Spray Drift Mitigation Using Opposing Synchronized Air-Blast Sprayers

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Abstract

BACKGROUND: Pesticide drift is a serious environmental and safety concern that affects all of U.S. agriculture. A number of mitigation techniques to reduce pesticide drift have been recommended by industry, academic and government agencies. These techniques are very costly or reduce the efficacy of the pest control product and have not been implemented by U.S. agriculture.

RESULTS: When using a novel spray technique (Air-in), pesticide drift was significantly reduced between 53% to 99% at 7.6 m from the orchard drip line when compared to the grower standard. This technique not only reduced pesticide drift but also maintained or improved the amount of pesticide residue deposited (0.7 to 2.6 times) and the percent pesticide coverage (1.0 to 1.4 times) with different air-blast speed sprayers on almond, walnut and pistachio.

CONCLUSION: The Air-in technique shows great promise in reducing pesticide drift while maintaining or improving pesticide coverage with minimal cost to the grower.

Keywords: spray coverage; drift; air-blast speed sprayer; almond; walnut; pistachio; navel orangeworm

1 INTRODUCTION

Pesticide drift is the airborne movement of pesticides away from the intended target. Off-site movement of pesticides from air-blast speed sprayers is of particular concern when an orchard is adjacent to schools, residences, environmentally sensitive sites or to a crop in which the pesticide is not registered.[1,2,3,4] Many studies conducted by industry as well as academic and government agencies have developed recommendations for mitigating the off-site movement of pesticides. Reduction of drift has been achieved through several methods. These methods include limiting the direction of the spray solution into the orchard or implementing the “Inward Only” spray technique for the outside rows. Other techniques to mitigate drift include the “Gear Up/Throttle

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Down” technique, “Smart” sprayer technology, and increasing droplet size through the use of air induction nozzles for the first few rows of the orchard.[5,6,7,8,9] However, these techniques provide less coverage in the outside rows compared to the conventional grower standard. An alternate method to achieve drift mitigation is the construction of windbreaks or buffer zones, but in many situations these are not economically practical due to the lack of open ground adjacent to the orchard.[10] In order to obtain grower acceptance of improvements that reduce spray drift, there must be excellent pesticide coverage of the outside rows combined with minimal economic impact.

Two novel spray techniques were evaluated in order to address grower concerns with “Inward Only” and “Gear Up/Throttle Down” spray techniques as well as the use of windbreaks and buffer zones. The techniques evaluated in this paper use two synchronized air-blast speed sprayers driving and spraying parallel to each other. Off-site spray movement was measured by quantifying deposition of spray material at various distances from the dripline of the orchard edge. Additionally, the amount of methoxyfenozide residue, coverage using a dye marker, and the contact mortality of methoxyfenozide against navel orangeworm (NOW) *Amyelois transitella* Walker (Lepidoptera: Pyralidae), the principal lepidopteran pest of tree nuts in California, were assessed at two canopy heights.

2 MATERIALS AND METHODS

2.1 Study sites

Almond

Power take-off (PTO) trial No. 1 was conducted on 2 May, 2018 on the outside row of a mature ‘Nonpareil’ almond orchard on Hansen (6.7 m row by 5.5 m tree spacing off-set) in full canopy (9.1 m to 10.2 m tall) near Huron, CA. Air temperature during the study was 15.5º to 22.2º C. The rows were oriented in a north to south direction. The outside row was sprayed with two PTO air-blast speed sprayers (Air-O-Fan 600 GB-36R, Reedley, CA 93654) operating at 620.5 kPa and delivering 935.4 L ha^{-1} at 3.7 kmh^{-1} with TeeJett hollow cone nozzles (Spray Systems Glendale Heights, IL 60187) that directed 66% of the spray volume to the upper half of the tree. Each treatment was replicated two times and each replicate was 16 to 19 trees long. For all studies, the entire outside row of the orchard was used and each of the four treatments in the replicate immediately followed one another. For all of the Air-O-Fan PTO and engine-driven air-blast speed sprayers the baffles and diverter plate were closed in the outer manifold, restricting most of the air flow. The air speed, as measured from the closed output manifold of the three Air-O-Fan air-blast speed sprayers at 1.5 m, ranged from 1.6 to 3.2 kmh^{-1}. The spray solution used in all trials contained 0.5% Superior horticultural oil (J.R. Simplot, Boise, Idaho 83707).

PTO trial No. 2 was conducted on 8 June, 2018 on the outside row of a mature ‘Nonpareil’ almond orchard on Nemaguard (5.5 m row by 6.7 m tree spacing) in full canopy (7.6 m to 9.1 m tall) near Crows Landing, CA. Air temperature during the study was 13.9º to 27.8º C. The rows were oriented in a northeast to southwest direction. The outside row was sprayed with two PTO air-blast speed sprayers (Air-O-Fan Predator) operating at 689.5 kPa and delivering 1169 L ha^{-1}

at 3.2 kmh^{-1}. Each treatment was replicated eight times and each replicate was 15 to 16 trees long.

Engine trial No. 1 was conducted on 3 May, 2018 on the outside row of mature 'Nonpareil' orchard almond on Hansen (6.7 m row by 5.5 m tree spacing off-set) in full canopy (9.1 m to 10.2 m tall) near Huron, CA. Air temperature during the study was 15.0º to 22.8º C. The rows were oriented in a north to south direction. The outside row was sprayed with two engine-driven (Air-O-Fan D-240) air-blast speed sprayers operating at 620.5 kPa and delivering 935 L ha^{-1} at 3.7 kmh^{-1} with ceramic disks and cores (Spray Systems Glendale Heights, IL 60187) that directed 66% of the spray volume to the upper half of the tree. Each treatment was replicated four times and each replicate was 16 to 19 trees long.

Walnut

Engine trial No. 2 was conducted on 30 May, 2018 on the outside row of a mature 'Chandler' walnut orchard on Pardox (6.7 m row by 7.3 m tree off-set spacing) in full canopy (10.2 m to 11.2 m tall) near Crows Landing, CA. Air temperature during the study was 16.1º to 22.2º C The rows were oriented in a northeast to southwest direction. The outside row was sprayed with two engine-driven (Durand-Wayland 1705A, LaGrange, GA 30241) air-blast speed sprayers operating at 1241 to 1379 kPa and delivering 1169 L ha^{-1} at 3.2 kmh^{-1} with ceramic disks and cores (Spray Systems Glendale Heights, IL 60187) that directed 66% of the spray volume to the upper half of the tree. Since the Durand-Wayland air-blast speed sprayer does not have adjustable baffle plates, a collar was attached to the output manifold that prevented all air from leaving the outside manifold. The air speed from the closed output manifold was measured at 1.5 m was 0.0 kmh^{-1}. Each treatment was replicated five times and each replicate was 14 to 18 trees long.

Pistachio

Engine trial No. 3 was conducted on 27 June, 2018 on the outside row of a mature 'Kerman' pistachio orchard on PG1 (5.8 m row by 5.2 m tree spacing) in full canopy (4.6 m to 5.5 m tall) near Three Rocks, CA. Air temperature during the study was 20.0º to 28.3º C The rows were oriented in a north to south direction. The outside row was sprayed with two engine-driven (Air-O-Fan D-240) air-blast speed sprayers operating at 551.5 kPa and delivering 2245 L ha^{-1} at 4.0 kmh^{-1} with baffles and diverter plate closed in the outside manifold. Each treatment was replicated six times and each replicate was 12 to 17 trees long.

2.2 Treatments

Grower standard: An air-blast speed sprayer is driven between the first and second row, spraying both rows one and two. The sprayer then returns along the outside of the orchard and sprays the first row with the spray solution and air "on" and the outside spray solution "off" but the air "on" (Fig. 1).

Air-in: An air-blast speed sprayer is driven between the first and second rows, spraying both rows. A second air-blast speed sprayer drives parallel to and in synchrony with the inside sprayer along the outside of the orchard and sprays the first row, with the inside spray solution "off" and air “on” and the outside spray solution and air “off”. The sprayer then returns along the outside of the orchard and sprays the first row with the inside spray solution and air “on” and the outside spray solution and air “off” (Fig. 2).

Double-spray: An air-blast speed sprayer is driven between the first and second row spraying both rows one and two. A second air-blast speed sprayer drives parallel to and in synchrony with the inside sprayer along the outside of the orchard and sprays the first row, with the inside spray solution and air “on” and the outside spray solution and air “off” (Fig. 3). There was also an untreated control.

The air-blast speed sprayers used in this study were Air-O-Fan and Durand-Wayland. The Air-O-Fan speed sprayers have adjustable baffles and a diverter plate that could be closed, which would restrict most of the air flow. In all studies that used Air-O-Fan speed sprayers, the baffles and diverter plate were closed on the outer manifold. Durand-Wayland did not have adjustable baffles or diverter plate. An air collar was constructed with a 0.4 m by 1.25 m piece of diamond plate and bent to the shape of the Durand-Wayland manifold. The collar was bolted to theouter manifold and prevented the delivery of any air.

2.3 Drift measurements

Water-sensitive paper (25.4 mm by 76.2 mm), manufactured by TeeJet Spraying System Co. (Wheaton IL), was used to collect the spray droplets in the drift area outside the orchard. The drift area was a level open field. Water-sensitive papers were placed perpendicular to the orchard at distances of 7.6 m, 11.4 m, 15.2 m, 30.5 m and 45.7 m from the orchard drip line for all studies and additionally at 76.2 m and 121.9 m from the orchard drip line for walnut and pistachio studies. At each distance there were two sampling stations per replicate, consisting of two water-sensitive papers laid horizontally on a plastic-covered platform 0.91 m above the ground. The papers were attached to the platform with double-sided tape. The sampling stations were placed 4 m apart in the center of each replicate at each distance. Water-sensitive papers were collected after the spray had dried (at least 2 min after the replicate was sprayed). The papers were placed in labeled Ziploc bags and taken to the laboratory for analysis using ImageJ computer droplet-scanning program.[11]

2.4 Insecticide deposition, coverage and NOW bioassay

The insecticide deposition, coverage, and bioassay studies were conducted on the same day and in the same orchard as the drift mitigation studies. Within 1/2 h following the completion of the drift mitigation studies, an interior row of each orchard was sprayed using the same application equipment and speed. However, the spray solution included 0.5% v/v of NR – 415 Superior horticultural oil, methoxyfenozide (Intrepid 2F at 295.74 ml/378.5 l, Dow AgroSciences LLC, Indianapolis, IN 46268) and 0.15% v/v of Aquashade (Applied Biochemists, Alpharetta, GA 30004) as a dye marker. Methoxyfenozide was selected because of its low mammalian toxicity and low volatilization. The three spray techniques and untreated control were replicated four times along a single row in a randomized complete block design. Each replicate was 7 to 10 trees long. The first and last two trees of each replicate served as treated buffers.

Methoxyfenozide deposition, spray coverage and contact toxicity bioassays were assessed at two areas in the tree canopy, high-center canopy and mid-center canopy, which varied by tree type. In almond, high-center canopy was ca. 6.5 m and mid-center canopy was ca. 4.0 m, in walnut, high-center canopy was ca. 7.0 m and mid-center canopy was ca. 5.0 m and in pistachio, high-center canopy was ca. 4.0 m and mid-center canopy was ca. 2.5 m.

Methoxyfenozide deposition was determined at two points in the tree canopy using 55 mm diameter filter paper (Whatman No. 1). Two filter papers were placed at each location in each replicate (16 total filter papers per treatment) immediately before application and then collected after the insecticide had dried. The filter papers were placed in labeled Ziploc bags and returned to the laboratory. The filters papers were not wrapped in aluminum foil and potential loss of methoxyfenozide to the Ziploc bags not recorded. The filter papers were held at -20 ºC until shipment to the analytical laboratory (Primera Analytical Solutions Corp., Princeton, NJ. 08540). The methoxyfenozide was removed from the filter papers. The amount of methoxyfenozide deposited was determined and reported as ng/cm^2. Methoxyfenozide on the filter paper was assumed to be homogenously distributed.

Spray coverage was assessed at two points in the tree canopy using 8.9 cm X 20.3 cm rectangular piece of Kromekote paper (CTI Paper USA, Sun Prairie, WI) wrapped around an aluminum beverage can (354.9 ml) placed in the tree canopy.[12] Kromekote papers were collected and placed in labeled Ziploc bags after the spray dried and taken to the laboratory for analysis. Spray droplet density and distribution were analyzed using ImageJ.

Contact toxicity bioassays were assessed at two points in the tree canopy using 55 mm diameter filter paper (Whatman No. 1). Twelve to thirteen filter papers were clipped to a plastic strand with small binder clips and placed at each location in each replicate (100 total filter papers per treatment).[13] The filter papers were collected after the insecticide residue was dry. The filter papers were placed in labeled Ziploc bags and returned to the laboratory. Each filter paper was placed on the surface of a separate petri dish containing bran-wheat germ diet. An egg strip containing 50 viable navel orangeworm eggs (orange in color) was placed in the center of each filter paper. Percent mortality was determined after the petri dishes were incubated at 30° C at 16:8 photoperiod for 18 days. The NOW eggs used in this study came from a laboratory colony reared at 30°C, 16:8 photoperiod, on a modified bran-wheat germ diet in Parlier, CA.[13]

2.5 Field weather station

On-site ambient conditions (temperature, wind speed and direction over time) were monitored every minute with a Vantage Vue - Precision weather station (Davis Instruments, Hayward, CA 94545) during the applications. The weather station was located approximately 61.0 m from the outside row in the adjacent drift area with the anemometer positioned at a height of 2.9 m. Ambient conditions were measured during both the drift and coverage experiments.

2.6 Wind Velocity and Direction

Wind data were transformed in a multi-step process to obtain the mean speed and direction for each study. In orchards that were not laid out in a N-S orientation, the wind direction was adjusted to bring the orchards into a N-S orientation. For example, if an orchard was oriented NW-SE, then all measurements were shifted 45^0 for correction to a N-S orientation. Since each application took several minutes to complete, multiple wind direction and speed readings were recorded for each replicate. The wind direction was converted from degrees (N is 0^0, E is 90^0, W is 270^0, etc.) to radians (degrees $*$ $\pi/180$) [14]. The sine and cosine were calculated for each radian and then averaged for each replicate. The arctan of the mean sine divided by the mean cosine was calculated and then converted back to degrees by multiplying by $180/\pi$. If the mean cosine was negative (regardless of whether the mean sine was negative or positive), 180^0 was added to the result. If the mean sine alone was negative, 360^0 was added, and when both were positive, the values were not adjusted. This provided the mean direction in degrees for each replicate. The cardinal direction closest to this degree measurement was used as the wind direction for that replicate (direction provided is the direction the wind was coming from). These data for each replicate were then used in the same manner to calculate the average wind direction for the whole trial. Since all orchards were reoriented N-S, winds coming from the west (pushing outward from the orchard edge) would increase drift while winds coming from the east (into the orchards) would decrease drift. The average wind speeds were calculated by taking the means of all of the speeds at each reading.

Wind was also included as an effect in the statistical model. Both wind speed and direction were converted into a wind vector that quantified the impact wind had on drift. Orchards were transformed into a N-S orientation as described above and wind direction was converted from degrees to radians (degrees* $\pi/180$). In creating this wind vector, wind direction is best defined using the sine of the angle (in radians) off the E-W line (the direction with the most impact on drift). [16] The sign of the transformed wind direction was positive for winds blowing from the west as these winds increased drift, and negative for winds coming out of the east as these winds decreased drift. Wind direction was multiplied by wind speed to produce a single wind vector. This wind vector was then included in the statistical model.

2.7 Statistical Analyses Wind velocity and direction varied during the trials. In order to prevent cross-contamination from adjacent treatments in the analysis, replicates with unintentional drift on the untreated control were discarded (Table 1). To distinguish between incidental contamination and small amounts of drift, a minimum threshold of coverage was established by determining the lower detection limit of the ImageJ program. This was calculated using the mean reading of 20 blank papers ± two standard deviations and resulted in a value of 0.035% coverage. All untreated control replicates that had a reading above 0.035% were removed from the analysis. The area below this cutoff is not relevant to the study because it may not be related to drift and all values for percent area covered below 0.035% were set to zero.

Drift data were analyzed using linear mixed models in the lue4 package in R.[17] Data were log transformed (log[x + 0.01]) to meet the assumption of normality. For the PTO rig trials (all in almond), a full model was created with percent area covered as the dependent variable, treatment, and the wind vector as mixed effects, and replicate nested in trial as random effects. The nested random effects were specified to account for the nested structure of the experiment.[18] When treatment was significant, the least square means pair-wise differences were determined using the lsmeans function from emmeans package in R with a Tukey adjustment for multiple comparisons.[18] Significant p-values are those ≤ 0.05.

The three trials with engine-driven spray rigs were conducted in different crops – almond, walnut, and pistachio. Because there was only one trial per crop, crops were analyzed separately. Additionally, equipment differences also necessitated separate analyses. In each crop, the full model included the percent area covered as the dependent variable, treatment, and the wind vector as mixed effects and replicate as a random effect. When treatment was significant, the least square means pair-wise differences were determined using the lsmeans function from emmeans package in R with a Tukey adjustment for multiple comparisons.

Spray coverage, bioassay and insecticide deposition data were transformed using arcsine(sqrt(x)) and analyzed by ANOVA with mean separation using Tukey's HSD at $P \leq 0.05$.[19]

3 RESULTS

3.1 Drift

In the PTO spray rig trials in almond, there was significantly lower drift at 7.6 m and 11.4 m from the dripline in the Air-in and Double-spray techniques compared to the grower standard (Table 2). At 15.2 m, Air-in had significantly greater drift than the grower standard and the untreated control. Unadjusted means for Air-in are higher than expected due to a strong wind gust during the return pass of the Air-In technique, which was accounted for in the model (Fig. 4A). At 30.5 m, Air-in also had significantly greater drift than the other treatments. This drift was very minor as there was no drift at 45.7 m. Mean wind speed during the trial was light during the morning at 1 to 3 kmh^{-1} and increased during the day to 6 to 9 kmh^{-1}. The overall values for wind speed were moderate at 3.9 to 4.3 kmh^{-1}. Wind direction varied during individual runs from SE to NW to NNE with a mean wind direction of N.

In the almond engine-driven spray rig trial there was significantly lower drift in the Air-in technique compared to the grower standard at 7.6 m, 11.4 m and 15.2 m (Table 3). In contrast, there was significantly greater drift in the Double-spray technique compared to the grower standard at all distances except 15.2 m. There was also significantly greater drift for all techniques compared to the untreated control except at 45.7 m. Mean wind during the trial was light at 2.8 to 3.2 kmh^{-1} with wind gusts of 4 to 5 kmh^{-1} (Fig. 4B). Mean wind direction for Air-in and grower standard was from the SSW while the mean wind direction for the Double-spray was from the W. The wind direction for individual runs for Air-in varied between S, SSE and N, for

Double-spray it varied between WSW and N and for grower standard it varied between S, SW and N.

In the walnut engine-driven spray rig trial there was significantly lower drift in the Air-in and Double-spray techniques compared to the grower standard at 7.6 m, 11.4 m 15.2 m, and 30.5 m (Table 4). No drift was observed with any treatment at 45.7 m, 76.2 m and 121.9 m. Mean wind during the trial was moderate at 4.9 to 5.5 kmh^{-1} with wind gust of 7 to 8 kmh^{-1} (Fig. 4C). Mean wind direction for all spray techniques was from the NNE. The wind direction for individual runs was from the NW to NE for Air-in, NE to N for Double-spray and NE to NNE for grower standard. A collar was installed on the outer manifold of the Durand-Wayland air-blast speed sprayer, which prevented all outward spray drift.

In the pistachio engine driven spray rig trial there was significantly lower drift in the Air-in technique compared to the grower standard at 7.6 m, 15.2 m, 30.5 m and 45.7 m, but not at 11.4 m (Table 5). There was significantly lower drift for the Double-spray technique compared to the grower standard at 7.6 m, 30.5 m, 45.7 m and 76.2 m but not at 11.4 m and 15.2 m. Air-in and Double-spray were not significantly different from each other. Mean wind during the trial was moderate at 5.2 to 6.2 kmh^{-1} with wind gusts of 7 kmh^{-1} (Fig. 4D). Mean wind direction for all spray techniques was from the S. The wind direction for individual runs for Air-in was from the SSW to ESE. The wind direction for Double-spray and grower standard was from the SSW to SE.

3.2 Methoxyfenozide deposition, spray coverage and NOW bioassay

The mean amount (ng/cm^2) of methoxyfenozide was significantly greater on the filter papers placed in mid-canopy in the Air-in technique compared to the grower standard for the PTO almond trial No. 1 and engine driven almond trial (Table 6). For the methoxyfenozide deposition trials, there was no significant difference among Air-in, Double-spray and grower standard in the PTO almond trial No. 2 and engine driven walnut and pistachio trials. The Double-spray technique deposited numerically greater amounts of methoxyfenozide on the filter papers in PTO almond trials No. 1 and No. 2 and engine almond and walnut trials but not pistachio. There were significantly greater mean amounts of methoxyfenozide on the filter papers placed mid-canopy in PTO almond trial Nos. 1 and 2, engine walnut and pistachio Air-in and Double-spray treatments as compared to the untreated control. There were significantly greater amounts of methoxyfenozide on the filter papers placed in high-canopy in air-in technique as compared to the grower standard in PTO almond trials No. 1 and 2 (Table 7). The Double-spray technique also deposited significantly greater amounts of methoxyfenozide in PTO almond trial No. 2 than the grower standard. There was no significant difference in the amount of methoxyfenozide on the filter papers placed high in the canopy in engine-driven air-blast speed sprayers in almond, walnut and pistachio as compared to the grower standard. Air-in and Double-spray techniques deposited significantly greater amounts of methoxyfenozide on the filter papers compared to the untreated control.

In the dye coverage trials, there was significantly greater percent coverage on the Kromekote paper targets placed at mid-canopy in the Double-spray technique as compared to the grower standard in engine-driven air-blast speed sprayer almond trial (Table 8). There was no significant difference in percent coverage of the Kromekote paper targets between the two experimental application techniques and the grower standard in all other trials. A low amount of Aquashade dye (0.015%) was added to the spray solution in the PTO almond No. 2 by error and no data was collected from this trial. There was no significant difference in dye coverage between the two experimental application techniques and the grower standard for all Kromekote paper targets placed high in the canopy (Table 9). There was significantly greater coverage for the two experimental application techniques and the grower standard compared to the untreated control in all trials when Kromekote paper targets were placed in both mid and high canopy.

In the NOW larval mortality bioassay trials, there was no significant difference in NOW mortality among the two experimental application techniques and grower standard at the mid-canopy height and all three spray techniques had significantly greater mortality compared to the untreated control (Table 10). There was no significant difference in NOW mortality among the two experimental application techniques and grower standard at high-canopy and all were significantly different compared to the untreated control except for PTO almond No. 2 (Table 11). The high untreated control mortality, which ranged from 31.7% to 65.5%, was a result of the cannibalistic nature of the NOW larvae at very high egg density[20]. This cannibalism elevated the control mortality and increased the variability in mortality among the replicates.

4 Discussion

4.1 Drift mitigation

Drift at 7.6 m and 11.4 m from the orchard dripline was reduced by the Air-in technique regardless of speed sprayer type. The Air-in technique reduced or eliminated the air-output from the outside manifold and prevented the spray movement of pesticides that were sucked into the air intake. The speed sprayers used in these studies were of different design (presence or absence of baffle and diverter plates, air speed and displacement) which affected drift. The Air-O-Fan PTO and engine-driven air-blast speed sprayers (600 GB-36R, D-240 and Predator) that were used in the almond and pistachio trials have adjustable baffles to direct the air and a diverter plate at the bottom of the spray manifold. These were all closed on the outer manifold in the Air-in and Double-spray techniques, but there was a 1 to 1.5 cm space on each side of each baffle that was open, and the bottom diverter plate could not be closed completely. Consequently, there was some air output (1.6 to 3.2 kmh^{-1}) from the outer manifolds of three Air-O-Fan air-blast speed sprayers. This could have increased the drift, particularly at 7.6 m in the Air-in and Double-spray treatments. If the air output could be prevented, then drift from the Air-O-Fan speed sprayers could be largely prevented. The engine-driven Durand-Wayland 1705A air-blast speed sprayer used in walnut did not have adjustable baffle plates. In order to prevent air output from the outer manifold, an air collar was constructed and placed over the entire outer manifold, which prevented any outward air movement. The complete elimination of outward air from the outer manifold may have contributed, in part, to the reduced drift observed in walnut.

Tree height and spray rig output as well as wind direction and velocity had an effect on drift. In the pistachio orchard, the spray height far exceeded the tree height while in the walnut orchard the spray height did not greatly exceed tree height. The pistachio trees were 4.6 m to 6.1 m tall while in contrast walnut trees were 10.7m to 12.2 m tall. Air speed and displacement may have affected drift. An Air-O-Fan D-240, with an air speed of 225 kmh^{-1} and air displacement of 6.23 X 10^6 Lm^{-1} while an Air-O-Fan 600 GB 36R has an air speed of 209 kmh^{-1} and an air displacement of 1.98 X 10^6 Lm^{-1}. Air speed and displacement was provided by manufacturer. Although, there is only 7% difference in air speed, there is a 314% difference in air displacement. The Durand Wayland 1705A used in walnuts has an air speed of 241 kmh^{-1}, which was 6.6% faster than the D-240 but its air displacement of 2.78 X 10^6 Lm^{-1}, which was 55% less than the D240. Air speed and displacement was provided by manufacturer. These disparities help explain the lack of drift in walnut and the much greater drift in pistachio. The almond trial using the Air-O-Fan 600 GB 36R had less drift with the Air-O-Fan D-240 in the same orchard. This indicates that air displacement contributes to drift with constant tree height.

4.2 Spray coverage, insecticide deposition and NOW bioassay

Air-in and Double-spray techniques provided similar or in some studies significantly better spray coverage and deposition of methoxyfenozide compared to the grower standard, while there was no significant difference among the experimental treatments in mortality of NOW larvae. There was high NOW mortality and variation in the untreated control due to the cannibalistic nature of the NOW larvae at the egg density used to assess contact toxicity. This high background mortality may be responsible for the lack of difference in NOW mortality among the application techniques. Similar findings were reported for the “Gear Up/Throttle Down” application technique, which had lower pesticide deposition compared to the grower standard, but little difference in NOW mortality.[2] However, the contact mortality assay is influenced by neonate behavior. If the larvae remain on the filter paper, it increases the likelihood of exposure to a toxic level of insecticide, even if the insecticide deposition is lower.

Synchronization of the two spray rigs was problematic and required attention by the principle investigator to keep the spray rigs in tandem. When the spray rigs fell out of synchronization and the two output manifolds did not line up, the benefits of greater air turbulence and air displacement by the Air-in and Double-spray techniques were lost. Research is currently underway to develop a vision-based synchronization guidance system, which will allow communication of the manifold position to the spray rig operators and greatly improve synchronization of the two spray rigs. With increased synchronization, there will be improved coverage and reduced drift. The small percent of dye coverage and trace amounts of methoxyfenozide on the filter papers placed in the untreated control were the result of carryover from the previous sprayed plot. Since the nozzles did not have spring loaded check valves, a small amount of spray solution that remained in the spray lines was inadvertently carried forward into the next plot. This can be corrected by the addition of check valves or by clearing the line between replicates.

5 CONCLUSIONS

Pesticide drift mitigation was successfully achieved with the Air-in application technique for different types of spray rigs and for different tree species while coverage in the Air-in technique as measured by three different methods (dye marker, insecticide deposition and bio-assay), was similar to the grower standard. However, this study only measured aqueous phase drift not gaseous phase drift. For pesticides with high volatilization, an air sampling technique would be required. The Air-in technique requires minimal spray rig modification that can be easily implemented. More importantly, the Air-in technique does not require a change in nozzle configuration compared to the “Gear Up/Throttle Down” technique. Once the outside rows have been sprayed, the rigs can continue in the orchard without nozzle reconfiguration. However, this technique requires two spray rigs Growers with limited acreage and only one spray rig cannot implement this technique. However, growers with limited acreage can share equipment or use custom applicators that have multiple spray rigs. In addition, the outside row will need to be sprayed twice, once with the spray solution off and then again with spray solution on. The development of a vision-based synchronization guidance system and an air collar on the outside manifold could reduce drift even further. Although the Double-spray technique did not reduce drift, this technique could increase coverage within the orchard and be of particular use for almond orchards that have a planting configuration of a pollinizer cultivar alternating every other row with a Nonpareil cultivar. The Nonpareil cultivar commands a higher price than other almond cultivars and for maximum Nonpareil yield, an early bloom and late bloom pollinizer are grown on either side of the Nonpareil cultivar.

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Table 1. Number of replicates conducted and used in analysis of drift measurements by study

Studies	Commodity	Replicates	
		Conducted	Analyzed
PTO No. 1	Almond	2	1
PTO No. 2	Almond	8	8
Engine No. 1	Almond	4	3
Engine No. 2	Walnut	5	4
Engine No. 3	Pistachio	6	4

Table 2. Unadjusted mean percent area covered with spray solution on water-sensitive papers at five distances for the three spray techniques in almond using a PTO air-blast speed sprayer and an untreated control in 2018 near Huron and Crows Landing, CA

	Mean[a] percent covered				
Treatment	7.6 m	11.4 m	15.2 m	30.5 m	45.7 m
Air-in	0.34 b	0.15 b	0.14 b	0.02 b	0.00
Double-spray	0.28 b	0.11 b	0.07 bc	0.00 a	0.00
Grower standard	0.73 c	0.38 c	0.12 c	0.00 a	0.00
Untreated control	0.00 a	0.00 a	0.00 a	0.00 a	0.00
F	89.90	61.90	17.20	4.03	
P	<0.01	<0.01	<0.01	<0.01	

[a]Means followed by the same letter in a column are not significantly different (Tukey's HSD, P ≤ 0.05).

Table 3. Unadjusted mean percent area covered with spray solution on water-sensitive papers at five distances for the three spray techniques in almond using an air-blast engine-driven speed sprayer and an untreated control in 2018 near Huron, CA

	Mean[a] percent covered				
Treatment	7.6 m	11.4 m	15.2 m	30.5 m	45.7 m
Air-in	2.17 b	2.32 b	1.39 b	0.33 ab	0.10 a
Double-spray	9.85 d	6.00 d	3.14 c	1.60 c	0.75 b
Grower standard	5.80 c	3.25 c	2.26 c	0.60 b	0.11 a
Untreated control	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a
F	569.00	485.00	168.00	21.50	20.40
P	<0.01	<0.01	<0.01	<0.01	<0.01

[a]Means followed by the same letter in a column are not significantly different (Tukey's HSD, P ≤ 0.05).

Table 4. Unadjusted mean percent area covered with spray solution on water-sensitive papers at seven distances for the three spray techniques in walnut using an air-blast engine-driven speed sprayer and an untreated control in 2018 near Crows Landing, CA

	Mean[a] percent covered						
Treatment	7.6 m	11.4 m	15.2 m	30.5 m	45.7 m	76.2 m	121.9 m
Air-in	0.02 a	0.01 a	0.00 a	0.00 a	0.00	0.00	0.00
Double-spray	0.02 a	0.00 a	0.00 a	0.00 a	0.00	0.00	0.00
Grower standard	2.81 b	2.89 b	2.33 b	0.06 b	0.00	0.00	0.00
Untreated control	0.00 a	0.00 a	0.00 a	0.00 a	0.00	0.00	0.00
F	47.30	54.50	43.30	5.72			
P	<0.01	<0.01	<0.01	<0.01			

[a]Means followed by the same letter in a column are not significantly different (Tukey's HSD, P ≤ 0.05).

Table 5. Unadjusted mean percent area covered spray solution on water-sensitive papers at seven distances for the three spray techniques in pistachio using an air-blast engine-driven speed sprayer and an untreated control in 2018 near Three Rocks, CA

	Mean[a] percent covered						
Treatment	7.6 m	11.4 m	15.2 m	30.5 m	45.7 m	76.2 m	121.9m
Air-in	9.28 b	4.36 b	2.62 b	0.14 ab	0.08 b	0.00 a	0.00
Double-spray	14.29 b	8.73 b	5.15 bc	0.51 b	0.05 ab	0.00 a	0.00
Grower standard	19.38 c	8.34 b	6.74 c	1.07 c	0.23 c	0.04 b	0.00
Untreated control	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00
F	878.00	152.00	198.00	15.60	24.20	6.40	
P	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	

[a]Means followed by the same letter in a column are not significantly different (Tukey's HSD, P ≤ 0.05).

Table 6. Mean recovery of methoxyfenozide from targets placed mid-canopy in the tree

	Mean[ab] amount (ng/cm^2) methoxyfenozide				
	PTO		Engine		
Treatments	Almond No.1	Almond No. 2	Almond	Walnut	Pistachio
Air-in	17.5 a	4.8 a	11.0 a	4.8 a	2.5 a
Double-spray	8.5 ab	7.0 a	7.3 ab	5.4 a	2.5 a
Grower standard	8.2 b	6.4 a	4.3 bc	4.4 a	3.5 a
Untreated control	0.1 c	0.0 b	0.1 c	0.1 b	0.2 b
F	10.61	11.12	10.68	7.27	15.93
P	<0.01	<0.01	<0.01	<0.01	<0.01

[a] Means followed by the same letter in a column are not significantly different (Tukey's HSD test, $P \leq 0.05$).
[b]Data was transformed using arcsine(sqrt(x)). Untransformed data presented.

Table 7. Mean recovery of methoxyfenozide from targets placed high in the tree canopy

	Mean[ab] amount (ng/cm^2) methoxyfenozide				
	PTO		Engine		
Treatments	Almond No.1	Almond No. 2	Almond	Walnut	Pistachio
Air-in	8.2 a	1.2 a	4.1 a	3.4 a	1.5 ab
Double-spray	4.9 ab	1.1 a	4.4 a	4.8 a	2.3 a
Grower standard	3.1 bc	0.5 b	2.4 ab	3.4 a	1.9 a
Untreated control	0.1 c	0.0 b	0.1 b	0.0 b	0.3 b
F	9.36	22.21	9.22	8.91	5.85
P	<0.01	<0.01	<0.01	<0.01	<0.01

[a] Means followed by the same letter in a column are not significantly different (Tukey's HSD test, $P \leq 0.05$).
[b]Data was transformed using arcsine(sqrt(x)). Untransformed data presented.

Table 8. Mean percent dye coverage from targets placed mid-canopy in the tree

	Mean[ab] percent coverage			
	PTO	Engine		
Treatments	Almond No.1	Almond	Walnut	Pistachio
Air-in	64.4 a	69.0 ab	73.7 a	52.8 a
Double-spray	68.9 a	81.2 a	66.5 a	44.0 a
Grower standard	64.4 a	47.7 b	74.9 a	48.7 a

Untreated control	0.0 b	0.1 c	0.1 b	0.2 b
F	85.56	54.67	109.95	42.20
P	<0.01	<0.01	<0.01	<0.01

[a] Means followed by the same letter in a column are not significantly different (Tukey's HSD test, P ≤ 0.05).

[b]Data was transformed using arcsine(sqrt(x)). Untransformed data presented.

Table 9. Mean percent dye coverage from targets placed high in the tree canopy

	Mean[ab] percent coverage			
	PTO	Engine		
Treatments	Almond No.1	Almond	Walnut	Pistachio
Air-in	53.7 a	38.6 a	53.1 a	16.5 a
Double-spray	43.4 a	58.6 a	56.0 a	19.7 a
Grower standard	46.1 a	38.0 a	55.9 a	25.8 a
Untreated control	0.0 b	0.0 b	0.1 b	0.1 b
F	8.20	17.80	18.90	16.81
P	0.01	<0.01	<0.01	<0.01

[a] Means followed by the same letter in a column are not significantly different (Tukey's HSD test, P ≤ 0.05).

[b]Data was transformed using arcsine(sqrt(x)). Untransformed data presented.

Table 10. Mean percent navel orangeworm larval mortality from targets placed mid-canopy in the tree

	Mean[a] percent mortality				
	PTO		Engine		
Treatments	Almond No.1	Almond No. 2	Almond	Walnut	Pistachio
Air-in	81.7 a	85.9 a	81.7 a	90.6 a	86.5 a
Double-spray	81.5 a	84.0 a	89.6 a	93.2 a	83.6 a
Grower standard	82.2 a	82.4 a	91.2 a	90.2 a	81.6 a
Untreated control	32.8 b	45.4 b	65.5 b	51.9 b	45.8 b
F	27.42	47.53	95.11	29.21	152.82
P	<0.01	<0.01	<0.01	<0.01	<0.01

[a] Means followed by the same letter in a column are not significantly different (Tukey's HSD test, P ≤ 0.05).'

[b]Data was transformed using arcsine(sqrt(x)). Untransformed data presented.

Table 11. Mean percent navel orangeworm larval mortality from targets placed high in the tree canopy

	Mean[a] percent mortality

	PTO		Engine		
Treatments	Almond No.1	Almond No. 2	Almond	Walnut	Pistachio
Air-in	63.5 a	66.1 a	75.4 a	83.7 a	77.3 a
Double-spray	73.2 a	53.1 a	79.5 a	86.0 a	76.9 a
Grower standard	75.0 a	70.3 a	74.2 a	84.7 a	76.9 a
Untreated control	31.7 b	46.3 a	37.7 b	53.2 b	44.6 b
F	13.52	3.40	25.45	17.23	13.04
P	<0.01	0.07	<0.01	<0.01	<0.01

[a] Means followed by the same letter in a column are not significantly different (Tukey's HSD test, $P \leq 0.05$.

[b]Data was transformed using arcsine(sqrt(x)). Untransformed data presented.

Fig. 1. Grower Standard: An air-blast sprayer drives between the first and second row and sprays both rows one and two. Then the air-blast sprayer returns along the outside row of the orchard and sprays the first row with the spray solution and air of the inside manifold on and with the spray solution of the outside manifold off but air on (standard application).

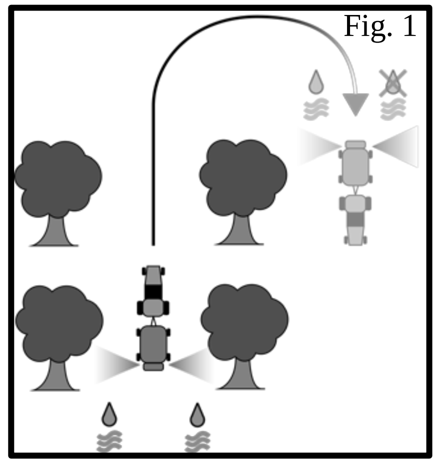


Fig. 2. Air in: An air-blast sprayer drives between the first and second row and sprays both rows one and two. A second air-blast sprayer drives in parallel with the inside sprayer along the outside of the orchard and sprays the first row with the inside manifold spray solution off and air on and the outside manifold spray solution off and air off. Then the air-blast sprayer returns along the outside of the orchard and sprays the first row with the spray solution and air of the inside manifold on and with the spray solution and air of the outside manifold off.

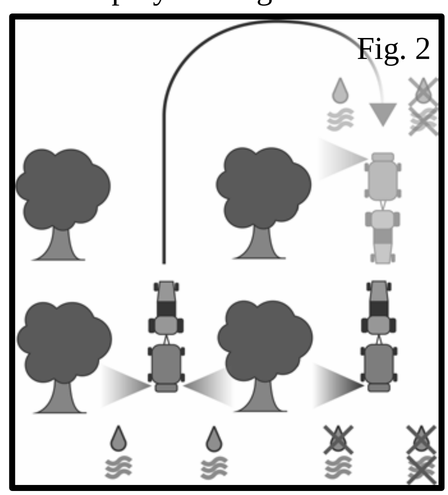


Fig. 3. Double-spray: An air-blast sprayer drives between the first and second row and sprays both rows one and two. A second air-blast sprayer drives in parallel with the inside sprayer along the outside of the orchard and sprays the first row with the inside manifold spray solution and air on and the outside manifold spray solution and air off.

Fig. 3

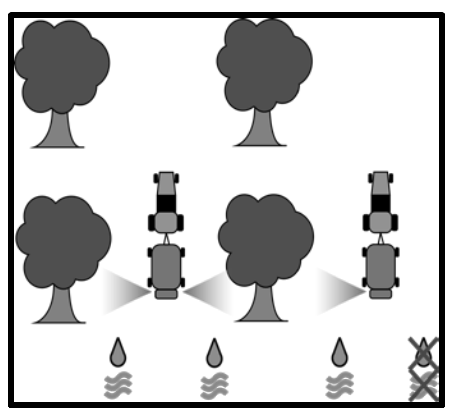
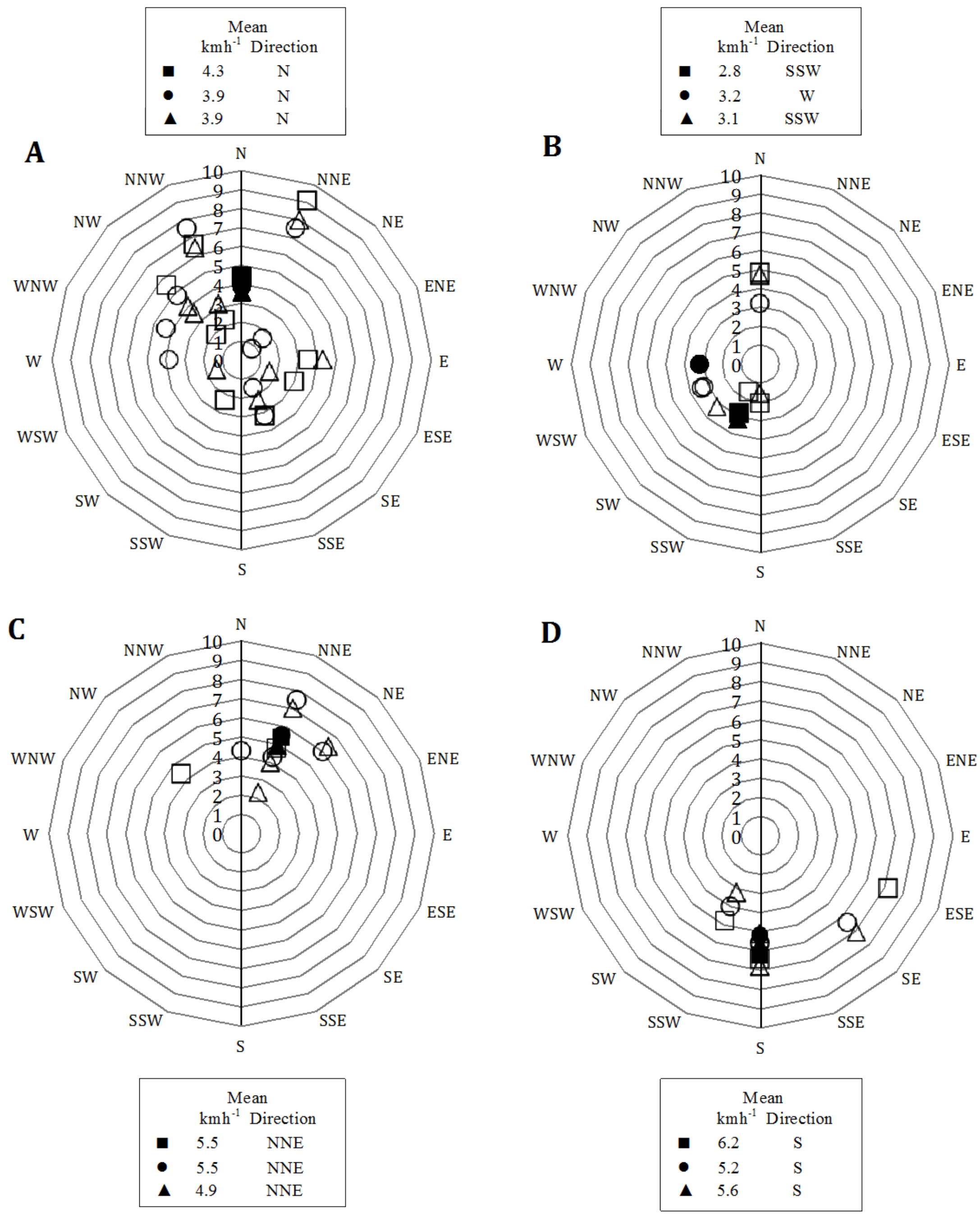


Figure 4. Wind Stars depicting the wind direction and speed during the drift trials. Wind direction is the direction that wind was coming from. Air-In is denoted by ■, Double Spray by ● and Grower's Standard by ▲. The area west of the vertical line represents where the orchard was located. An empty shape represents an individual replicate, while a filled in shape denotes the average wind direction and speed across all of the replicates. A is the combined Almond PTO, B is the Almond Engine, C is the Walnut Engine, D is the Pistachio Engine. Each ring represents an increase in wind speed in kilometers per hour. For example, the ● in sub-figure B shows that during the Almond Engine Trial, the Grower's Standard treatment had an average wind from the west between 3 and 4 kmh^{-1}.


Mean
kmh-1 Direction
4.3 N
3.9 N
3.9 N
A
Mean
kmh-1 Direction
2.8 SSW
3.2 W
3.1 SSW
B
C
Mean
kmh-1 Direction
5.5 NNE
5.5 NNE
4.9 NNE
D
Mean
kmh-1 Direction
6.2 S
5.2 S
5.6 S
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