controlled *P. viteana* (Table 2). This suggests

that deposition patterns associated with the AARA are adequate for contact poisons like fenprothrin, but are not optimal for ingestion-active IGRs like methoxyfenozide.

All treatments provided significant activity on *P. viteana* in terms of survival of the insect to pupation (Table 2). Survival was significantly lower in plots treated with insecticide compared to untreated plots at both 1 and 6 DAT. The only treatment combination that did not significantly reduce survival was fenprothrin with the airblast sprayer at the lower water volume of 187 L/ha at 1 DAT. When results from the fenprothrin treatments were analyzed to compare water volumes within each sprayer separately (excluding the untreated plot), *P. viteana* survival was significantly lower at 1 and 6 DAT for the airblast sprayer at 468 L/ha compared to 187 L/ha ( $F = 6.95$ ; df = 1,9;  $P = 0.027$  and  $F = 10.75$ ; df = 1,9;  $P = 0.0095$ , respectively). Survival of *P. viteana* was also significantly lower in fenprothrin-treated plots at 1 DAT for the AARA sprayer at 47 L/ha compared to 187 L/ha ( $F = 20.53$ ; df = 1,6;  $P = 0.004$ ), but there was no significant difference between water volumes at 6 DAT ( $F = 4.33$ ; df = 1,9;  $P = 0.067$ ). A similar analysis of the methoxyfenozide data found no significant differences between water volumes in *P. viteana* survival for either sprayer at either of the times after treatment ( $F < 1.72$ ,  $P > 0.23$ ).

### 3.3. Control of fungal diseases

Different diseases predominated in 2005 and 2007; August 2005 was relatively dry, resulting in considerable foliar powdery mildew pressure; whereas in late July and early August 2007 the greater incidence of precipitation led to more downy mildew infection periods. Powdery mildew was absent in 2007. In addition, black rot on fruit clusters was more severe in 2005, whereas *Phomopsis* cluster infection was more severe in 2007. This allowed the evaluation of the effects of fungicide and spray volume against a variety of diseases. The untreated control usually sustained the most disease, although Ziram applied at 187 L/ha often was not significantly different from the untreated control (Fig. 1). In general, the type of fungicide affected disease control more than did water volume. In 2005, the systemic fungicide Abound provided significantly better control of foliar powdery mildew ( $F = 7.38$ ; df = 1,8;  $P = 0.0264$ ), black rot ( $F = 6.97$ ; df = 1,8;  $P = 0.0297$ ), *Phomopsis* rachis infection ( $F = 10.26$ ; df = 1,8;  $P = 0.0126$ ), and *Phomopsis* fruit infection ( $F = 9.61$ ; df = 1,8;  $P = 0.0139$ ) than the protectant

**Table 2**

Mean (SE) number of berries infested and percent survival of *P. viteana* on juice grape (var. "Niagara") clusters evaluated at 1 day after treatment application (DAT) and 6 DAT, resulting from field-treated fenpropathrin (224 g AI/ha) or methoxyfenozide (210 g AI/ha) with an airblast or air-assisted rotary atomizer (AARA) sprayer, each tested at two water volumes. Means within a column followed by the same letter are not significantly different at  $\alpha < 0.05$ .

Insecticide	Sprayer	Volume (L/ha)	# Berries Infested				% Survival			
			1 DAT		6 DAT		1 DAT		6 DAT	
Untreated			22.0 (1.8)	a	19.1 (2.0)	a	81.2 (3.1)	a	78.0 (6.1)	a
Fenpropathrin	AARA	47	6.1 (1.5)	c	11.4 (1.7)	b	23.9 (11.5)	b	37.0 (6.3)	b
		187	9.1 (0.9)	abc	15.4 (1.9)	ab	33.1 (4.9)	b	51.0 (7.2)	b
	Airblast	187	12.6 (1.5)	ab	13.9 (1.7)	ab	42.3 (5.6)	ab	44.0 (4.0)	b
		468	8.6 (2.6)	bc	9.2 (1.1)	b	23.7 (6.2)	b	26.0 (4.0)	b
			$F = 7.92$ $P = 0.0001$		$F = 5.03$ $P = 0.0025$		$F = 6.55$ $P = 0.0007$		$F = 11.77$ $P < 0.0001$	
Untreated			22.0 (1.8)	a	19.1 (2.0)	a	81.2 (3.1)	a	78.0 (6.1)	a
Methoxyfenozide	AARA	47	7.1 (1.8)	c	9.8 (1.1)	abc	24.2 (6.8)	b	19.0 (3.5)	b
		187	11.4 (1.5)	abc	11.2 (1.1)	ab	32.4 (9.7)	b	29.0 (6.0)	b
	Airblast	187	15.4 (2.3)	ab	10.0 (1.7)	bc	42.6 (9.3)	b	27.8 (4.9)	b
		468	8.5 (1.0)	bc	7.0 (1.9)	c	24.8 (10.0)	b	18.0 (5.5)	b
			$F = 7.03$ $P = 0.0003$		$F = 7.45$ $P = 0.0002$		$F = 5.55$ $P = 0.0018$		$F = 16.16$ $P < 0.0001$	

fungicide Ziram. Foliar downy mildew severity was low that year such that both fungicides provided complete control. Spray volume of the airblast sprayer significantly affected fungicide performance against foliar powdery mildew in 2005 ( $F = 9.37$ ;  $df = 1,8$ ;  $P = 0.0156$ ), with 468 L/ha being better than 187 L/ha. This was most apparent in the case of Ziram (Fig. 1). Although a spray volume of 468 L/ha showed a consistent trend towards being more efficacious than 187 L/ha, the effect of spray volume was not statistically significant at  $\alpha = 0.05$  for the other diseases. However, the effect of spray volume on *Phomopsis* fruit infection was significant at  $\alpha = 0.10$  ( $F = 4.38$ ;  $df = 1,8$ ;  $P = 0.0658$ ). The interaction of spray volume and fungicide type was significant only for powdery mildew ( $F = 5.51$ ;  $df = 1,8$ ;  $P = 0.0469$ ), where the efficacy of Ziram was sensitive to spray volume than that of Abound (Fig. 1).

In 2007, the effect of fungicide type was significant for downy mildew ( $F = 60.68$ ;  $df = 1,8$ ;  $P = 0.0001$ ), *Phomopsis* rachis infection ( $F = 8.80$ ;  $df = 1,8$ ;  $P = 0.0180$ ) and *Phomopsis* fruit infection ( $F = 9.37$ ;  $df = 1,8$ ;  $P = 0.0005$ ), but not for black rot in 2007 (Fig. 2). Abound generally showed higher levels of disease control than Ziram. Spray volume did not significantly affect fungicide efficacy against any of the diseases in 2007, nor were there significant interactions between spray volume and fungicide type.

#### 4. Discussion

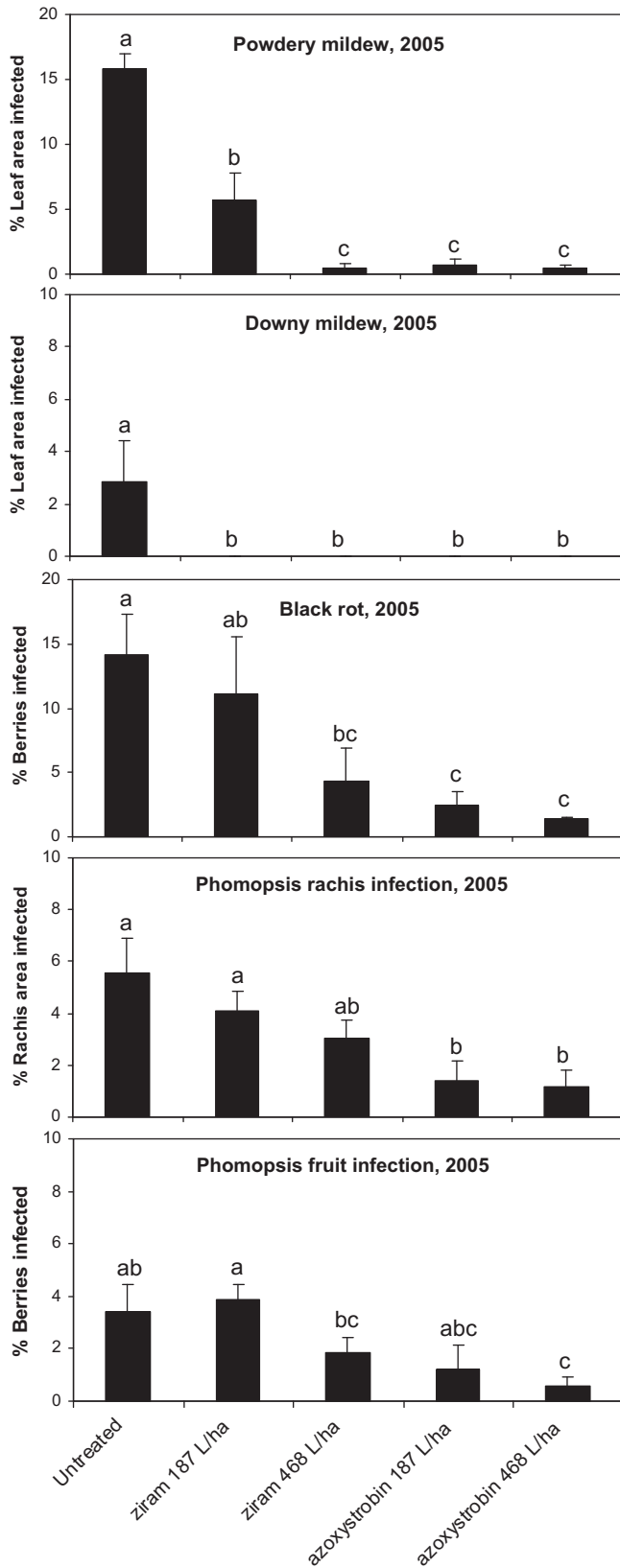
Our study demonstrated the influence of water volume on the ability of vineyard sprayers to effectively cover grape clusters with pesticides. The results show that unique combinations of sprayer type, water volume and pesticide provide optimal performance against key insect pests and fungal diseases of vineyards in the eastern United States. Water volume was shown to influence the quality of pesticide deposition by the airblast sprayer and by the AARA sprayer. Deposition of the kaolin tracer by the airblast sprayer operated at 468 L/ha provided the highest percentage of coverage of the inner and outer berry surfaces, one of the highest deposit densities, and the highest deposit diameter on the inside-facing and outside-facing of the berry. While these measurements of coverage are interrelated, they provide evidence that coverage of the target can be optimized for an airblast sprayer by selecting the appropriate water volume.

For the AARA sprayer, increasing water volume had little effect on the coverage of clusters, and bioassays showed that water volume can be reduced to 47 L/ha without loss of performance. This is highly desirable for efficient farm operation and to minimize the

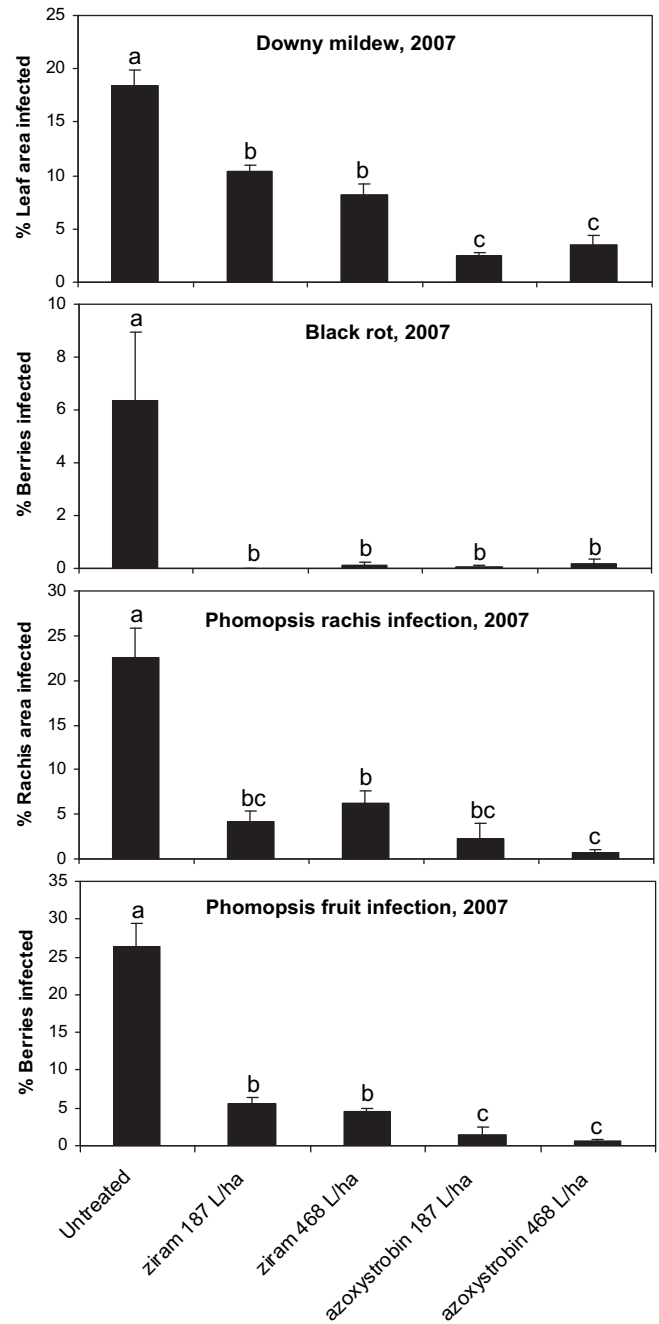
expense of pesticide application. Our bioassays with *P. viteana* showed that grape cluster coverage does not directly correspond with pest control. Even though the AARA sprayer (47 L/ha) produced significantly lower percentage surface area coverage than the airblast sprayer, both on inside-facing and outside-facing berry surfaces, its performance was equal to or better at either volume in controlling *P. viteana*. Landers et al. (2000), with a similar AARA sprayer to the one used in this study at a rate of 281 L/ha, showed improved performance compared to an airblast sprayer at 468 L/ha in grape efficacy trials against diseases and insect pests in New York (Landers et al., 2000). The diameter of the deposits may be a key variable to explain the consistently high level of performance of the AARA (47 L/ha) in terms of *P. viteana* control. While total kaolin deposition by AARA and airblast sprayers on grape clusters in this study was very similar, the AARA sprayer generally produced lower percentage surface area coverage and smaller diameter deposits, suggesting that this deposition pattern is more efficient in controlling *P. viteana*. Spray deposition efficiency has similarly been shown by others to decrease as spray droplet size increases (Smith et al., 2000; Giles et al., 2002). In a laboratory setting, Alm et al. (1989) found that 90% mortality of *P. viteana* larvae was achieved with a reduced concentration of fenpropathrin and 1.1% coverage with 120  $\mu\text{m}$  droplets (0.125  $\mu\text{g}$  [AI]/ $\text{cm}^2$ ), as was achieved with a higher insecticide rate and 1.3% coverage with 200  $\mu\text{m}$  droplets (0.250  $\mu\text{g}$  [AI]/ $\text{cm}^2$ ).

Our study indicates, however, that this optimal concentration pattern, shown by Alm et al. (1989), may be in part dependant on the mode-of-action of the insecticide being used. Our bioassays showed when insecticide residues are fresh (1 day old) and thus at their highest toxicity, that water volume does not influence infestation levels of *P. viteana* for either sprayer. After insecticide residues had aged in the field for 6 days, however, only fenpropathrin provided significant control with both the AARA and airblast sprayer. When methoxyfenozide was sprayed by the AARA it did not maintain control of *P. viteana* out to 6 DAT, whereas applied with the airblast sprayer it did.

This is likely because of the differences in mode of action between these two insecticide chemistries, methoxyfenozide being an ingestion-active IGR, and fenpropathrin a contact nerve poison. The optimal deposition patterns of the AARA (47 L/ha) and airblast sprayer (468 L/ha) are both adequate when exposure of a mobile insect stage is to a contact insecticide. When pest exposure must result in ingestion of the insecticide, as in the case of this IGR, the deposition pattern by the airblast sprayer is superior. Future



**Fig. 1.** Disease control efficacy (mean ± SE) of two fungicides (ziram and azoxystrobin) applied with an airblast sprayer at two spray volumes (187 or 468 L/ha) in *Vitis labrusca* “Niagara” grapes in Fennville, MI, in 2005. Sprays were applied five times at 2- to 3-week intervals starting at immediate pre-bloom. Bars sharing the same letter are not significantly different according to Fisher’s Protected LSD at  $P < 0.05$ .



**Fig. 2.** Disease control efficacy (mean ± SE) of two fungicides (ziram and azoxystrobin) applied with an airblast sprayer at two spray volumes (187 or 468 L/ha) in *Vitis labrusca* “Niagara” grapes in Fennville, MI, in 2007. Sprays were applied five times at 2- to 3-week intervals starting at immediate pre-bloom. Bars sharing the same letter are not significantly different according to Fisher’s Protected LSD at  $P < 0.05$ .

evaluation of the effects of treated fruit and foliage on the survival of insect egg and adult stages (Dennehy et al., 1990) may provide a more complete understanding of the relative effect of varying canopy coverage on the control of this pest.

The effect of spray deposition on control of diseases is another component of the vineyard management system that can be optimized according to sprayer, water volume and pesticide chemistry. Viret et al. (2003) found that sprayer type had a significant effect on coverage and control of powdery mildew on Swiss wine grapes, with large differences among sprayers in the amount of off-target pesticide deposition. We found that spray volume of the airblast

sprayer significantly affected control of foliar powdery mildew in 2005. However, the effect of fungicide type was more apparent, with the systemic fungicide Abound generally providing better control of foliar and cluster diseases than the protectant fungicide Ziram. While this difference may be due to better inherent activity of Abound, it may also be the result of Ziram washing off more readily since it is strictly a surface fungicide. In the case of powdery mildew in 2005, spray volume affected the efficacy of Ziram but not that of Abound. This demonstrates that the systemic movement of Abound within plant tissues compensates for differences in deposition, whereas the protectant fungicide Ziram is more directly dependent on the quality of surface coverage achieved from the spray. A tendency towards better performance of both fungicides at the higher spray volume (486 L/ha) was noticeable. This suggests that under high disease pressure, when fungicide performance is crucial, using an airblast sprayer with a low spray volume will provide less effective disease control. This is an important consideration, particularly as fungicide inputs continue to become more expensive, without concomitant increases in economic returns in juice grape production. A systemic fungicide such as Abound, however, may be able to maintain high levels of performance with low-volume sprayers represented by the AARA sprayer in this study. Further research is needed to confirm this.

The results of this study emphasize the need for appropriate water volume relative to the sprayer being used to achieve pest control in juice grape vineyards, particularly as canopy density increases after bloom. Our results also demonstrate that pest control in vineyards is not only influenced by sprayer type and water volume, but also the individual characteristics of the pesticide being selected for the given target pest. Exploration of approaches to optimize cluster coverage should provide significant benefit in terms of improved pest control and reduced need for pesticide application.

## Acknowledgments

We would like to thank Dr. Gary Van Ee and Richard Ledebuhr, TNRC staff members Jason Seward, Ryan VanderPoppen, and Ann Hanley, the Schilder lab, and Mark Vander Werp for their technical assistance with this project. We gratefully acknowledge the funding for this project provided by Michigan Agricultural Experiment Station, Project GREEN, the National Grape Cooperative, and the Michigan Grape and Wine Industry Council.

## References

- Alm, S.R., Reichard, D.L., Williams, R.N., Hall, F.R., 1989. Mortality of first-instar grape berry moths (Lepidoptera: Tortricidae) due to dosage and size of spray drops containing fenprothrin. *J. Econ. Entomol.* 82, 1180–1184.
- Balsari, P., Marucco, P., 2005. Sprayer adjustment and vine canopy parameters affecting spray drift: The Italian experience. In: Proceedings, International Conference on Pesticide Application for Drift Management, Washington, DC, pp. 109–115.
- Biever, K.D., Hostetter, D.L., 1989. Phenology and pheromone trap monitoring of the grape berry moth, *Endopiza viteana* Clemens (Lepidoptera: Tortricidae) in Missouri. *J. Entomol. Sci.* 24, 472–481.
- Carlson, G.R., Dhadialla, T.S., Hunter, R., Jansson, R.K., Jany, C.S., Lidert, Z., Slawewski, R.A., 2001. The chemical and biological properties of methoxyfenozide, a new insecticidal ecdysteroid agonist. *Pest Manag. Sci.* 57, 115–119.
- Dami, I., Bordelon, B., Ferree, D.C., Brown, M., Ellis, M.A., Williams, R.N., Doohan, D., 2005. Midwest Grape Production Guide. The Ohio State University Extension Bulletin 919-05.
- Dennehy, T.J., Hoffman, C.J., Nyrop, J.P., Saunders, M.C., 1990. Development of low-spray, biological, and pheromone approaches for control of grape berry moth, *Endopiza viteana* Clemens, in the eastern United States. In: Bostanian, N.J., Wilson, L.T., Dennehy, T.J. (Eds.), *Monitoring and Integrated Management of Arthropod Pests of Small Fruit Crops*. Intercept Ltd., Andover, NH, pp. 261–282.
- Giles, D.K., Andersen, P.G., Nilars, M., 2002. Flow control and spray cloud dynamics from hydraulic atomizers. *Trans. ASABE* 45, 539–546.
- Hanson, E., Hancock, J., Ramsdell, D.C., Schilder, A.M.C., Van Ee, G., Ledebuhr, R., 2000. Sprayer type and pruning affect the incidence of blueberry fruit rots. *HortScience* 35, 235–238.
- Hartley, B.S., Brunskill, R.T., 1958. Reflection of water drops from surfaces, pp. 402–469. In: Danielli, J.F., Pankhurst, K.G.A., Riddiford, A.C. (Eds.), *Surface Phenomena in Chemistry and Biology*. Pergamon Press, New York, NY.
- Hewitt, A.J., 2005. Pesticide chemistry and adjuvants. In: Proceedings, International Conference on Pesticide Application for Drift Management, Washington, DC, pp. 132–135.
- Isaacs, R., Mercader, R.J., Wise, J.C., 2004. Activity of conventional and reduced-risk insecticides for protection of grapevines against the rose chafer, *Macroctylus subspinosus* (Coleoptera: Scarabaeidae). *Am. J. Enol. Vitic* 128, 371–376.
- Isaacs, R., Mason, K.S., Maxwell, E., 2005. Stage-specific control of grape berry moth, *Endopiza viteana* (Clemens) (Lepidoptera: Tortricidae), by selective and broad-spectrum insecticides. *J. Econ. Entomol.* 98, 415–422.
- Jenkins, P.E., Isaacs, R., 2007. Reduced-risk insecticides for control of grape berry moth (Lepidoptera: Tortricidae) and conservation of natural enemies. *J. Econ. Entomol.* 100 (3), 855–865.
- Landers, R., 2002. Airblast sprayers. In: Pimentel, D. (Ed.), *Encyclopedia of Pest Management*. Marcel Dekker, New York, NY, pp. 11–12.
- Landers, A., 2004. Optimizing spray penetration and deposition with airblast sprayers in New York and Pennsylvania. *Am. J. Enol. Vitic*, 55, p 434A.
- Landers, A., Wilcox, W., English-Loeb, G., Martinson, T.E., Dunst, R., 2000. Evaluation of a controlled droplet sprayer to control disease and insects on grapes in New York. New York State Agricultural Experiment Station, Geneva, NY.
- Landers, A., Farooq, M., 2005. Reducing drift and improving deposition in vineyards. In: Proceedings, International Conference on Pesticide Application for Drift Management, Washington, DC, pp. 385–391.
- Pergher, G., Gubiani, R., 1995. The effect of spray application rate and airflow rate on foliar deposition in a hedgerow vineyard. *J. Agric. Eng. Res.* 61, 205–216.
- Puterka, G.J., Glenn, D.M., Sekutowski, D.G., Unruh, T.R., Jones, S.K., 2000. Progress toward liquid formulations of particle films for insect and disease control in pear. *Environ. Entomol.* 29, 329–339.
- Reilly, C.C., Taylor, K.C., Hotchkiss, M.W., 2004. A comparison of airblast and air assisted rotary atomizer spray technologies in peach production. *HortTech* 14, 555–559.
- Reynold, A.G., Vanden Heuvel, J.E., 2009. Influence of grapevine training systems on vine growth and fruit composition: A review. *Am. J. Enol. Vitic* 60 (3), 251–268.
- SAS Institute, 2003. SAS/STAT User's Manual, version 9.1. SAS Institute, Cary, NC.
- Schilder, A.M.C., Gillett, J.M., Sysak, R.W., Wise, J.C., 2002. Evaluation of fungicides for control of foliar and fruit diseases in Niagara grapes, 2001. Fungicide and Nematicide Test Reports 57, SMF15.
- Schilder, A.M.C., Gillett, J.M., Sysak, R.W., 2006. Evaluation of fungicides and spray timing for control of Phomopsis in Niagara grapes, 2005. Fungicide and Nematicide Tests (online) 57: SMF15. DOI:10.1094/FN57. The American Phytopathological Society, St. Paul, MN.
- Smith, D.B., Askew, S.D., Morris, W.H., Shaw, D.R., Boyette, M., 2000. Droplet size and leaf morphology effects on pesticide spray deposition. *Trans. ASAE* 43 (2), 255–259.
- Tadros, T.F., 1987. Interactions at interfaces and effects on transfer and performance. *Aspects Appl. Biol.* 14, 1–22.
- Tobin, P.C., Nagarkatti, S., Saunders, M.C., 2003. Phenology of grape berry moth (Lepidoptera: Tortricidae) in cultivated grape at selected geographic locations. *Environ. Entomol.* 32, 340–346.
- Usda Nass (United States Department of Agriculture, National Agricultural Statistics Service), 2008. 2007 Farm Production Expenditures Summary. Available from: [http://www.nass.usda.gov/Newsroom/2008/08\\_07\\_2008.asp](http://www.nass.usda.gov/Newsroom/2008/08_07_2008.asp) (11.2009).
- USEPA (United States Environmental Protection Agency), 1996. Food Quality Protection Act. U.S. Public Law 104-170. U.S. Congressional Record vol. 142, 1489–1538. Available from: <http://www.epa.gov/pesticides/regulating/laws/fqpa/gpogate.pdf> (11.2009).
- USEPA (United States Environmental Protection Agency), 1997. Guidelines for expedited review of conventional pesticides under the reduced-risk initiative and for biological pesticides. Pesticide Registration (PR) Notice 97-3(1997). Available from: [http://www.epa.gov/PR\\_Notices/pr97-3.html](http://www.epa.gov/PR_Notices/pr97-3.html) (11.2009).
- Van Ee, G., Ledebuhr, R., Hanson, E., Hancock, J., Ramsdell, D.C., 2000. Canopy development and spray deposition in highbush blueberry. *HortTech* 10, 353–359.
- Viret, O., Siegfried, W., Holliger, E., Raisigl, U., 2003. Comparison of spray deposits and efficacy against powdery mildew of aerial and ground-based spraying equipment in viticulture. *Crop Protect* 22, 1023–1032.
- Walklate, P.J., Cross, J.V., Richardson, G.M., Murray, R.A., Baker, D.E., 2002. Comparison of different spray volume deposition models using LIDAR measurements of apple orchards. *Biosyst. Eng* 82, 253–267.
- Ware, G., Whitecre, D., 2004. *The Pesticide Book*. Meister Media, Willoughby, OH, USA.
- Wise, J.C., Schoenborn, K., Isaacs, R., 2005. Control of grape berry moth in “Concord” grape, 2004. *Arthropod Manage. Tests*. 30, C26.
- Wise, J.C., Schilder, A.M.C., Zandstra, B., Hanson, E., Gut, L., Isaacs, R., Sundin, G., 2008. 2009 Michigan fruit management guide. MSUE Bulletin E-154. Michigan State University, East Lansing, MI.
- Wong, F.P., Wilcox, W.F., 2001. Comparative physical modes of action of azoxystrobin, mancozeb, and metalaxyl against *Plasmopara viticola* (grapevine downy mildew). *Plant Dis* 85, 649–656.