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Title: Canopy spray deposition and related mortality impacts of commonly used insecticides on *Drosophila suzukii* Matsumura (Diptera: Drosophilidae) populations in blueberry

Running Title: Spray deposition and mortality of insecticides on *Drosophila suzukii* in blueberry

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/ps.5672

Abstract

BACKGROUND: Insecticide applications in blueberry production systems play a crucial role in the control of *Drosophila suzukii*. Here, the quantitative spray deposition patterns were obtained under replicated field experiments in blueberry during two field seasons with three sprayers i.e. cannon, electrostatic, and airblast. Seven insecticides were tested (at six hours by using a Potter spray tower) to determine the mortality on adult *D. suzukii*. Spray deposition and mortality data on adult *D. suzukii* were used to create model simulations for insect populations. Model simulations included field deposition rates of sprayers and insecticide mortality as factors. Simulations were applied in different combinations with five applications over a six-week period.

RESULTS: Cannon sprayer deposition rates were relatively elevated in the upper zones of the canopy while airblast sprayer deposition was greater in the bottom zones. Electrostatic spray deposition was relatively uniform within the six canopy zones. Clear *D. suzukii* laboratory mortality trends with lowest to highest mortality were recorded for phosmet, spinetoram, spinosad, malathion, cyantraniliprole, zeta-cypermethrin, and methomyl respectively. The maximum *D. suzukii* population impacts as shown by model outputs were observed with airblast sprayers used together with zeta-cypermethrin.

CONCLUSION: The electrostatic sprayer had the least variable canopy deposition among the three types of spray equipment, and the airblast sprayer had the highest overall deposition rates. The present study provides new hypotheses that can be used for field verification with these spray technologies and insecticides as key factors.

Keywords: Blueberry, Spray Equipment, Integrated Pest Management, Dose-Response, Population Modeling, Insecticide

1 INTRODUCTION

Blueberry is one of many worldwide crops that is susceptible to *Drosophila suzukii* Matsumura (Diptera: Drosophilidae) infestation[1-5]. The farm gate value of blueberry fruit was approximately USD 105 million in Oregon and 94 million in Washington in the USA[6]. Currently, *D. suzukii* poses the biggest challenge to blueberry production in all US production regions[1, 7-10].

Several methods including cultural, biological, and chemical can be used to manage *D. suzukii* damage[2]. Chemical control is the most prominent way to manage *D. suzukii* damage with an average of 5-8 chemical applications per growing season [10]. The canopy architecture can strongly affect spray deposition due to the compact nature of canopy in many crops, resulting in uneven deposition of spray droplets, especially within inner and lower parts of the canopy[11-15] . Therefore, it is essential to choose appropriate spray equipment that provides relatively uniform spray deposition in all portions of the plant canopy. In addition, the inner and middle parts of the canopy could be an optimal environment for *D. suzukii* egg laying[16] due to shading, which results in lower temperatures coupled with higher humidity[17]. Inner parts of the canopy are crucial zones within the blueberry bush in the context of *D. suzukii* biology and management because of a more favorable microclimate and higher population levels of *D. suzukii*[18, 19]. *D. suzukii* population levels and crop damage can be relatively high within inner and lower parts of the canopy, highlighting the importance to obtain uniform spray deposition in the canopy [18]. Spray techniques undoubtedly impact insecticide efficacy for insects such as *D. suzukii*[20, 21]. Several types of sprayers are used by growers however, air-assisted sprayers are the most commonly used so far. In some cases, growers opt to use cannon, electrostatic and airblast sprayers [8, 22-24]. Airblast sprayers are the most commonly used air-assisted sprayers due to even and high deposition levels on the crop canopy. The droplets from nozzles are transferred to the canopy by high inertial air movement created by airblast axial fan [25]. Cannon sprayers are often used for border spray applications to limit canopy disruption and minimize application time[8]. Cannon sprayers are intended to spray 30-meter swaths, which can be applied along crop perimeters as opposed to spraying the entire field block. Electrostatic sprayers are often preferred by the growers because of perceived uniform application levels throughout the targeted canopy areas[24, 26]. Electrostatic sprayers typically require lower spray volumes compared to cannon and airblast sprayers, because of pneumatic nozzles that use air to form very fine droplets. The fine droplets are presumed to carry an electric charge imparted on the droplet[27].

Several insecticide classes (organophosphate, carbamate, pyrethroid, spinosyn, and diamide) are used to control *D. suzukii* populations [7, 10, 22, 28]. The insecticides differ by levels of efficacy under ideal application rates, but little information is available at suboptimal dose rates, as is found under typical field application conditions because of shielding from adjacent branches and leaves. Growers can use information about sub-optimally low field deposition rates as a decision-making tool to optimize seasonal spray strategies [29]. In addition, optimizing spray application can also increase the insecticide efficiency through more even and optimal canopy deposition rates while reducing the cost and potential adverse environmental impacts from off-target drift[21, 30, 31].

Significant progress has been made in understanding *D. suzukii* population dynamics, which enables us to model the response of insect populations to insecticide applications[32-34].

The population density of *D. suzukii* is based on a variety of environmental and biological parameters [32, 35, 36]. Model outputs simulating *D. suzukii* population response in relation to environmental factors, spray technologies, insecticides and biological control agents are useful to practitioners because they can simulate multiple scenarios allowing for testing optimal strategies. The model outputs therefore can be used to eliminate strategies that show less promise, thereby resulting in an accelerated optimization process[34].

The aim of the present study was (1) to quantify spray deposition patterns of three spray equipment(s) that are used in blueberries for *D. suzukii* management, (2) to estimate *D. suzukii* mortality at a range of spray deposition levels as is typically found under field conditions, (3) to simulate *D. suzukii* population response with spray deposition and insecticide as factors.

2. MATERIALS AND METHODS

2.1 Spray deposition field experiment

Field trials were conducted during 2015 and 2016 in a 0.2-ha 'Duke' blueberry block planted in 2008 at Oregon State University's North Willamette Research and Extension Center (NWREC), Canby, Oregon (45°16'51.2"N, 122°45'13.7"W). Plants were spaced at 1 m within rows and at 3±0.1 m between rows. Plant height and diameter were 2±0.1 m and 1±0.1 m, respectively. The blocks were managed based on industry-standard practices for pruning, irrigation and fertilization in both years[37]. The application row was divided into three subplots. Each subplot consisted of six individual plants for a total of 18 plants in the row. The subplots were 15.2 m long with a 15.2 m buffer zone between each subplot. Weather records were obtained from the Agrimet weather station (45°16'54"N, 122°45'00"W, Elevation: 42.7 m above sea level). The station was equipped with a temperature and humidity sensors that logged data to a data logger (Model CR1000, Campbell Scientific, Inc. Logan, UT, USA) and wind monitoring sensor at a 3 m above ground level (Model 05103, RM Young, Inc. Traverse City, MI, USA)[38]. The average temperature, wind and humidity were recorded every 15 minutes. The weather station was located 250 m northeast of the experimental blueberry plot and at the same elevation (Table 1). The experiments were designed to follow ISO protocols 22522: 2007E[39], but were slightly adapted in order to obtain data relevant for the most optimal management of *D. suzukii*.

2.2 Spray equipment

Cannon (Jacto J400, Jacto Inc. Pompea, Brazil), electrostatic (OnTarget Sprayer, OnTarget Spray Systems, Mt. Angel, OR, USA), and airblast (Pakblast, Rears MFG. Co. Coburg, OR, USA) sprayers were set up according to manufacturer specifications and in-field assistance from technical representatives. The width of the first row closest to the passing sprayer was the target (Figure 1). Manufacturer instructions were followed to optimize the spray head angle, distance from the canopy, pump pressure, fan speed, tractor speed and spray volume ha^{-1}. The calibration parameters for the nozzles and the specifications of the three sprayers, as well as realistic application volumes typically applied by growers, were used for each sprayer (Table 2). These parameters were used after consulting industry representatives. Prior to field spray application, each sprayer was calibrated for an optimal tractor speed of 4.82 km h^{-1}.

2.3. Tracer application and sampling

Green plastic polypropylene cards (size: 25.4 mm x 25.4 mm, 6.45 cm^2) were used for within canopy deposition measurements [40]. The size of the spray cards was based on the typical size of blueberry leaves found within the canopy of trial plots. The size of the cards is believed to be representative of the typical spray deposition on leaves by the respective sprayers. The plant canopy was divided into six zones relative to the path of the spray equipment and named as follows: top right (TR), top middle (TM), top left (TL), bottom right (BR), bottom middle (BM), and bottom left (BL) (Figure 1a). Top zones were 1.5 m and bottom levels were 0.5 m above ground level. In 2015, cards stapled to the adaxial surface of blueberry leaves in the center of each zone and only the upper sides of the cards were exposed to the spray application because the bottom side was adhered directly to the blueberry leaf blade. In 2016, polyvinyl chloride (PVC) poles were placed within the canopies in similar positions to each of the six canopy zones.

The cards were attached to the poles using sprung metal clips centered in each zone. The orientation of the cards during both 2015 and 2016 was similar.

A food–grade fluorescent tracer, Pyranine 10G®, (Keystone Aniline Corporation, Chicago, IL, USA), was mixed in water (190 g in 200 liters of water)[25] to give a final concentration of 1000 mg L^{-1} for each sprayer [40]. To quantify the parts per billion of tracer within each tank, a tank mixture sample was collected on each of spray dates. Tank samples were taken for each sprayer prior to each application and measured by using the same protocol as those for cards and used to standardize concentration. The tractor passed the rows one-time cannon application and tracer was sprayed onto the first three rows (Figure 1b), which is consistent with the operation of this type of sprayer. Electrostatic and airblast sprayers (Figure 1c), designed to spray a single row, passed both sides of the first row cards were collected ~15 minutes after the spray application for each sprayer. cards were collected into a plastic bag and stored in a cooler box for transportation to the laboratory.

2.4 Spray deposition assessment

Canopy deposition was measured using a fluorometer (10-AU™ Turner Design, Inc., Sunnyvale, CA, USA) with excitation and emission filters of 365 nm and >570 nm respectively. The fluorometer was calibrated to manufacturer specifications. All samples including cards were analyzed within one week of collection in the laboratory at 20±2°C. A known wash volume (e.g. 20 ml) of deionized water was added to the plastic bags containing samplers and were agitated for 30 seconds. Two aliquots were subsequently transferred into standard glass 9 ml test tubes and fluorescence was measured twice using the fluorometer. After the first measurement, the tube was rotated 90 degrees and a second reading was recorded. Samples were diluted as necessary to fit into the linear calibration curve and additional dilution was accounted for during spray deposition calculations for each cards in ng cm^{-2}.

The analyses of field deposition data were performed using the statistical software program SAS Studio (University edition, SAS Institute Inc., Cary, NC, USA). The procedure proc mixed was used to perform the split-plot ANOVA analysis to determine if there was sprayer or zone effect (fixed effects) while accounting for possible correlation within each subplot (random effect). Tukey-Kramer's Honest Significant Difference test was used to compare differences among the treatment means. All data were log10-transformed prior to the analysis to meet the assumptions of normality, and appropriate residual analysis showed the model assumptions were satisfied. R studio[41] (R version 3.6.1) ggplot package[42] was used to plot the figures.

2.5 *Drosophila suzukii* mortality experiment

The range of insecticide concentrations, including the field application rate (Table 3), were prepared by serial dilution with deionized water and applied using the Potter's precision spray tower on glass plates in order to estimate the acute mortality of *D. suzukii* adults. In total, six to nine concentrations (mg ai L^{-1}) were used as laboratory exposure rates for each insecticide in order to determine impacts of suboptimal deposition rates typically found under field conditions. Deionized water was used for control treatment. Dilutions were applied onto two glass plates using a Potter precision spray tower (Burkard Manufacturing Co. Ltd., Rickmansworth, England)[43] and deposited spray were allowed to dry for 30 minutes before being assembled onto the ventilated Munger cells with the treated side facing to the interior of the cell [44, 45].

Chemicals that are reported to have acceptable field mortality for adult *D. suzukii* were used. All insecticides were used within a one-year period after their donation by the respective companies.

A colony of *D. suzukii* was established and continuously supplemented with from wild-caught adult individuals, found under field conditions where insecticides are often used, in the Willamette Valley, Oregon up to the laboratory study[46]. Ten seven-day-old male and ten seven-day-old female *D. suzukii* adults were introduced into Munger cells that ventilated at a rate of 1 L h^{-1} of air extracted from the laboratory. Munger cells were held at a 14:10 daily light and dark regime at 21±1°C and 70-80% relative humidity for the duration of the experiment. Adult *D. suzukii* within each Munger cell were supplied deionized water on cotton wool threaded through a small opening within the side of each cell throughout the experimental period. The experimental setup allowed adult *D. suzukii* to freely move within each cell. Control treatments were provisioned with deionized water only.

Mortality of *D. suzukii* was recorded 6 hours after exposure in order to determine immediate insecticide effect under high-pressure *D. suzukii* situations. The reason to obtain 6 hours mortality is that *D. suzukii* adults start egg laying soon after emergence[47] and reducing egg laying using fast-acting insecticides will decrease crop damage. The data were fitted to a three-parameter log logistic non-linear regression function with lower limit 0 within the dose response curve package with drm (fitting dose response model) function[48, 49],

$$f(x) = \frac{d}{1+\exp[b\ \log(x)-\log(e)]}\ \ (M3p).$$

Optimal model fittings were determined using the mselect function; LC_{50} and LC_{90} values (lethal concentration) were estimated using the ED function (estimated effective doses)[48] (Table 4). The Neill's lack-of-fit test was used to determine the F and p values to evaluate the adequacy of fitted nonlinear model[50]. R studio was used to calculate LC_{50} and LC_{90} values[41].

2.6 *Drosophila suzukii* population modeling

A mortality-matrix (*MM*, Table 5) was created, which included two contributing factors. The first factor was the percent median field deposition values of each sprayer type within each canopy zone (*%D)* as was found under field conditions. Second, the registered field rate of each insecticide, (active ingredient, *R*) was multiplied with *%D* to determine the percent deposition of active ingredient (%*DAG*). These values were used as inputs in the estimated three-parameter models (M_{3p}) for each active ingredient to obtain the *MM* values i.e.: $\%D \times R = \%DAG \ \rightarrow\ M_{3p} \ \rightarrow MM$. It is important to note that the *MM* values consisted out of Middle Zone (MZ_{43}) and Outer Zone (OZ_{57}) fractions. The respective mortality fractions were based on the previously reported *D. suzukii* spatial occurrence within each canopy zone[18]. Therefore, MM = (MZ_{43}+OZ_{57}) values therefore contributed 43% and 57% to the overall *D. suzukii* mortality. For the purposes of this study, Middle Zones consisted out of TM & BM. Outer zones consisted out of TL, TR, BL, BR. For the purposes of this manuscript, we did not take into consideration the impact of the respective insecticides on immature *D. suzukii* stages i.e. egg, larvae, pupae. The model however does take into consideration hatching and developing eggs laid by adults. For the purposes of the present paper, the mortality of adult life stages was only measured as affected by the insecticides in the current study. Immigrating adults are commonly found under commercial field conditions where insecticides are often applied, and for this reason the adult mortality effects of the insecticides are of most importance in this perspective. We classified mortality rates from the laboratory experiment, into high (~57-96%), medium (~35-75%) and low (0.02-25%) acute mortality. The model simulations used daily weather data from the same weather station used for our field deposition experiment from early August to mid-September 2016 as inputs. The acute mortality rates of *D. suzukii* adults from the laboratory mortality experiments were used in the model runs during this late-variety blueberry cropping period. The model parameters for *D. suzukii* included temperature-dependent fecundity and survival and provided outputs for all life stages[34] (Supporting Information). This model structure contained the refinement of *D. suzukii* maturation delays. The parameter was implemented using a chain of coupled ordinary differential equations instead of a time scaling technique [51]. This additional model feature added a small but realistic variance to maturation delays, as is typically found within individuals in a population. Maturation rates are still temperature-dependent and vary accordingly. For these model runs, we assumed that fruit availability was not limiting, and that individuals were not affected by competition. Model runs were conducted by starting *D. suzukii* populations at 100 adult individuals on August 1, with no intervention runs providing baseline data of population increase during the selected period.

The modeled scenarios included each sprayer type. The three classified mortality rates (high, medium and low mortality) and five applications of each classification were applied as factors from early August until mid-September. We used the same mortality rate (high, medium and low) for each of the respective model runs. We simulated a typical spray timing of 7-day intervals over the total model run period to include five total applications. The simulations were implemented using Wolfram Mathematica[52]. Codes can be obtained from the authors upon request.

3. RESULTS

3.1 Canopy spray deposition

A comparison of data collected across both years revealed similar deposition patterns (Figure 2). Numerically higher deposition rates were recorded during 2015 than during 2016. In 2015, canopy deposition within each of the six zones was significantly different, ranging from ~3 to ~200 ng cm^{-2} ($F_{10,54}$=13.93, p< 0.0001). The deposition ranged from ~1 to ~200 ng cm^{-2}

($F_{10,53}$=7.61, p<0.0001) in 2016. Statistical significance was found among the sprayers as well as sprayer * zone interaction in both years.

Tracer dye deposition patterns varied by sprayer across the six zones. For the cannon sprayer, the highest deposition level was recorded on the top zones compared to the bottom zones. During 2015, the cannon sprayer delivered the highest deposition rates on the TL (33% of the cannon sprayer deposition) and the lowest deposition on BM zones (2.7%), the difference was found statistically different ($F_{5,10}$=23.23, p<0.0001). In 2016, the cannon sprayer had the highest deposition on the TL (59%) zone and the lowest deposition in the BM (0.68%) zone ($F_{5,10}$=24.81, p<0.0001).

The electrostatic sprayer had the highest deposition on the BL (33%) while depositing the least amount of tracer on TM (7.5%) ($F_{5,10}$=6.12, p=0.0075) in 2015, which was significantly different. During 2016, the highest deposition occurred on the BR (43%) zone while the lowest deposition occurred on the BM zone (8.4%) but these differences were not statistically different ($F_{5,10}$=1.61, p=0.2432).

The airblast sprayer deposited the most tracer on the BL zone (33%) while the lowest deposition was seen on the TR zone (0.48%) ($F_{5,10}$=27.62, p<0.0001) in 2015 and the difference is statistically different. In 2016, airblast sprayer deposition was greatest on the BR zone (28%) and lowest on the TM zone with a statistical difference (4.1%) ($F_{5,10}$=7.65, p=0.0046).

3.2 *Drosophila suzukii* mortality and log-logistic fit

Proportional mortality of *D. suzukii* adults after 6 hours of exposure to zeta-cypermethrin, methomyl, cyantraniliprole, malathion, spinosad, spinetoram, and phosmet were plotted using log logistic non-linear regression (Figure 3). The fit for all data was significant and the data were well described by the three-parameter log-logistic function. Adult mortality after 6 h was 90% for zeta-cypermethrin (4.6% of field dose), and methomyl (2.1% of field dose) (Table 4). For malathion, 90% mortality was reached at 62.7% of the field dose. With spinetoram 90% mortality at six hours was achieved with 98.2% of field dose. We were not able to obtain ninety percent mortality (90%) within six hours for cyantraniliprole, spinosad and phosmet likely because of their slower-acting residual properties. Residual mortality could increase by days for certain insecticides after the day of application i.e. spinosad, and phosmet[7, 10, 53]. The LC_{50} of zeta-cypermethrin was estimated as 0.3 mg ai L^{-1} (F=0.42, p=0.61), while for methomyl LC_{50} was 14.25 mg ai L^{-1} (F=0.55, p=0.61). The LC_{50} for malathion and spinetoram was 120 mg ai L^{-1} (F=0.12, p=0.89) and 119 mg ai L^{-1} (F=0.18, p=0.85) respectively.

3.3. *Drosophila suzukii* population modeling

The estimated mortality using the described parameters and population model inputs is presented in a mortality-matrix table from the field-generated deposition levels and lab-generated mortality trials (Table 5). Model input parameters allowed us to estimate hypothetical population dynamics of *D. suzukii* using different factors as inputs. Although the population outputs from the present study were not empirically validated, the data do provide direction of future studies to most optimally study the management of *D. suzukii* .The model outputs showed that populations are able to increase steadily under all modeling scenarios, although the rate of increase could slow when different scenarios of treatments were used as input factors (Figure 4). Furthermore, the application order that used in the modeling was maintained in the field and similar trend of response was observed in the open-field experiment with natural infestation (Rossi-Stacconi et al. unpublished).

Model runs demonstrated that the insecticides with lower acute mortality rates had a lesser impact on the rate of population growth, irrespective of the sprayer type (Figure 4a). The lowest immediate *D. suzukii* population impacts were obtained for spinetoram, which showed no visual difference compared to the no-intervention control plots. Immediate *D. suzukii* population level impact was observed when applying parameters developed from malathion applications. The greatest acute and most immediate *D. suzukii* population impacts were obtained from zeta cypermethrin and methomyl.

When looking at sprayer type as input, the airblast sprayer resulted in the highest estimated *D. suzukii* population impact for each of the model runs. This was slightly lower for the electrostatic sprayer, while the cannon sprayer had the lowest estimated population impact (Figure 4b, c).

Overall, the most significant estimated reductions in *D. suzukii* populations were gained by a combination of airblast sprayers and chemicals resulting in >95% acute mortality. The population model outputs displayed the lowest mortality rates with the cannon sprayer and spinetoram in the middle zones at 0.02% mortality. Mortality was estimated at 75% and 39%

within the outer canopy zones for malathion delivered by airblast or cannon sprayers, respectively. Population model outputs resulted in the numerically highest mortality rates using the airblast sprayer together with either zeta-cypermethrin or methomyl at 96 and 99% mortality respectively, warranting future empirical validation.

4. DISCUSSION AND CONCLUSION

In this study, the relative spray deposition levels and patterns of three commonly used air-assisted sprayers were characterized in the 'Duke' blueberry plant canopies during two growing seasons (2015 and 2016). Additionally, acute *D. suzukii* mortality was determined through laboratory studies over a six-hour period in order to show differential immediate impact of insecticides on potential pest populations. Mortality data was presented in a mortality matrix table, which served as basic inputs for *D. suzukii* population modeling. Together, field deposition and *D. suzukii* mortality data incorporated key management system components within a population model to illustrate possible scenarios that growers may encounter during the blueberry growing season.

The deposition patterns of sprayers differed; however, these patterns were consistently dependent on sprayer type during both seasons. The deposition patterns recorded in this study were relatively consistent with those in other published studies with lower deposition rates in more sheltered portions of the canopy, and larger distances away. The airblast sprayers always resulted in higher deposition levels compared to electrostatic and cannon sprayers[21, 54]. In the current study, the spray deposition quantity however differed between the seasons in some cases.

It was not possible for us to determine which of these factors resulted in the recorded differences between seasons in this study, because there were no significant differences in environmental conditions recorded during either growing season. The canopy deposition levels were high and relatively consistent for the airblast sprayer, followed by the electrostatic and then by the cannon sprayer during both seasons. Both the airblast and electrostatic sprayers deposited relatively uniform levels of tracer in each of the six canopy zones. The airblast sprayer delivered relatively greater levels of tracer to the bottom canopy zones. The cannon sprayer deposited more elevated levels of tracer to the top zones of the canopy. The electrostatic sprayer delivered comparatively similar deposition levels to all zones of the canopy, compared to the other two sprayers.

The results of this work focus attention on the importance of directed or targeted sprays in order to optimize pesticide applications [11]. Each of the respective sprayers have unique benefits and drawbacks. For example, cannon sprayers cover relatively large areas in a short time period within the crop, without knocking berries off bushes. In addition, first three rows were used to compare the deposition of cannon sprayer to other sprayers in order to achieve realistic application outcomes as growers' practices. Electrostatic sprayers provide relatively uniform coverage and reduce non-target deposition and have the potential to utilize lower water volumes. Airblast sprayers provide relatively uniform canopy coverage, with intermediate levels of non-target deposition. The choice of spray application technology is thus highly dependent on the unique conditions of the production unit.

In addition, using tracer dye in water as spray mix is representative of the deposition of insecticide residues on different canopy zones, dependent on application technology. Although it is possible that the electric charge of water droplets may have affected tracer deposition patterns, we believe that this influence is minimal[55]. Several studies have successfully validated the use of tracer dyes to evaluate the deposition of pesticide spray residues[56-59]. For this reason, the spray deposition data generated in this study are representative of expected insecticide deposition rates during a standard management program for adult *D. suzukii* in blueberry. Although adult mortality as was determined in this study does not represent the total insecticidal effects of each insecticide, the data allows us to compare the impact on adult populations. Little information is available on the impacts of the respective ingredients on immature life stages[22, 60], i.e. egg, larvae, and pupae and studies are being finalized on this topic (Mermer et al. unpublished). Experimental results of the respective insecticides provide several insights into possible benefits and disadvantages of the insecticides included in our trials. The rapid toxic insecticide efficiency experiment data indicated that zeta-cypermethrin and methomyl resulted in >95% adult mortality of *D. suzukii* within the 6-hour experimental period. Malathion applications resulted in 35-67 % acute mortality. The *D. suzukii* mortality levels for spinetoram, spinosad, and phosmet were, however, below 1% within the experimental period. Longer-term *D. suzukii* data generated in this study (data not shown), resulted in similar mortality levels to studies conducted earlier. Generally, mortality obtained for adults in earlier studies showed that insecticides such as malathion, spinetoram, zeta-cypermethrin, and methomyl are in the range of similar mortality as found in the present study and effective at managing this insect[7, 9, 10, 22, 28, 53] . The present study however does provide more detailed insights into rapid toxic effects of different insecticides. The value of rapid toxicity levels generated in this study lies in the immediacy of the effect, often an important factor for crops that are susceptible to continuous pest attack as fruits ripen. Population modeling in pest management is a tool which allows growers, researchers and practitioners to test theoretical field scenarios and management strategies against insect pests[34, 35]. It is acknowledged that this study does not provide empirical validation to the model outputs, but the data generated here do provide some valuable insights into promising directions of future study. Here we evaluated impacts of the use of commonly used sprayer types and insecticides on changes in the modeled population density of a *D. suzukii* adult populations. Model outputs from this study show that the most significant reductions in rates of adult *D. suzukii* population change were gained from the use of airblast sprayer and the most effective laboratory trialed insecticides. Behavioral avoidance because of the movement of spray equipment, repellent properties of insecticides, air displacement of pest populations or other possibly relevant factors were not included in model simulations. The authors acknowledge that these are of unknown importance, therefore warranting future research on these topics.

There is evidence that growers have had success producing high quality crops, even in scenarios where less optimal coverage was obtained, including alternate row and border sprays comparing airblast and cannon sprayers[8]. The data from a previous study however, did note that cannon-applied border sprays resulted in numerically higher levels of *D. suzukii* larvae, compared to full cover sprays using airblast sprayers [8]. Although this previous observation does provide limited empirical validation of the current model, additional studies are essential. This previous study reported that plots receiving reduced applications of less effective insecticide compounds suffered numerically greater damage from *D. suzukii* larvae [8]. The infestation data from the previous study however did not provide information of the effects of different spray technologies and insecticides on crop infestation levels. Earlier studies of *D. suzukii* insecticide mortality was relatively consistent compared to the data generated in this study[9] with zeta-cypermethrin being the most effective of the tested compounds[9, 10, 28]. One difference in reported mortality rates shower higher relative efficacy of spinetoram compared to the present study[9] . Our study found similar toxicity levels between malathion and spinetoram, where one previous study showed higher relative mortality when using malathion[28]. One previous study found a significant increase in larval infestation due to precipitation events, signaling increased *D. suzukii* infestation risk when such climatic events come into play[8].

The current and earlier studies each provide unique perspectives of the importance of spray technology, canopy coverage, and insecticides on *D. suzukii* pest populations under different production conditions. An important next step would be to follow up additional hypotheses from this body of work with additional empirical validation trials in order to quantify their relative impacts.

ACKNOWLEDGEMENTS

This project was funded in part by Oregon Blueberry Commission, United States Department of Agriculture (USDA), National Institute for Food and Agriculture awards #2010-51181-21167, #2015-51181-24252, and USDA OREI #2014-51300-22238. We thank Jacto and On Target Spray Systems for providing equipment and technical assistance. We also thank Dr. Bernadine Strik and Wei Yang for kindly providing the blueberry plots, OSU NWREC staff, WSU Research and Extension Center Staff, Prosser, WA for helping during field trials and sample analysis. Melinda Guzman, Mukesh Bhattarai and Giuseppe Maddalena provided technical support during field experiments. We thank Dr. Jennifer Field from Department of Environmental and Molecular Toxicology, Oregon State University for assistance during manuscript drafting and editing and Francisco Mauro Gutierrez for helping format figures and prepare statistical analysis.

REFERENCES

1. Asplen MK, Anfora G, Biondi A, Choi DS, Chu D, Daane KM, Gibert P, Gutierrez AP, Hoelmer KA, Hutchison WD, Isaacs R, Jiang ZL, Karpati Z, Kimura MT, Pascual M,

Philips CR, Plantamp C, Ponti L, Vetek G, Vogt H, Walton VM, Yu Y, Zappala L and Desneux N, Invasion biology of spotted wing Drosophila (Drosophila suzukii): a global perspective and future priorities. *J Pest Sci*; **88**(3): 469-494 (2015).

2. Cini A, Ioriatti C and Anfora G, A review of the invasion of Drosophila suzukii in Europe and a draft research agenda for integrated pest management. *B Insectol*; **65**(1): 149-160 (2012).
3. Walsh DB, Bolda MP, Goodhue RE, Dreves AJ, Lee J, Bruck DJ, Walton VM, O'Neal SD and Zalom FG, Drosophila suzukii (Diptera: Drosophilidae): Invasive Pest of Ripening Soft Fruit Expanding its Geographic Range and Damage Potential. *Journal of Integrated Pest Management*; **2**(1): G1-G7 (2011).
4. Dos Santos LA, Mendes MF, Kruger AP, Blauth ML, Gottschalk MS and Garcia FR, Global potential distribution of Drosophila suzukii (Diptera, Drosophilidae). *Plos One*; **12**(3): e0174318 (2017).
5. Rodriguez-Saona C, Cloonan KR, Sanchez-Pedraza F, Zhou YC, Giusti MM and Benrey B, Differential Susceptibility of Wild and Cultivated Blueberries to an Invasive Frugivorous Pest. *J Chem Ecol*; **45**(3): 286-297 (2019).
6. NASS, Natl. Agric. Stat. Serv. Press Release. https://wwwnassusdagov/Statistics_by_State/Oregon/Publications/Fruits_Nuts_and_Berries/indexphp 5.31.18 (2017).
7. Bruck DJ, Bolda M, Tanigoshi L, Klick J, Kleiber J, DeFrancesco J, Gerdeman B and Spitler H, Laboratory and field comparisons of insecticides to reduce infestation of Drosophila suzukii in berry crops. *Pest Manag Sci*; **67**(11): 1375-1385 (2011).
8. Klick J, Yang WQ, Lee JC and Bruck DJ, Reduced spray programs for Drosophila suzukii management in berry crops. *Int J Pest Manage*; **62**(4): 368-377 (2016).
9. Van Timmeren S, Mota-Sanchez D, Wise JC and Isaacs R, Baseline susceptibility of spotted wing Drosophila (Drosophila suzukii) to four key insecticide classes. *Pest Manag Sci*; **74**(1): 78-87 (2018).
10. Van Timmeren S and Isaacs R, Control of spotted wing drosophila, Drosophila suzukii, by specific insecticides and by conventional and organic crop protection programs. *Crop Prot*; **54**(126-133 (2013).
11. Duga AT, Ruysen K, Dekeyser D, Nuyttens D, Bylemans D, Nicolai BM and Verboven P, Spray deposition profiles in pome fruit trees: Effects of sprayer design, training system and tree canopy characteristics. *Crop Prot*; **67**(200-213 (2015).
12. Chen Y, Ozkan HE, Zhu H, Derksen RC and Krause CR, Spray Deposition inside Tree Canopies from a Newly Developed Variable-Rate Air-Assisted Sprayer. *T Asabe*; **56**(6): 1263-1272 (2013).
13. Solanelles F, Escola A, Planas S, Rosell JR, Camp F and Gracia F, An electronic control system for pesticide application proportional to the canopy width of tree crops. *Biosyst Eng*; **95**(4): 473-481 (2006).

14. VanEe G, Ledebuhr R, Hanson E, Hancock J and Ramsdell DC, Canopy development and spray deposition in highbush blueberry. *Horttechnology*; **10**(2): 353-359 (2000).
15. Pascuzzi S, Cerruto E and Manetto G, Foliar spray deposition in a "tendone" vineyard as affected by airflow rate, volume rate and vegetative development. *Crop Prot*; **91**(34-48 (2017).
16. Tochen S, Woltz JM, Dalton DT, Lee JC, Wiman NG and Walton VM, Humidity affects populations of Drosophila suzukii (Diptera: Drosophilidae) in blueberry. *J Appl Entomol*; **140**(1-2): 47-57 (2016).
17. Rendon D and Walton VM, Drip and Overhead Sprinkler Irrigation in Blueberry as Cultural Control for Drosophila suzukii (Diptera: Drosophilidae) in Northwestern United States. *J Econ Entomol*; **112**(2): 745-752 (2019).
18. Diepenbrock LM and Burrack HJ, Variation of within-crop microhabitat use by Drosophila suzukii (Diptera: Drosophilidae) in blackberry. *J Appl Entomol*; **141**(1-2): 1-7 (2017).
19. Evans RK, Toews MD and Sial AA, Diel periodicity of Drosophila suzukii (Diptera: Drosophilidae) under field conditions. *Plos One*; **12**(2)2017).
20. Wise JC, Jenkins PE, Schilder AMC, Vandervoort C and Isaacs R, Sprayer type and water volume influence pesticide deposition and control of insect pests and diseases in juice grapes. *Crop Prot*; **29**(4): 378-385 (2010).
21. Owen-Smith P, Perry R, Wise J, Jamil RZR, Gut L, Sundin G and Grieshop M, Spray coverage and pest management efficacy of a solid set canopy delivery system in high density apples. *Pest Manag Sci* 2019).
22. Shawer R, Tonina L, Tirello P, Duso C and Mori N, Laboratory and field trials to identify effective chemical control strategies for integrated management of Drosophila suzukii in European cherry orchards. *Crop Prot*; **103**(73-80 (2018).
23. Gautam BK, Little BA, Taylor MD, Jacobs JL, Lovett WE, Holland RM and Sial AA, Effect of simulated rainfall on the effectiveness of insecticides against spotted wing drosophila in blueberries. *Crop Prot*; **81**(122-128 (2016).
24. Scherm H, Savelle AT and Law SE, Effect of electrostatic spray parameters on the viability of two bacterial biocontrol agents and their deposition on blueberry flower stigmas. *Biocontrol Sci Techn*; **17**(3): 285-293 (2007).
25. Khot LR, Ehsani R, Albrigo G, Larbi PA, Landers A, Campoy J and Wellington C, Air-assisted sprayer adapted for precision horticulture: Spray patterns and deposition assessments in small-sized citrus canopies. *Biosyst Eng*; **113**(1): 76-85 (2012).
26. Law SE and Scherm H, Electrostatic application of a plant-disease blocontrol agent for prevention of fungal infection through the stigmatic surfaces of blueberry flowers. *J Electrostat*; **63**(5): 399-408 (2005).
27. Braekman P, Foque D, Van Labeke MC, Pieters JG and Nuyttens D, Influence of Spray Application Technique on Spray Deposition in Greenhouse Ivy Pot Plants Grown on Hanging Shelves. *Hortscience*; **44**(7): 1921-1927 (2009).

28. Smirle MJ, Zurowski CL, Ayyanath MM, Scott IM and MacKenzie KE, Laboratory studies of insecticide efficacy and resistance in Drosophila suzukii (Matsumura) (Diptera: Drosophilidae) populations from British Columbia, Canada. *Pest Manag Sci*; **73**(1): 130-137 (2017).
29. Gress BE and Zalom FG, Identification and risk assessment of spinosad resistance in a California population of Drosophila suzukii. *Pest Manag Sci*; **75**(5): 1270-1276 (2019).
30. Miranda-Fuentes A, Rodriguez-Lizana A, Cuenca A, Gonzalez-Sanchez EJ, Blanco-Roldan GL and Gil-Ribes JA, Improving plant protection product applications in traditional and intensive olive orchards through the development of new prototype air-assisted sprayers. *Crop Prot*; **94**(44-58 (2017).
31. Xiao K, Ma YJ and Gao GD, An intelligent precision orchard pesticide spray technique based on the depth-of-field extraction algorithm. *Comput Electron Agr*; **133**(30-36 (2017).
32. Wiman NG, Walton VM, Dalton DT, Anfora G, Burrack HJ, Chiu JC, Daane KM, Grassi A, Miller B, Tochen S, Wang X and Ioriatti C, Integrating temperature-dependent life table data into a matrix projection model for Drosophila suzukii population estimation. *Plos One*; **9**(9): e106909 (2014).
33. Wiman NG, Dalton DT, Anfora G, Biondi A, Chiu JC, Daane KM, Gerdeman B, Gottardello A, Hamby KA, Isaacs R, Grassi A, Ioriatti C, Lee JC, Miller B, Stacconi MV, Shearer PW, Tanigoshi L, Wang X and Walton VM, Drosophila suzukii population response to environment and management strategies. *J Pest Sci (2004)*; **89**(653-665 (2016).
34. Pfab F, Stacconi MVR, Anfora G, Grassi A, Walton V and Pugliese A, Optimized timing of parasitoid release: a mathematical model for biological control of Drosophila suzukii. *Theoretical Ecology*; **11**(4): 489-501 (2018).
35. Wiman NG, Dalton DT, Anfora G, Biondi A, Chiu JC, Daane KM, Gerdeman B, Gottardello A, Hamby KA, Isaacs R, Grassi A, Ioriatti C, Lee JC, Miller B, Stacconi MVR, Shearer PW, Tanigoshi L, Wang XG and Walton VM, Drosophila suzukii population response to environment and management strategies. *J Pest Sci*; **89**(3): 653-665 (2016).
36. de la Vega GJ and Corley JC, Drosophila suzukii (Diptera: Drosophilidae) distribution modelling improves our understanding of pest range limits. *Int J Pest Manage*; **65**(3): 217-227 (2019).
37. Strik BC, Vance AJ and Finn CE, Northern Highbush Blueberry Cultivars Differed in Yield and Fruit Quality in Two Organic Production Systems from Planting to Maturity. *Hortscience*; **52**(6): 844-851 (2017).
38. USBR, United States Bureau of Reclamation [WWW Document]. USBR Hydromet Achives Data US Dep. Inter. Bur. Reclam. Pac. Northwest Reg. URL https://www.usbr.gov/pn/agrimet/webarcread.html. 2017).

39. ISO, Int. Organ. Stand. https://wwwevsee/products/iso-22522-2007 **(accessed 6.5.18).**(2007).
40. Salyani M, Zhu H, Sweeb RD and Pai N, Assessment of spray distribution with water-sensitive paper. *Agric Eng Int: CIGR Journal*; **15**(2): 101-111 (2013).
41. R Development Core Team. R: A language and environment for statistical computing,. R Foundation for Statistical Computing,: Vienna, Austria. (2018).
42. Wickham H. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, New York, (2016).
43. Herron GA, Beattie GAC, Kallianpur A and Barchia I, A Potter spray tower bioassay of two petroleum spray oils against adult female Panonychus ulmi (Koch) and Tetranychus urticae Koch (Acari : Tetranychidae). *Experimental & Applied Acarology*; **22**(9): 553-558 (1998).
44. Druciarek T, Lewandowski M and Kozak M, Demographic parameters of Phyllocoptes adalius (Acari: Eriophyoidea) and influence of insemination on female fecundity and longevity. *Exp Appl Acarol*; **63**(3): 349-360 (2014).
45. Mansour F, Field and Laboratory Experiments on the Response and Development of Resistance to Pesticides and Population-Density of Tetranychus-Cinnabarinus in Israel. *Phytoparasitica*; **16**(3): 239-245 (1988).
46. Dalton DT, Walton VM, Shearer PW, Walsh DB, Caprile J and Isaacs R, Laboratory survival of Drosophila suzukii under simulated winter conditions of the Pacific Northwest and seasonal field trapping in five primary regions of small and stone fruit production in the United States. *Pest Manag Sci*; **67**(11): 1368-1374 (2011).
47. Tochen S, Dalton DT, Wiman N, Hamm C, Shearer PW and Walton VM, Temperature-Related Development and Population Parameters for Drosophila suzukii (Diptera: Drosophilidae) on Cherry and Blueberry. *Environ Entomol*; **43**(2): 501-510 (2014).
48. Ritz C, Baty F, Streibig JC and Gerhard D, Dose-Response Analysis Using R. *Plos One*; **10**(12)2015).
49. Ritz C, Toward a unified approach to dose-response modeling in ecotoxicology. *Environ Toxicol Chem*; **29**(1): 220-229 (2010).
50. Neill JW, Testing for Lack of Fit in Nonlinear-Regression. *Ann Stat*; **16**(2): 733-740 (1988).
51. Metz JAJ and Diekmann O. *Exact finite dimensional representations of models for physiologically structured populations. I: The abstract foundations of linear chain trickery.* . Marcel Dekker Inc., 1991, (1991).
52. Wolfram Research I. Mathematica. Wolfram Research, Inc.: Champaign, Illinois (2019).
53. Beers EH, Van Steenwyk RA, Shearer PW, Coates WW and Grant JA, Developing Drosophila suzukii management programs for sweet cherry in the western United States. *Pest Manag Sci*; **67**(11): 1386-1395 (2011).

54. Siegel JP, Strmiska MM, Niederholzer FJ, Giles DK and Walse SS, Evaluating insecticide coverage in almond and pistachio for control of navel orangeworm (Amyelois transitella) (Lepidoptera: Pyralidae). *Pest Manag Sci*; **75**(5): 1435-1442 (2019).
55. Hussain MD and Moser E, Some fundamentals of electrostatic spraying. *Agricultural Mechanization*; **17**(35-39 (1986).
56. Law SE, Spatial-Distribution of Electrostatically Deposited Sprays on Living Plants. *J Econ Entomol*; **75**(3): 542-546 (1982).
57. Kirk IW, Hoffmann WC and Carlton JB, Aerial electrostatic spray system performance. *T Asae*; **44**(5): 1089-1092 (2001).
58. Pascuzzi S and Cerruto E, Spray deposition in "tendone" vineyards when using a pneumatic electrostatic sprayer. *Crop Prot*; **68**(1-11 (2015).
59. Martin DE, Latheef MA and Lopez JD, Electrostatically charged aerial application improved spinosad deposition on early season cotton. *J Electrostat*; **97**(121-125 (2019).
60. Wise J, Vanderpoppen R, Vandervoort C, O'Donnell C and Isaacs R, Curative activity contributes to control of spotted-wing drosophila (Diptera: Drosophilidae) and blueberry maggot (Diptera: Tephritidae) in highbush blueberry. *The Canadian Entomologist*; **147**(1): 109-117 (2015).

Table 1. Weather conditions measured at the beginning of each spray application in a 'Duke' blueberry in Canby, Oregon during 2015 and 2016.

	RH (%)		**T (°C)**		**Wind Speed (m s^{-1})**		**Wind Direction (°)**	
Season	2015	2016	2015	2016	2015	2016	2015	2016
Sprayer								
Cannon	66	65	16	17	2.26	0.96	233.18 (SW)	350.91 (N)
Air–blast	73	80	14	16	0.97	1.62	318.31	221.05

							(NW)	(SW)
Electrostatic	73	77	14	17	0.97	0.37	318.31 (NW)	29.62 (NE)

Table 2. Calibration parameters for nozzles, key technical specifications, and industry-standard application volume for three sprayer types typically used on ‘Duke’ blueberry in Canby, Oregon during 2015 and 2016.

Sprayer type	Cannon	Electrostatic	Airblast
Parameter			

Power required (HP)	20	20	35
Nozzle number and orientation (Degrees relative to ground surface)	Three outlets Main = 0 Aux = 30, 45	14 nozzles each a 0	5 nozzles Bottom three = 0 Second from top = 30 Top 40
PTO speed (RPM)	540	540	1500
Deflector position (Degrees relative to ground surface)	NA	NA	Top = 45 Bottom = 0
Pressure (KPA)	Rate controller opened to 27.5	827.3	827.3
Fan rotation speed (rpm)	3180	No fan	1000
Air flow rate (km/h)	50	27.77	90
Nozzle size	NA (no nozzle)	Singe proprietary flow nozzle at 180ml/min	D4/25
Application Volume Rate (L ha^{-1})	420.9	204.6	748.3
Tractor speed (km/h)		4.82	
Tractor model		Kubota narrow M8200	

Table 3. Insecticide active ingredients and concentrations applied under controlled laboratory conditions against *Drosophila suzukii* adults during a six-hour period.

Chemical Group[¥]	Brand Name	Active Ingredient	Concentration applied (mg ai L^{-1})	Manufacturing Company
Spinosyn	Delegate	Spinetoram	**222**; 167; 110; 55; 0.05; 0	Dow AgroSciences LLC, Indianapolis, IN
	Entrust	Spinosad	710; 475; 350; **221**; 165; 110; 55; 0.07; 0	
Pyrethroid	Mustang Maxx	Zeta-cypermethrin	**60**; 44; 30; 14.3; 10.5; 6.7; 2.9; 0.02; 0	FMC Corporation, Philadelphia, PA
Diamide	Exirel	Cyantraniliprole	1680; 1120; **360**; 270; 180; 90; 0.11; 0	Dupont, Wilmington, DE
Organophosphate	Malathion 8F	Malathion	**5900**; 4500; 3000; 1450; 0.95; 0	Gowan Co, Yuma, AZ
	Imidan 70 WP	Phosmet	**2100**; 1600; 1000; 600; 0.7; 0	
Carbamate	Lannate SP	Methomyl	**2100**; 1600; 1000; 530; 45; 0.90; 0.6; 0	Dupont, Wilmington, DE

¥ https://www.irac-online.org/modes-of-action
Field application rates are indicated in bold in the table

Table 4. Estimable acute 6-hour lethal concentration for *Drosophila suzukii* adults, (LC_{50}, and LC_{90} values) for each of four insecticides under controlled laboratory experimental conditions.

Insecticides	LC_{50} (mg ai/L)	LC_{90} (mg ai/L)	Field rate (mg ai/L)
Zeta-cypermethrin	0.35	2.70	60
Methomyl	14.25	45	2100
Malathion	120	3700	5900
Spinetoram	120	218	222

Table 5. Mortality-matrix (MM) table using two contributing factors for adult *Drosophila suzukii* mortality. First, the estimated 6-hour mortality rate (from laboratory experiments), based on the typical deposition rate of the respective sprayers (M_{3p}). Second, the median deposition rate (%D) as was found by each of the respective sprayers within each canopy zone under field conditions. These values were used to calculate percent deposition of active ingredient (%DAG). Middle zones (TM & BM) and outer zones (TL, TR, BL, BR) respectively contribute to MZ_{43} (43%) and OZ_{57} (57%) of the total occurrence of *D. suzukii* populations within the canopy, and these numbers were used to calculate the relative contribution to *D. suzukii* mortality.

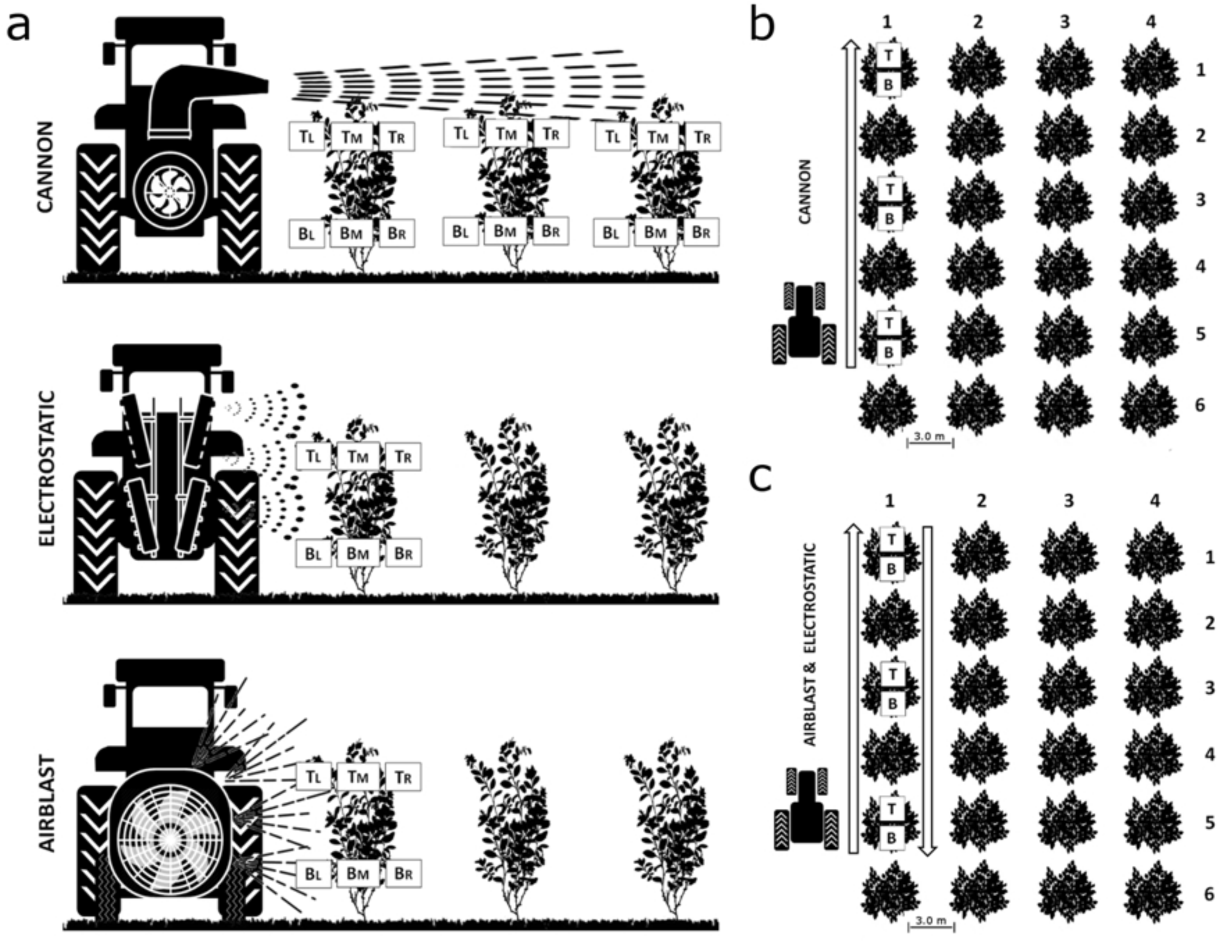
Insecticides (Active ingredient)	**Airblast**		**Cannon**		**Electrostatic**		**Six-hour mortality rating**
	Middle canopy zones	Outer canopy zones	Middle canopy zones	Outer canopy zones	Middle canopy zones	Outer canopy zones	
Zeta-cypermethrin	93%	96%	57%	63%	72%	85%	High
Methomyl	99%	99%	57%	68%	81%	95%	
Malathion	67%	75%	35%	39%	44%	57%	Medium
Spinetoram	0.04%	0.25%	0.0002%	0.0005%	0.0003%	0.003%	Low
Cyantraniliprole	Not estimable within six hours because of slow-acting nature of compounds						
Spinosad							
Phosmet							

Figure 1. Experimental design for spray deposition application with three types of spray equipment. Side view of the applications with three sprayers in ‘Duke’ blueberry plot in Canby, Oregon during 2015 and 2016 (a). Top view of the spray applications in the ‘Duke’ blueberry plots using the cannon sprayer (b). Top view of the sprayer applications in the ‘Duke’ blueberry plots using airblast and electrostatic sprayers (c).

Figure 2. Cannon, electrostatic and airblast sprayer deposition on individual canopy zones during 2015 and 2016 in ‘Duke’ blueberry in Canby, Oregon, (*Mean±standard error*). Canopy deposition levels in each of six canopy zones, B=bottom, T=top, M=middle, L=left, R=right.

Figure 3. Log logistic-fitted proportion of adult *Drosophila suzukii* mortality under several deposition rates at six hours for each of seven commonly used insecticides using a Potter’s Precision spray tower and Munger cells under controlled laboratory conditions. The filled dot represents the field rate of the corresponding insecticide.

Figure 4. Population model outputs for *Drosophila suzukii* using 6-hour mortality rates for three classes of effective insecticides (low= L, medium = M, high = H) and typical deposition rates from field recording of three types of sprayers (airblast, cannon, electrostatic). *D. suzukii* mortality contributions by these factors were used as input factors to model population responses using weather data from early August until mid-September 2016. Insecticide spray inputs were simulated (dotted line) at seven-day intervals to simulate seasonal control strategies against *D. suzukii*.



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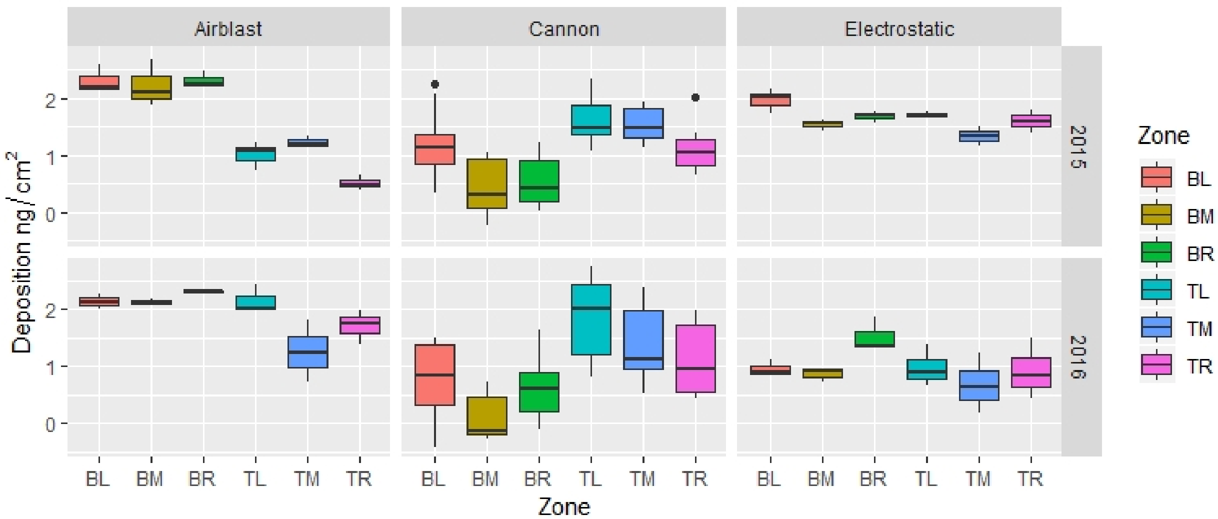

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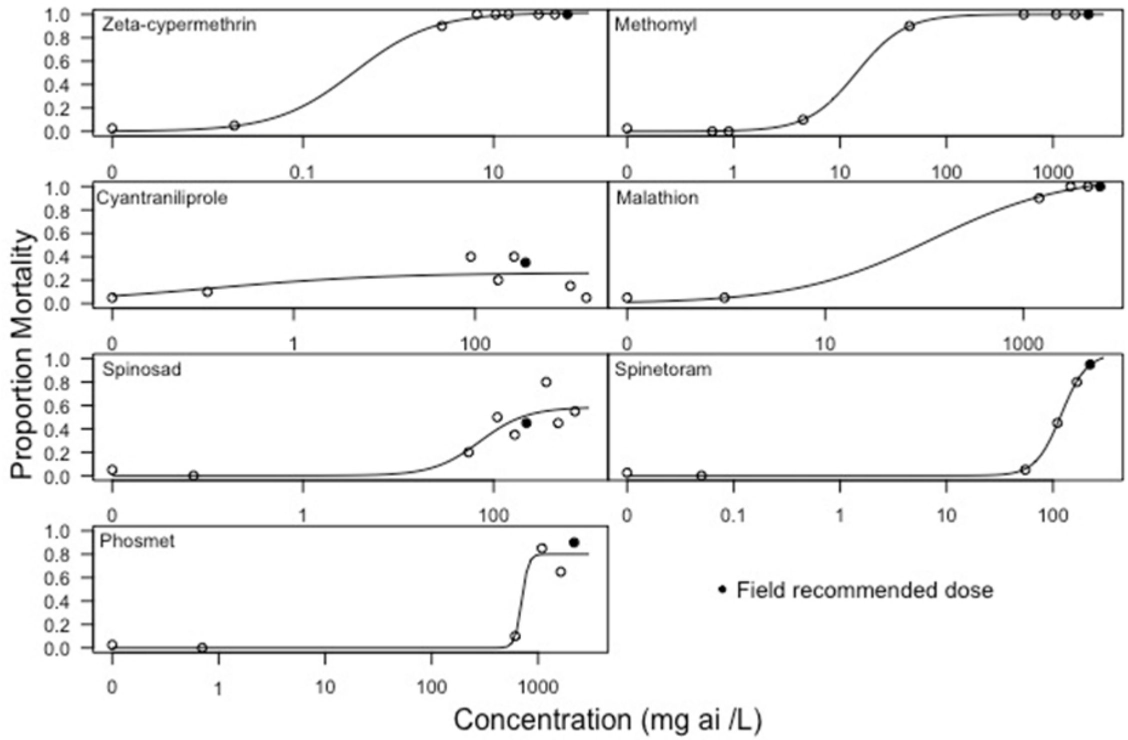

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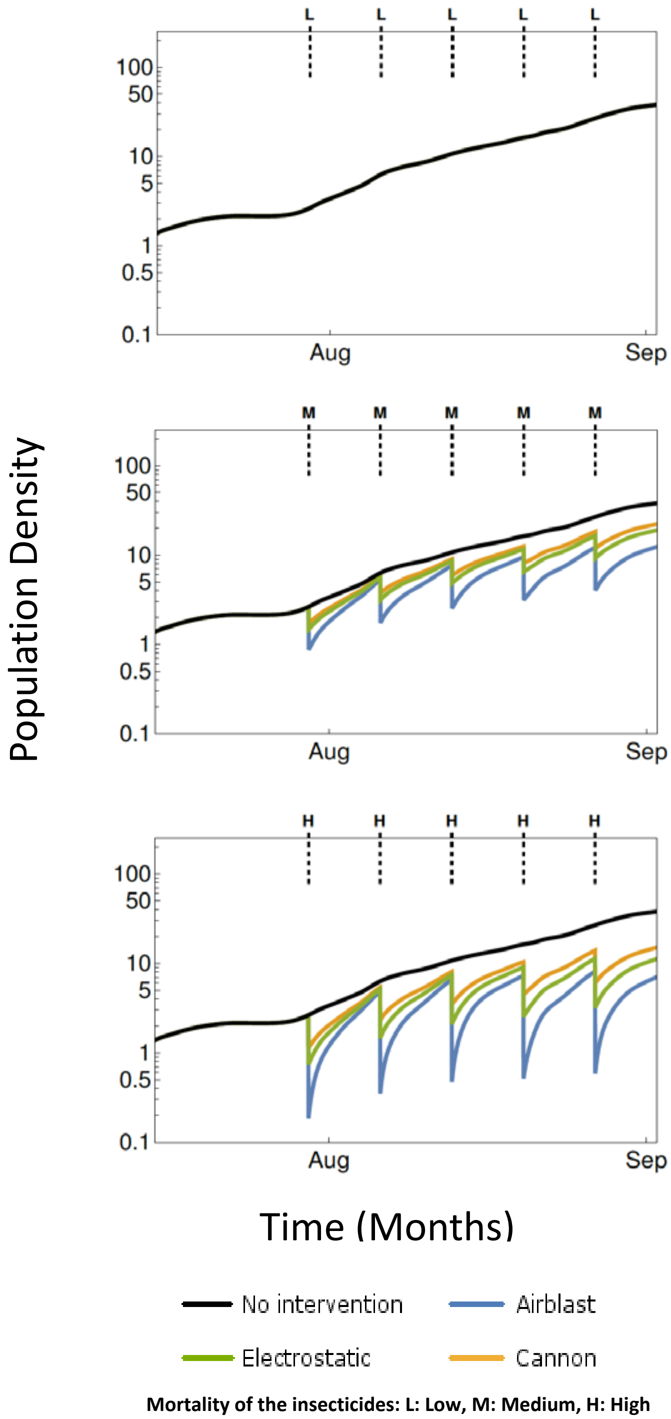

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simulated (dotted line) at seven-day intervals to simulate seasonal control strategies against *D. suzukii*.

Title: Canopy spray deposition and mortality impacts of commonly-used insecticides on *Drosophila suzukii* Matsumura (Diptera: Drosophilidae) populations in blueberry

Running Title: Spray deposition and mortality of insecticides on *Drosophila suzukii* in blueberry

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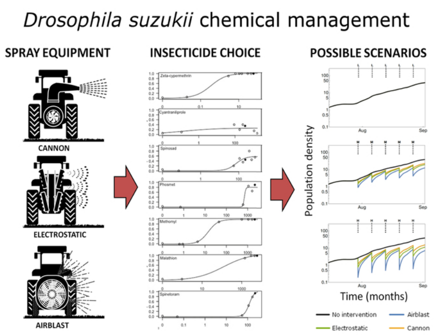
Graphical Abstract

The highest population impact on *Drosophila suzukii* was found when using the airblast sprayer combined with zeta-cypermethrin in blueberry.



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