FOLIAR DEPOSITION AND OFF-TARGET LOSS WITH DIFFERENT SPRAY TECHNIQUES IN NURSERY APPLICATIONS

H. Zhu, R. C. Derksen, H. Guler, C. R. Krause, H. E. Ozkan

ABSTRACT: Information is lacking on spray techniques to improve deposit uniformity within nursery canopies and reduce off-target loss on the ground and via spray drift from the treated area. Spray deposits at various elevations within crabapple trees and on the ground were investigated with an air blast sprayer equipped with conventional hollow-cone nozzles, air-induction nozzles, and conventional hollow-cone nozzles with a drift retardant in a commercial nursery field. Airborne deposits at three elevations on sampling towers and on the ground at several distances from the sprayer were also investigated with the three spray treatments in an open area without trees. To compare field test results, wind tunnel experiments were conducted to assess spray deposits on the floor beyond 0.4 m downwind distance from the nozzles and airborne deposits at 2.1 m downwind from the spray discharge point with the three spray techniques without air assist. Droplet size distributions across spray patterns without air assist were measured with a laser particle/droplet image analysis system. In general, there was no significant difference for deposits within nursery tree canopies and on the ground with three different spray techniques. At the 700 L/ha application rate, which was 360 L/ha lower than the rate typically used in nursery application, the tree canopies received over 4 to 14.5 times as much spray deposit as actually needed from all treatments, and a large portion of spray volume deposited on the ground. Compared with conventional hollow-cone nozzles, drift reduction from air-induction nozzles or the spray mixture with drift retardant treatment was significant in wind tunnel tests but was not significant in field tests.

Keywords. Air blast sprayer, Airborne, Air-induction nozzle, Drift, Drift retardant, Ground deposit, Low-drift nozzle, Nursery crop, Spray nozzle.

The floral and nursery industries produce high-value crops that require more complicated pest control strategies and more intensive labor than field crop production. Applications of pesticides and other production strategies have ensured adequate and high-quality plants that meet consumer preferences for a wide variety of canopy structure characteristics, growing conditions, and marketing requirements. However, concerns have been raised over the extent of pesticide contamination to the soil, surface water, and ground water from excessive amounts of pesticides. Pesticide contamination in the environment potentially threatens the quality of life and safety of nearby residents because many nurseries operate in small areas close to residential districts and urban or suburban areas. Consequently, environmentally friendly pesticide application is essential for nursery production.

Although the nursery and horticultural industries are among the fastest growing enterprises in U.S. agriculture, little research has been done to optimize their spray application strategies (Krause et al., 2004). Due to crop similarity, air-assisted application technologies for apple and citrus orchards (Fox et al., 1993; Salyani et al., 1987; Doruchowski et al., 1996) are normally adapted to nursery tree crops. However, compared with orchard crops, nursery trees are usually narrow and sharp and are difficult to apply pesticide with conventional delivery systems. Derksen et al. (2004) investigated canopy deposits, spray coverage, and downwind ground deposits from an air blast sprayer and an air curtain sprayer in a nursery field with red maple trees, and found adjustments were necessary to sprayer settings used for orchard applications to obtain uniform spray deposits in nursery applications.

Drift retardants were reported to reduce spray drift in many laboratory studies (Yates et al., 1976; Haq et al., 1982; Ozkan et al., 1992; Salyani and Cromwell, 1992; Smith, 1993). Laboratory tests indicated that drift retardants increased the volume median diameter of spray initially, but most polymer-based drift retardants lost effectiveness when recirculated through pumps (Bouse et al., 1988; Reichard et al., 1996; Zhu et al. 1997). In addition, considerable time and care is required to mix drift retardants with spray carriers. Although there are some disadvantages with adding drift retardant additives to spray mixtures, some nursery growers have expressed an interest in using these chemicals if they...
Air-induced nozzles can reduce potential drift damage to adjacent crops or contamination of nearby residential areas.

During the past decade, several types of hydraulic air-induction nozzles (also called “low-drift” nozzles) were introduced into the market for improving pesticide delivery methods and reducing drift. These nozzles have been reported to have greater volume deposits in the lower part of canopies (Zhu et al., 2004) because they produce a greater portion of large droplets than conventional hydraulic nozzles (Koch et al., 2001). Some reports indicated these “low-drift” nozzles did not significantly reduce drift in orchards (Heijne et al., 2002; Landers, 2000). Most air-induction nozzles were configured with two small holes in the nozzle chamber just upstream from the nozzle orifice. Those holes induce air into the liquid flow due to the Venturi effect and reduce pressure at the nozzle orifice.

To obtain the optimum pesticide spray management practices in nurseries, delivery systems must be operated economically and effectively with minimum canopy disturbance and minimum spray drift. Transport of spray to target plant surfaces with high-quality atomization is essential to ensure effective spray application in crop protection. Limited information is available on nursery crop production practices for applications of required amounts of pesticides to achieve effective pest control with minimum chemical loss. Spray trials with drift retardants or air-induction nozzles used for nursery tree applications have not been reported in the literature. Questions remain whether drift retardants and air-induction nozzles have potential advantages over conventional nozzles in nurseries, and whether performance similar to air-induction nozzles can be achieved with larger conventional hydraulic nozzles operating at reduced pressure.

The objectives of this research were: (1) to investigate and compare spray deposits within tree canopies and off-target loss to the ground from an air blast sprayer with conventional hollow-cone nozzles, conventional hollow-cone air-induction nozzles applying a drift retardant, and air-induction nozzles in a commercial nursery field; and (2) to verify the results from tests in the nursery field by further investigating airborne and ground deposits with the three spray techniques in an open field and in a wind tunnel under simplified conditions.

**Materials and Methods**

**Foliar Spray Deposits and Ground Deposit Loss in Field 1**

A model 1500 air blast sprayer (Durand-Wayland, Inc., LaGrange, Ga.) was used, and operated with five identical nozzles equally spaced on one side of the 0.91 m diameter air deflector. The sprayer produced 40 m/s average air velocity near the nozzles when operated at the high gear setting. The air from the fan was discharged toward the sprayed tree rows. Spray deposits within crabapple tree canopies and on the ground were compared with three different spray treatments: hollow-cone nozzles with water only (HC), hollow-cone nozzles with water and a drift retardant (HCDR), and air-induction nozzles with water only (AI). Nozzles used for HC and HCDR were five conventional hollow-cone nozzles (D5-45, Spraying Systems Co., Wheaton, Ill.), and nozzles used for AI were five flat-fan air-induction nozzles (AI110-08, Spraying Systems Co., Wheaton, Ill.). The flow rate from the sprayer was maintained at 24.2 L/min for all three application methods. To obtain the 24.2 L/min flow rate, the sprayer operating pressure was adjusted to 1660 kPa for HC and HCDR and 830 kPa for AI. The sprayer travel speed was 6.4 km/h, resulting in an application rate of 700 L/ha. A typical application rate in commercial nurseries is 1060 L/ha with varying nozzle flow rates so that the capacity of the nozzles at the top of the sprayer is three times the capacity of individual nozzles. This is similar to the recommendation for orchard applications.

The spray mixture used in the two trials was 3 g of Brilliant Sulfaflavine (MP Biomedicals, Inc., Aurora, Ohio) per liter of water for HC, HCDR, and AI. For HCDR, the spray mixture was additionally mixed with STA-PUT drift retardant distributed by Helena Chemical Company (Collierville, Tenn.). The drift retardant was a liquid formulation with 1% polyvinyl polymer as active ingredient. Concentration of the drift retardant used in the HCDR tank mixture was 0.49% (v/v), as recommended by the manufacturer.

Spray deposits within tree canopies and on the ground were evaluated with two trials in field 1 at different times during the growing season. Spray settings for both trials were the same. Field 1 was 200 m long and 30 m wide with seven rows of Spring Snow crabapple trees and five rows of short shrubs. The two species were alternately planted with one row of crabapple trees and one row of shrubs after the first three rows of crabapple trees at the south side of the field. The fourth row of crabapple trees was selected for the spray test. The crabapple trees averaged 2.6 m tall, and the average width of trees 0.9 m above the ground was 1.05 m. Within the first 0.9 m from the ground, there were very few leaves on the stem. Spacing between trees within a row was 1.5 m. The shrubs averaged 1.2 m tall and 1.1 m wide. Except for an open area to the north, field 1 was surrounded by many other plantings with different species of nursery trees, and all plantings and nursery trees were shorter than 3.2 m.

Ten crabapple trees in the fourth row at the south side of field 1 were randomly selected for sampling in trials 1 and 2 (fig. 1). Monofilament nylon screens (Filter Fabrics, Inc., Goshen, Ind.) were used to simulate leaves to collect foliar spray deposits within ten crabapple tree canopies. Each screen size was 5 × 5 cm. Fox et al. (2004) reported the airborne collection efficiency of spray droplets for this type of screen ranged from 50% to 70%, which was much better than flat solid collectors. The screen had a nominal porosity of approximately 56% or fiber frontal area percentage of 44%. Each tree had 12 screens located in four different elevations (fig. 2), and each screen was hung with a clip attached to a branch of the tree. The screens at the 0.9 m elevation were near the bottom edge of the tree leaf area. Positions of screens shown in figure 2 were at the approximately average locations of screens in ten trees. Screens were placed as close as possible to the tree row centerline.

Spray deposits on the ground beneath trees and between two trees in the sprayed row were collected with two rows of 15 × 33 cm plastic plates (fig. 1). The first row of plastic plates was placed 0.15 m in front of the tree centerline, and the second row of plastic plates was 0.15 m behind the tree centerline. Each plastic plate was stabilized on a 15 × 33 cm wooden board with two clips to prevent the plate from being blown away by air from the sprayer.

Spray deposits on the ground beyond the sprayed row were collected with 5 cm wide × 245 cm long plastic tapes at four
different distances downstream from the sprayer centerline (fig. 1). The distances of the four rows of tapes were 4.5, 7.5, 10.5, and 15.0 m from the sprayer centerline, respectively. Except for the first row of plastic tapes, each row had five plastic tapes placed near the front of trees, as shown in figure 1. The first row of plastic tapes was 2.6 m downstream from the first row tree line and was near the front of short shrubs. The ten tapes were placed in such a way that the centers of five tapes were behind trees in the first sprayed row and the centers of the other five tapes were behind gaps between two trees in the first sprayed row. Second-row tapes were placed near the front of the crabapple trees of the same size as the first sprayed row trees. Third-row tapes were near the front of the shrubs of the same size as the shrubs near the first-row tapes. Fourth-row tapes were near the front of the crabapple trees of the same size as the first sprayed row trees.

**Airborne and Ground Deposits in Field 2**

Airborne spray deposits at three elevations and four distances downwind from the sprayer were measured in field 2, which was approximately 60 m north of field 1. Field 2 was a 200 m long × 30 m wide open field. Airborne spray deposits were collected with 20 × 20 cm nylon screens at elevations of 0.91, 1.83, and 3.05 m and distances of 15, 30, 60, and 90 m downwind from the sprayer (fig. 3). At each of the four distances, three 3.20 m tall vertical towers were used to mount screens at three different elevations. The measurement of airborne deposits was also planned to be part of trials 1 and 2 in field 1, but it was cancelled because the wind direction suddenly changed just before trials started.
In field 2, spray deposits on the ground were collected with 5 cm wide × 245 cm long plastic tapes at distances of 7.5, 15, and 30 m from the sprayer at the same time the airborne deposits were collected. The test in the open area in field 2 was conducted immediately following completion of trial 1 in field 1, which could provide a relative comparison of airborne and ground deposits among three treatments without influence of tree shape and tree spacing on test results.

A portable weather station was used to monitor ambient temperature, relative humidity, and wind velocity and azimuth at 1 s intervals in both fields. The weather station was positioned 3.7 m high and 7 m upstream from the spray line. The average ambient air temperature was 22°C and relative humidity was 58% during the test in the wind tunnel. Details of the structure of the wind tunnel and measurement of wind velocity were described by Reichard et al. (1992). The nozzles were mounted in the test section of the wind tunnel at 0.67 m above the wind tunnel floor, midway across the width of the tunnel, and 2.5 m upwind from the downstream end of the test section. All nozzles were oriented to discharge downward toward the wind tunnel floor. For the AI nozzle, the long axis of the spray pattern from the nozzle was across the width of the tunnel. A 5 cm thick sponge panel was mounted on each sidewall of the wind tunnel to prevent droplets from rebounding from the sidewall to the test section. Nozzle flow was controlled with a solenoid valve. A timer was used to operate the valve for 5 s during each test. Liquid was delivered to the nozzle at 830 kPa for AI and 1660 kPa for HC and HCDR from a diaphragm pump, and the bypass liquid was recirculated back to the reservoir. The same spray mixtures used in field tests were used in the wind tunnel.

A combination of 1.70 m long × 0.10 m wide strips of a muslin fabric and plastic were used to collect spray drift downwind from the nozzle. The plastic strip covered the upper surface of a 1.70 m long, 0.10 m wide, and 1.9 cm thick plywood board. The muslin fabric strip was evenly divided into 17 pieces that were clipped over the top of the plastic to the plywood. The plastic strip prevented spray deposits transferring from the fabric to the plywood. The plywood was supported horizontally with its upper surface 0.17 m above the wind tunnel floor to avoid collecting any droplets rebounding from the floor. The target was placed in the center of the wind tunnel and with its long axis parallel to the wind direction. The upwind side of the target was placed 0.40 m

Table 1. Wind velocity and azimuth during field tests with the AI, HC, and HCDR treatments at two trials in field 1 and airborne deposit measurement in field 2. Standard deviations are given in parentheses.

<table>
<thead>
<tr>
<th>Test Location</th>
<th>Wind Velocity (m/s)</th>
<th>Wind Azimuth[^d] (°)</th>
<th>Wind Velocity (m/s)</th>
<th>Wind Azimuth (°)</th>
<th>Wind Velocity (m/s)</th>
<th>Wind Azimuth (°)</th>
<th>Ambient Air Temp. (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field 1, trial 1</td>
<td>2.7 (0.9)</td>
<td>285 (18)</td>
<td>3.1 (0.5)</td>
<td>316 (20)</td>
<td>2.1 (0.7)</td>
<td>296 (22)</td>
<td>21</td>
<td>48</td>
</tr>
<tr>
<td>Field 1, trial 2</td>
<td>2.0 (0.7)</td>
<td>283 (22)</td>
<td>1.2 (0.4)</td>
<td>193 (15)</td>
<td>3.4 (0.8)</td>
<td>272 (24)</td>
<td>27</td>
<td>66</td>
</tr>
<tr>
<td>Field 2</td>
<td>1.3 (0.4)</td>
<td>306 (24)</td>
<td>2.3 (1.2)</td>
<td>308 (21)</td>
<td>1.8 (0.8)</td>
<td>311 (17)</td>
<td>22</td>
<td>50</td>
</tr>
</tbody>
</table>

[^a] AI = air-induction nozzle with water only.
[^b] HC = hollow-cone nozzle with water only.
[^c] HCDR = hollow-cone nozzle with water and drift retardant.
[^d] Wind velocity angle as measured clockwise from north to wind direction (see fig. 1).
downstream from the nozzle to avoid collecting unusually large droplets during the brief period of starting or stopping spray.

For each test, an array strip formed with seven 10 × 10 cm nylon screens was mounted vertically at the downstream end of the plywood to collect samples of airborne droplets above the downstream end of the fabric strip.

The combination of each 10 × 10 cm fabric and plastic sample was placed in a clean glass bottle and each screen sample was placed in another clean bottle at 5 min following each spray run. The fluorescence intensity of each sample was then determined with the LS 50B luminescence spectrometer. Each test was replicated three times. Data were averaged from the three replications for each test condition.

Droplet sizes from nozzles for AI at 830 kPa, and for HC and HCDR at 1660 kPa, which were similar to wind tunnel test settings, were measured with a VisiSizer particle/droplet image analysis system (Oxford Lasers, Oxfordshire, U.K.). Droplet size distributions were determined 0.5 m below the nozzle orifice across the centerline of the spray pattern width with 5 cm intervals. A minimum 10,000 droplets were counted at each sampling position for the droplet size distribution analysis.

**RESULTS AND DISCUSSION**

**FOLIAR DEPOSITS IN FIELD 1**

Except for the screen position at the 0.9 m elevation, there were no significant differences in spray deposits on screens at different elevations within crabapple tree canopies among the three spray techniques (AI, HC, and HCDR) in both trials (table 2). Therefore, statistically, the AI, HC, and HCDR treatments produced almost the same quantity of spray deposits within tree canopies. In addition, there were no significant differences among deposits at four elevations within the tree canopy for the three treatments. To produce uniform spray deposits across the tree canopy, air blast sprayers for nursery applications are usually recommended to operate with the same nozzle settings as orchard applications. Specifically, recommendations are to use a larger nozzle at the top of each side, with the capacity of the top nozzle at least three times greater than other individual nozzles. However, results in this study with three different spray techniques showed that spray deposit was uniform across the tree canopy from top to bottom with the equal capacity nozzles on the air blast sprayer. Nursery trees are usually much thinner and sharper with less canopy volume per area than orchard trees. It was reasonable to assume from this study that the sprayer with the equal capacity nozzles had the capability to deliver uniform spray deposits throughout the trees.

Figure 4 shows average spray deposits in volume on 12 nylon screen collectors for ten crabapple trees with the air blast sprayer using AI, HC, and HCDR in two trials. In trial 1, the average spray deposit on 12 nylon screen collectors within each tree canopy was 1.70 µL/cm² with a 6% coefficient of variation for AI, 2.12 µL/cm² with a 14% coefficient of variation for HC, and 1.95 µL/cm² with an 8% coefficient of variation for HCDR. In trial 2, the average spray deposit on 12 nylon screen collectors was 1.27 µL/cm² with a 12% coefficient of variation for AI, 1.28 µL/cm² with a 26% coefficient of variation for HC, and 1.50 µL/cm² with an 11% coefficient of variation for HCDR. Although wind velocities and directions were not the same for the three spray methods, total spray deposits on 12 screens within a tree canopy were not significantly different among sprays for the AI, HC, and HCDR treatments.

The volume median diameter of water droplets in the main spray sheet from a conventional hollow-cone nozzle at 1660 kPa was 202 µm (table 3). The volume of 1.28 µL/cm² spray deposit is equivalent 296 droplets of 202 µm sustained on a 1 cm² area. The recommended droplet density in the target area ranged from 20 to 30 droplets per square centimeter for spraying insecticides and from 50 to 70 droplets per square centimeter for spraying fungicides (Syngenta, 2004). The number of 202 µm droplets with the 1.28 µL volume within the tree canopy was 4 to 15 times the number of 202 µm droplets actually required for the target area. Based on the insecticide and fungicide coverage recommendation, the tree canopies received excessive spray deposits discharged from the AI, HC, and HCDR treatments at the 700 L/ha application rate.

**GROUND DEPOSITS BENEATH THE SPRAYED TREES IN FIELD 1**

For the plastic plate targets placed beneath trees and between two trees for the AI, HC, and HCDR treatments in
Table 3. Average spray droplet sizes at 0.5 m below the nozzle orifice for AI across the spray pattern width (90 cm) at 830 kPa, and for HC and HCDR across the main spray sheet (5 cm) at 1660 kPa. The droplet size measurement was conducted with the laser particle/droplet image analysis system under laboratory conditions without air blast.\[a\]

<table>
<thead>
<tr>
<th>Nozzle</th>
<th>$D_{v,1}$</th>
<th>$D_{v,5}$</th>
<th>$D_{v,9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI[^b^]</td>
<td>158</td>
<td>407</td>
<td>824</td>
</tr>
<tr>
<td>HC[^c^]</td>
<td>150</td>
<td>202</td>
<td>290</td>
</tr>
<tr>
<td>HCDR[^d^]</td>
<td>157</td>
<td>222</td>
<td>332</td>
</tr>
</tbody>
</table>

\[^a^\] For HC and HCDR, droplet sizes were counted for only 5 cm of the cone spray sheet because a very small portion of spray volume was found in the center of the hollow-cone spray pattern.

\[^b^\] AI = air-induction nozzle with water only.

\[^c^\] HC = hollow-cone nozzle with water only.

\[^d^\] HCDR = hollow-cone nozzle with water and drift retardant.

The two trials, spray deposits on the ground 0.15 m in front of the sprayed tree row centerline were generally significantly less than those 0.15 m behind the centerline (table 4). This might be because the angled spray pattern delivered more spray to targets behind the centerline of the trees than the targets in front of the centerline due to different delivery distances to the two locations.

Statistical analysis indicated that there was no significant difference for ground deposits on targets beneath the sprayed trees and between two sprayed trees for the AI, HC, and HCDR treatments in two trials (table 4). Therefore, compared to the total amount of spray deposits on the ground near the sprayed trees, the amount of spray runoff from tree leaves to the ground was not significantly different among the three treatments. The average spray deposit per square centimeter on the ground beneath the sprayed trees was about 24% of the average foliar deposit per square centimeter within tree canopies with the AI, HC, and HCDR treatments in two trials, or about 8% of the total spray volume deposited on the ground beneath sprayed trees.

Ground deposits beneath the sprayed trees with HC were significantly higher in trial 1 but significantly lower in trial 2 than with AI and HCDR, regardless of target placement either in front of trees or behind trees (fig. 5). However, for the same conditions, there was no significant difference in deposits between AI and HCDR. This result might have been due to changes in wind velocity and direction for HC in two trials (table 1). Ground targets closer to the air blast sprayer should receive higher spray deposits if the spray direction was against the wind.

Figure 5. Average spray deposits collected with plastic plates on the ground at 0.15 m in front of and behind the sprayed tree row centerline for AI, HC, and HCDR in field 1. Bars in a group with different lowercase letters are significantly different (p < 0.05). Error bars represent standard deviations of means.

**GROUND DEPOSITS DOWNSTREAM FROM THE SPRAYER IN FIELD 1**

The data in table 5 illustrate there were no significant differences among spray deposits on the ground 4.5 m downstream from the sprayer for the AI, HC, and HCDR treatments in trial 1; however, the deposits from HC were significantly lower than those from AI and HCDR in trial 2, possibly due to changes in wind velocities and directions (table 1). There was no significant difference in deposits between the plastic tapes placed behind sprayed trees and between two sprayed trees (fig. 6) because there were very few leaves on the trees below 0.9 m from the ground. The average ground deposit collected by the plastic tapes at 4.5 m from the sprayer with AI, HC, and HCDR for the two trials was 1.51, 1.23, and 1.57 µL/cm², respectively, which was about 86% of the average spray deposit per square centimeter within tree canopies with AI, HC, and HCDR in the two trials. Therefore, a significant amount of spray volume was lost on the ground with all three treatments at the 700 L/ha application rate.

The data in table 5 also illustrate that spray deposits on the ground greatly decreased in different rates for AI, HC, and HCDR as the downstream distance from sprayer increased. At 10.5 m downstream from the sprayer in trial 1, HCDR produced the highest ground spray deposit among the three

Table 4. Spray deposits collected by plastic plates on the ground beneath sprayed trees and between two sprayed trees at locations in front of and behind the sprayed tree row centerline for AI, HC, and HCDR in field 1. Standard deviations are given in parentheses.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Target Location to First Row of Trees</th>
<th>AI[^b^]</th>
<th>HC[^c^]</th>
<th>HCDR[^d^]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Front Between</td>
<td>0.23 (0.15) bB</td>
<td>0.56 (0.23) aB</td>
<td>0.28 (0.10) bA</td>
</tr>
<tr>
<td>1</td>
<td>Front Beneath</td>
<td>0.24 (0.10) bB</td>
<td>0.80 (0.35) aAB</td>
<td>0.33 (0.15) bA</td>
</tr>
<tr>
<td>1</td>
<td>Behind Between</td>
<td>0.38 (0.13) bA</td>
<td>0.68 (0.45) aAAB</td>
<td>0.42 (0.16) bA</td>
</tr>
<tr>
<td>1</td>
<td>Behind Beneath</td>
<td>0.39 (0.14) bA</td>
<td>1.05 (0.64) aA</td>
<td>0.41 (0.19) bA</td>
</tr>
<tr>
<td>2</td>
<td>Front Between</td>
<td>0.58 (0.26) aA</td>
<td>0.26 (0.04) bB</td>
<td>0.69 (0.15) aB</td>
</tr>
<tr>
<td>2</td>
<td>Front Beneath</td>
<td>0.54 (0.28) aA</td>
<td>0.27 (0.06) bB</td>
<td>0.77 (0.15) aB</td>
</tr>
<tr>
<td>2</td>
<td>Behind Between</td>
<td>0.85 (0.55) abA</td>
<td>0.36 (0.04) bA</td>
<td>1.00 (0.30) aA</td>
</tr>
<tr>
<td>2</td>
<td>Behind Beneath</td>
<td>0.91 (0.51) aA</td>
<td>0.30 (0.07) bB/A</td>
<td>1.22 (0.20) aA</td>
</tr>
</tbody>
</table>

\[^a^\] Means in a row followed by different lowercase letters are significantly different (p < 0.05). Means in a column followed by different uppercase letters within the same trial are significantly different (p < 0.05).

\[^b^\] AI = air-induction nozzle with water only.

\[^c^\] HC = hollow-cone nozzle with water only.

\[^d^\] HCDR = hollow-cone nozzle with water and drift retardant.
spray methods, followed by AI and then HC, while wind conditions were 2.7 m/s with 285° azimuth (°A) for AI, 3.1 m/s with 316°A for HC, and 2.1 m/s with 296°A for HCDR, respectively. At the same locations in trial 2, the AI treatment produced the highest ground deposit among the three methods, followed by HC and then HCDR, while wind conditions were 2.0 m/s with 283°A for AI, 1.2 m/s with 193°A for HC, and 3.4 m/s with 272°A for HCDR, respectively. Obviously, wind conditions had more influence on the ground spray deposits at 10.5 m downwind and beyond than the spray methods.

AIRBORNE AND GROUND DEPOSITS IN FIELD 2

Screen collectors at 0.91, 1.83, and 3.05 m elevations at 15 m downwind from the sprayer in field 2 collected the highest airborne deposits from the AI, HC, and HCDR treatments among the four different downwind sample locations (table 6). There was no significant difference in airborne deposits for the three elevations at both 15 and 30 m downwind from the sprayer between the AI and HC treatments, except for the 3.05 m elevation at 15 m downwind. The average airborne deposits with AI were lower than that with HC; however, at the same screen collector locations, HCDR produced significantly higher airborne deposits than AI and HC. At 61 and 91 m downwind, the airborne spray deposits at the three elevations were very low and not significantly different among the three treatments.

In conjunction with the airborne spray deposits, figure 7 shows downwind spray deposits on ground plastic tapes at three distances from the air blast sprayer in field 2 for AI, HC, and HCDR. At 7.5 m downstream from the sprayer, the downwind spray deposits on the ground were 0.34, 0.68, and 0.92 µL/cm² for AI, HC, and HCDR, respectively, while they were 0.29, 0.11, and 0.23 µL/cm² 15 m from the sprayer. The downwind spray deposits on the ground at 15 and 30 m from the sprayer with AI were higher than with HC and HCDR. At 15 m downwind from the sprayer, there were more airborne deposits at all three elevations than ground deposits for HC and HCDR, while the opposite occurred for AI.

Statistical analysis indicated that the wind velocity during the airborne spray test with HC in field 2 was significantly higher than with AI and HCDR, while difference in wind velocities between AI and HCDR was not significant. However, the spray mixture with drift retardant in field 2 had

<table>
<thead>
<tr>
<th>Trial</th>
<th>Downwind Distance (m)</th>
<th>Air [b]</th>
<th>HC [c]</th>
<th>HCDR [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5</td>
<td>1.47 (0.16) a</td>
<td>1.33 (0.20) a</td>
<td>1.56 (0.32) a</td>
</tr>
<tr>
<td>1</td>
<td>7.5</td>
<td>1.06 (0.11) a</td>
<td>0.40 (0.23) b</td>
<td>0.96 (0.26) a</td>
</tr>
<tr>
<td>1</td>
<td>10.5</td>
<td>0.38 (0.18) a</td>
<td>0.00 (0.01) c</td>
<td>0.57 (0.11) a</td>
</tr>
<tr>
<td>1</td>
<td>15.0</td>
<td>0.00 (0.00) c</td>
<td>0.00 (0.00) b</td>
<td>0.10 (0.07) a</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>1.42 (0.31) a</td>
<td>1.13 (0.27) b</td>
<td>1.58 (0.27) a</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>0.54 (0.36) a</td>
<td>0.48 (0.04) b</td>
<td>0.58 (0.20) a</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
<td>0.39 (0.09) a</td>
<td>0.26 (0.04) b</td>
<td>0.11 (0.04) c</td>
</tr>
<tr>
<td>2</td>
<td>15.0</td>
<td>0.08 (0.07) a</td>
<td>0.02 (0.01) a</td>
<td>0.02 (0.01) a</td>
</tr>
</tbody>
</table>

[a] Means in a row followed by different letters are significantly different (p < 0.05).
[b] AI = air-induction nozzle with water only.
[c] HC = hollow-cone nozzle with water only.
[d] HCDR = hollow-cone nozzle with water and drift retardant.

Table 6. Average airborne deposits on screens at three elevations and four downwind distances from the sprayer with three spray methods in field 2. Standard deviations are given in parentheses.

<table>
<thead>
<tr>
<th>Downwind Distance (m)</th>
<th>Elevation (m)</th>
<th>AI [b]</th>
<th>HC [c]</th>
<th>HCDR [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.91</td>
<td>0.263 (0.096) b</td>
<td>0.418 (0.257) b</td>
<td>0.807 (0.130) a</td>
</tr>
<tr>
<td>15</td>
<td>1.83</td>
<td>0.174 (0.105) b</td>
<td>0.389 (0.371) ab</td>
<td>0.641 (0.195) a</td>
</tr>
<tr>
<td>15</td>
<td>3.05</td>
<td>0.066 (0.022) b</td>
<td>0.359 (0.429) a</td>
<td>0.561 (0.163) a</td>
</tr>
<tr>
<td>30</td>
<td>0.91</td>
<td>0.002 (0.002) b</td>
<td>0.006 (0.006) b</td>
<td>0.104 (0.054) a</td>
</tr>
<tr>
<td>30</td>
<td>1.83</td>
<td>0.001 (0.002) b</td>
<td>0.014 (0.014) b</td>
<td>0.081 (0.045) a</td>
</tr>
<tr>
<td>30</td>
<td>3.05</td>
<td>0.002 (0.002) b</td>
<td>0.011 (0.010) b</td>
<td>0.073 (0.050) a</td>
</tr>
<tr>
<td>61</td>
<td>0.91</td>
<td>0.000 (0.000) a</td>
<td>0.001 (0.001) a</td>
<td>0.000 (0.000) a</td>
</tr>
<tr>
<td>61</td>
<td>1.83</td>
<td>0.000 (0.000) a</td>
<td>0.001 (0.002) a</td>
<td>0.000 (0.000) a</td>
</tr>
<tr>
<td>61</td>
<td>3.05</td>
<td>0.000 (0.000) a</td>
<td>0.001 (0.001) a</td>
<td>0.000 (0.000) a</td>
</tr>
<tr>
<td>91</td>
<td>0.91</td>
<td>0.000 (0.000) a</td>
<td>0.000 (0.000) a</td>
<td>0.000 (0.000) a</td>
</tr>
<tr>
<td>91</td>
<td>1.83</td>
<td>0.000 (0.000) a</td>
<td>0.000 (0.000) a</td>
<td>0.000 (0.000) a</td>
</tr>
<tr>
<td>91</td>
<td>3.05</td>
<td>0.000 (0.000) a</td>
<td>0.000 (0.000) a</td>
<td>0.000 (0.000) a</td>
</tr>
</tbody>
</table>

[a] Means in a row followed by different letters are significantly different (p < 0.05).
[b] AI = air-induction nozzle with water only.
[c] HC = hollow-cone nozzle with water only.
[d] HCDR = hollow-cone nozzle with water and drift retardant.
the highest airborne spray deposits among the three spray methods. Zhu et al. (1997) reported that nonionic polymer drift retardants could lose their effectiveness and perform similar to water after 2 to 3 recirculations through a centrifugal pump. Laboratory measurements illustrated that the average $d_{V,1}$, $d_{V,5}$, and $d_{V,9}$ of droplets on the edge of hollow-cone spray sheet 0.5 m below the nozzle orifice from HCDR were slightly higher than HC (table 3), and the $d_{V,5}$ at locations 10 cm within the hollow-cone area for both HC and HCDR was almost equal and ranged from 30 to 82 $\mu$m (fig. 8). Bouse et al. (1988) reported increases in portions of spray volume in both droplet diameter smaller than 99 $\mu$m and larger than 415 $\mu$m for water-soluble polymer drift retardants discharged by conventional hollow-cone nozzles in the airflow of 53 m/s.

Likewise, the air-induction nozzles did not provide significant drift reduction, compared to using the conventional hollow-cone nozzles in field 2. For water droplets, the critical relative velocity at which the droplet will continue to break up is given by the following equation (Lefebvre, 1989):

$$U_R = \frac{784}{\sqrt{D}}$$

where $U_R$ is the critical relative velocity (m/s), and $D$ is droplet diameter ($\mu$m). For the air blast sprayer, the air velocity near the nozzle is approximately 40 m/s. According to equation 1, any droplets larger than 350 $\mu$m in diameter from AI, HCDR, and HC would be further broken up by the aerodynamic pressure produced by the parallel airflow from the air blast sprayer. The data in table 3 illustrate that more than 50% of spray volume from AI at 830 kPa was larger than 407 $\mu$m, more than 90% of spray volume from HC at 1660 kPa was smaller than 290 $\mu$m, and more than 90% of spray volume from HCDR at 1660 kPa was smaller than 332 $\mu$m. Obviously, a large portion of droplets with AI in the air blast sprayer might have encountered some breakup due to air shearing effect. The data in table 3 also shows that the AI treatment produced almost the same $d_{V,1}$ of droplets as the HC and HCDR treatments produced in the hollow-cone spray sheet. Therefore, AI and HCDR might not achieve their advantages of producing large droplets as normally claimed to reduce drift potential from the air blast sprayer in the nursery field tests.

**AIRBORNE AND GROUND DEPOSITS IN WIND TUNNEL**

In contrast to the field tests, wind tunnel test showed that the AI treatment had the lowest downwind spray deposit at both 1.0 and 2.5 m/s wind velocities among the three spray methods, followed by HCDR and then HC (figs. 9 and 10). For example, at 1.0 m downwind from the nozzle, the average spray deposit on the floor with HC was 2.0 times higher than

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**Figure 7.** Downwind spray deposits on the ground at three distances downstream from the air blast sprayer with AI, HC, and HCDR in field 2.

**Figure 8.** Comparison of volume median diameter ($d_{V,5}$) across the spray pattern width 0.5 m below the nozzle orifice for HC and HCDR at 1660 kPa and for AI at 830 kPa under laboratory conditions without air blast.

**Figure 9.** Wind tunnel spray deposits on targets 0.5 m below the nozzle at various horizontal distances downwind from spray discharge point for AI, HC, and HCDR with air velocities of 1.0 m/s (left) and 2.5 m/s (right). The horizontal distance between spray discharge point and screens was 2.1 m.

**Figure 10.** Wind tunnel downwind airborne spray deposits on screens at various heights above the floor for AI, HC, and HCDR with air velocities of 1.0 m/s (left) and 2.5 m/s (right).
with HCDR and 5.9 times higher than with AI at 1.0 m/s air velocity, and 2.7 times higher than HCDR and 16.4 times higher than AI at 2.5 m/s air velocity. Similarly, at 2.1 m downwind from the nozzle, the average total airborne deposit on the nylon screens with HC was 1.8 times higher than with HCDR and 2.2 times higher than with AI at 1.0 m/s air velocity. At 2.5 m/s air velocity, the deposit was 1.8 times higher than with HCDR and 11.0 times higher than with AI. However, at 2.5 m/s air velocity, HCDR had higher airborne deposits on the screens than HC when the screen height was 25 cm and higher (fig. 10). The airborne deposits decreased as the screen height increased for all three treatments.

There was a disagreement in drift potentials between the wind tunnel and field tests for the treatments studied. In wind tunnel conditions, the $D_{v5}$ of droplets for AI and HCDR at 0.5 m below the discharge point was 1.9 and 1.1 times the $D_{v5}$ of droplets for HC, but the $D_{v1}$ of droplets for the three treatments was almost the same (table 3). The influence of the fan air velocity from the air blast sprayer on droplet sizes further breaking down in field conditions, as discussed above, was not the case in the wind tunnel test. In addition, the spray direction in the wind tunnel was perpendicular to the wind direction and was vertically toward the floor. The wind tunnel test data represented performances of HCDR and AI only in laboratory conditions and not in actual field conditions. Therefore, improperly applying laboratory test results to field conditions could result in controversial outputs.

CONCLUSIONS

The AI, HC, and HCDR treatments produced no significant differences in quantity of spray deposits within tree canopies. Tree canopies received 4 to 15 times the number of spray droplets as actually needed with HC at the 700 L/ha application rate, which was 360 L/ha lower than the rate typically used in nursery application. The application rate should be reduced to better match canopy requirements and minimize pesticide waste and labor costs.

There was no significant variation in spray deposits at different elevations within the crabapple trees when the sprayer was equipped with five identical nozzles to discharge liquid with AI, HC, or HCDR. In nursery application, it was not necessary to place a large-capacity nozzle at the top of the air blast sprayer, as normally recommended for orchard spray applications.

Wind conditions had more influence on ground spray deposits than the spray method chosen (AI, HC, and HCDR) in field 1. A large portion of the spray volume was deposited on the ground with all three spray methods at the 700 L/ha application rate.

In field 2, although average airborne deposits with AI for elevations of 0.91 and 1.83 m at 15 and 30 m downwind distances from the sprayer were lower than deposits with HC, they were not significantly different. At the same locations, HCDR had significantly higher spray airborne deposits than AI and HC. Downwind spray deposits on the ground at 15 and 30 m from the sprayer with AI were higher than with HC and HCDR.

Spray drift potential from the wind tunnel experiments did not agree with results from the field experiments. Wind tunnel tests indicated that using drift retardant or air-induc-

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REFERENCES


