Season-long programs for control of *Drosophila suzukii* in southeastern U.S. blueberries

Running title: Season-long control of *Drosophila suzukii*

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Abstract

Drosophila suzukii is an invasive insect pest which has major impacts on small fruit production throughout North America. Current control programs use frequent applications of broad-spectrum insecticides. To prevent resistance, modes of action must be rotated. This study examines the acute and residual efficacy of rotational treatment programs designed to meet the needs of commercial growers in the southeastern United States, a region which experiences significant precipitation throughout the growing season. All insecticide applications had greater adult acute mortality than controls, and some had residual efficacy for three or more days after treatment. Programs had no residual effects at seven days after treatment. Within programs, organophosphates (phosmet and malathion) and pyrethroids (zeta-cypermethrin and fenpropathrin) were the most effective. Some programs also resulted in less offspring production by *D. suzukii* in bioassays and reduced field infestation compared to controls. Results show that effective, season-long rotational chemical treatment programs can be designed to minimize crop damage, meet exportation requirements and manage for resistance. Understanding the effect of regional climate on the performance of individual insecticide treatments and their efficacy will be critical for widespread implementation of effective control programs for *D. suzukii*.

Key words: *Drosophila suzukii*, season-long treatment program, integrated pest management, resistance management

1. Introduction

Drosophila suzukii Matsumura (Diptera: Drosophilidae), commonly referred to as spotted wing drosophila, is a polyphagous invasive pest of soft skinned fruits. Since its initial detection in the United States, it has quickly spread throughout North America, Europe, and South America (Walsh et al. 2011; Cini et al. 2012; Vilela and Mori 2014; Asplen et al. 2015). Native drosophilids primarily infest overripe or rotting fruit, but *D. suzukii* females possess a large, heavily sclerotized ovipositor, enabling them to oviposit in ripe and ripening fruits (Burrack et al., 2013; Goodhue et al., 2011; Hauser, 2011; Lee et al., 2011a). In North America, *D. suzukii* has resulted in over \$700 million in losses in host crops including blueberries, cherries, caneberries (raspberries and blackberries), grapes and strawberries (Bolda et al., 2010; Burrack et al., 2013; Cini et al., 2012; Goodhue et al., 2011; Kinjo et al., 2013; Lee et al., 2011b; USDA NASS, 2014; Vilela and Mori, 2014; Walsh et al., 2011b). Crop damage is caused both via direct consumption of fruit by larvae as well as by puncture wounds caused by egg laying. Puncture wounds enable the entrance of secondary contaminants, including other species of fruit flies and pathogens, into berries (Walsh et al. 2011).

D. suzukii has been detected in all fruit growing areas of the United States. Previous management studies have been performed in the western states of Washington, Oregon and California (Beers et al., 2011; Bruck et al., 2011) and in the Great Lakes region (Van Timmeren and Isaacs, 2013). However, none have explored the efficacy of management programs in the southeastern United States, a distinct climate region of North America (Karl and Koss, 1984). North Carolina and Georgia are the largest blueberry producing states in the southeastern United States, with an annual crop value of \$196.6 million (USDA NASS, 2014). Blueberry producers in the southeast mostly grow both southern highbush and rabbiteye blueberries. Southern

highbush (*Vaccinium corymbosum* L.) fruit ripen 3-4 weeks earlier than rabbiteye (*Vaccinium ashei* Reade), providing fresh fruit from mid-April through July (Nesmith and Krewer 2012; www.georgiablueberries.org). Since the arrival of *D. suzukii*, growers have increased pesticide use by 50% or greater and still have crop losses (eFly Working Group, n.d.). The most effective insecticides for use against *D. suzukii* include organophosphates, pyrethroids and spinosyns (Bruck et al., 2011), the use of which is complicated by their potential effects on non-target organisms, seasonal application restrictions, impractically long pre-harvest intervals, and trade related concerns due to insecticide residue tolerances. Our goal was to evaluate the efficacy of chemically-based season-long control programs against *D. suzukii* in blueberry crops in the southeastern U.S. We compared management programs designed to minimize pesticide residue levels on marketable fruit, maximize efficacy and residual activity, facilitate short time from application to harvest, and reduce risk to beneficial insects by using only insecticides considered to be less toxic to these organisms (Roubos et al. 2014a; Roubos et al. 2014b).

2. Experimental Methods

2.1 Experimental Design

Field experiments were conducted during 2013 and 2014 at seven sites in Georgia (GA) and North Carolina (NC). Three grower-cooperator sites were used in southeastern North Carolina. Two research farm and two grower-cooperator sites were used in southeastern Georgia. Trials included both southern highbush and rabbiteye blueberries (Table 1). Treatment programs were replicated within each site and randomly assigned to plots ranging from 0.08-0.4 ha. Treatments were applied weekly using grower equipment (Table 1), and replicated 3-4 times per site in a randomized complete block design.

Programs were designed to address marketing, harvest interval, non-target risk, and input cost concerns and compared to an untreated control (UTC) (Table 2). Three “Export-friendly” programs used insecticides for which major international trading partners have established Maximum Residue Levels (MRL) and included a maximum number of modes of action (Export 1, 2 and 3). Because of harvest conditions and variable labor available, growers need options with short pre-harvest intervals (PHI). Therefore the second program (Short PHI) included two materials with a 1 day PHI. The third program used insecticides considered to be “reduced risk” to non-target organisms (Roubos et al. 2014a; Roubos et al. 2014b). All insecticide applications were made at the maximum label rate for *D. suzukii* in blueberry in North Carolina and Georgia (Table 3), and sprays were done on every individual row to provide maximum coverage.

2.2 Data collection

2.2.1 Semi-field bioassays

Because *D. suzukii* field populations are highly variable, semi-field bioassays were conducted following treatments to assess program efficacy. A single branch with at least 10 leaves and 5 ripe berries was collected from the center of each plot for use in bioassays (Van Timmeren and Isaacs, 2013). In NC, bioassay samples were collected immediately after treatment and 7 days after treatment (DAT). In GA, samples were collected 1, 3 and 7 DAT at the research farm, and 5 DAT at grower sites to accommodate harvest schedules. Samples were collected at 3 DAT in GA to determine a precise period during which insecticides remain active on treated plants. Bioassay chambers were constructed using 946 ml plastic containers (PFS Sales Co., Raleigh, NC). Branches were inserted into floral water picks (Koyal Wholesale, CA) containing 10 ml of water and placed through a hole in the bottom of the chamber. Berries were placed at the bottom of chambers in a wire mesh (0.5 cm wire mesh) boat (GA) or 30 ml plastic

cup (NC- Dart container Corporation, Mason, MI)(Burrack et al., 2013; Van Timmeren and Isaacs, 2013). Chambers were ventilated through a 5 cm diameter opening in their lids, covered with white tulle mesh. Flies were provided a strip of filter paper soaked in liquid diet (1:2:3 sugar/yeast/water by weight (Burrack et al., 2013)) and supplemental water.

Ten reproductively mature adult *D. suzukii* (5 male, 5 female) from laboratory colonies (Burrack et al., 2013; Dalton et al., 2011) were placed into each chamber. Observations were made at 24, 72, and 120 h to assess mortality. In general, mortality at 24 h (acute mortality) is presented as we considered it unlikely that flies would remain in continuous contact with treated plants for up to 120 h. 72 and 120 h observations were conducted because some the insecticides compared were anticipated to be slower acting than others, and we wanted to capture potential differences in speed of induced mortality. After 120 h, any remaining flies were removed. In NC, fruit were held for additional 48 h and then dissected to count larvae.

2.2.2 Adult trapping (NC sites only)

One baited trap was suspended from a 1.2 m step-in fence post in the center of each plot and serviced weekly. Traps consisted of 946 ml plastic deli containers (PFS Sales Co., Raleigh, NC) with 12, 0.5 cm holes evenly spaced around the top of the container. Traps were baited with 150 ml each of yeast and sugar slurry, 4:2 tbsp. sugar/yeast (Domino Sugars, Iselin, NJ; Red Star dry active yeast, Milwaukee, WI) mixed in 946 ml water. Bait was replaced weekly and *D. suzukii* from each trap were counted and sexed under a stereomicroscope.

2.2.3 Larval infestation

Ripe, marketable berries were taken from the center of each field plot to determine infestation. In NC, 50 berries were collected weekly 7 DAT. Berries were held in 266 ml plastic containers (up and up brand, Target®, Raleigh, NC) vented on the bottom with a fine mesh

(white organza) to allow fermenting fruit by-product to drain at 20°C for 168 h (Burrack et al., 2013). Berries were then dissected under a stereomicroscope, and all *Drosophila* spp. larvae and pupae counted.

In GA, 100 blueberries were collected 1, 3 and 7 DAT at the research farm and 5 DAT at grower sites. Berries were held in 473 ml translucent containers (Dart Conex, The Webstaurant Store, WA) with 5x5 cm white tulle vents in lids at 20°C for 168 h. Larvae were extracted using boiling water (Van Timmeren and Isaacs, 2013), and larvae, pupae, and adult flies from each container were counted.

2.2.4 Pesticide residue sampling

Marketable blueberries were sampled weekly 7 DAT from the center of each plot except for the GA grower sites where samples for residue analysis were collected 5 DAT. Disposable nitrile gloves were worn to collect samples and changed between plots to minimize contamination. Samples of at least 50 g of fruit were collected and stored at 0°C prior to analysis. The Plant Industry Laboratory of the Georgia Department of Agriculture in Tifton, GA, analyzed the samples utilizing the QuEChERS Multi-Residue Method from the USDA Pesticide Data Program Analytical Methods (Anastassiades and Lehotay, 2003; USDA, 2010).

2.3 Data Analysis

All bioassay data were analyzed via ANOVA (PROC MIXED in SAS v. 9.4). In order to meet assumptions of normality and homogeneity of variance, data were arcsine-square root transformed to assess adult mortality in all bioassays. Offspring production and trap capture values did not require transformation for analysis. The Tukey-Kramer adjustment for multiple comparisons was used to separate means ($\alpha=0.05$). Data were analyzed weekly to show efficacy of individual insecticides within treatments, and when appropriate, pooled across season by site

for season-long trends. A trend indicating higher mortality for male than female flies emerged, so 24 h mortality data were pooled across years and sites from acute mortality trials then analyzed using t-tests (PROC TTEST in SAS v. 9.4).

3. Results

3.1 Semi-field bioassays

Mortality was generally higher for male *D. suzukii* than for female flies across all sites and years (24 h acute mortality pooled across all sites and years: mean male mortality = 52.10 %, mean female mortality = 43.75%; $t_{105} = 14.99$, $p < 0.0001$). These data suggest that male and female *D. suzukii* interact differently with treated plant materials within bioassay arenas. Because female flies are more intimately tied to fruit damage via oviposition, we will consider data relating primarily to females and offspring production in the following sections.

3.1.1 NC Southern Highbush (2013)

All treatment programs had a higher percentage of adult mortality than the controls (Tables 4, 5). At Site 1, all programs had a similarly high percentage of adult mortality (Table 4) and low offspring production (Supporting Information Table 1; data pooled across treatments and season: $F_{3,38} = 7.54$, $p = 0.0004$). Most insecticides caused significant mortality for adult flies, with the exception of acetamiprid, which did not produce higher mortality than the untreated control (Table 4, weeks 2, 4). At Site 2 all programs had a higher percentage of adult mortality (Table 5) and less offspring produced than the untreated control (Supporting Information Table 1; data pooled across season: $F_{3,57} = 12.8$, $p < 0.0001$). At this location, there was higher mortality in the first three weeks of the program, likely due to a pre-harvest application of fenpropathrin made by the grower to control cranberry (*Acrobasis vaccinia* Riley)

and cherry (*Grapholita packardi* Zeller) fruitworms. Similar to Site 1, there was no difference in acute mortality between acetamiprid treatments and the untreated control (Table 5; weeks 2, 4 and 6).

There was no residual impact of any program in bioassays conducted at 7 DAT (data pooled across sites and season, female mortality: $F_{3,31} = 0.57$, $p = 0.6415$).

3.1.2 NC Rabbiteye (2014)

In 2014, all programs had a higher acute adult mortality than the untreated control (Table 6; data pooled across season, female $F_{4,5} = 6.92$, $p = 0.0286$), and had less offspring production than the untreated control (Table 6; data pooled across season and treatments: $F_{4,88} = 27.45$, $p < 0.0001$). Heavy rainfall during week 1 prevented application of the Export 2 program and may have impacted the other materials. Mortality was consistently high in both export programs, but was variable in both the Reduced Risk and Short PHI programs. In the short PHI program, there was a higher percentage of female mortality during weeks when malathion was applied compared to weeks when zeta-cypermethrin was applied ($F_{1,3} = 17.94$, $p = 0.0241$).

Similar to 2013, there was no residual activity in bioassays conducted at 7 DAT (data pooled across season, female mortality $F_{4,75} = 1.62$, $p = 0.1775$).

3.1.3 GA Southern Highbush (2014)

All programs had a higher percentage of *D. suzukii* mortality than the untreated control (Table 7; data pooled across season: male mortality $F_{3,16} = 7.27$, $p = 0.0027$, female mortality $F_{3,16} = 9.96$, $p = 0.0006$). The only exception was the second week of the trial when survivorship across all programs was high. Residual efficacy was observed at 3 DAT (Table 7; data pooled across season, female mortality $F_{3,16} = 9.11$, $p = 0.0009$). At 7 DAT, males exposed to phosmet (Short PHI, week 5) or zeta-cypermethrin (Export, week 1; Short PHI, week 3) had higher

mortality than males exposed to the other chemicals or the control (data not shown; data pooled across season: male mortality $F_{3,16} = 3.25$, $p = 0.0495$). Females did not have significant acute mortality in any of the programs at 7 DAT (data pooled across season: female mortality $F_{3,16} = 0.64$, $p = 0.6031$).

Residual efficacy (120h) was apparent on treated plant materials in all programs resulting in high mortality relative to the untreated control (Table 8; data pooled across season, 1 DAT: female mortality $F_{3,16} = 66.81$, $p = <.0001$; 3 DAT: female mortality $F_{3,16} = 17.54$, $p = <.0001$; 7 DAT: female mortality $F_{3,16} = 5.97$, $p = 0.0063$).

There were no differences in acute or long-term exposure mortality between programs for trials conducted at a conventional blueberry grower's farm (Supporting Information Table 2).

3.1.4 GA Rabbiteye (2014)

There was no difference in female acute mortality of individual insecticides at 1, 3 or 7 DAT at the research farm (Table 9; data pooled across season, 1 DAT: $F_{3,20} = 2.52$, $p = 0.088$; 3 DAT: $F_{3,20} = 1.59$, $p = 0.223$; 7 DAT: $F_{3,20} = 2.00$, $p = 0.147$). However, differences emerged after 120 h of exposure in bioassays, and all programs had a higher percentage of mortality than the control (Table 10; data pooled across season, $F_{3,20} = 5.21$, $p = 0.0081$). The rabbiteye season experienced frequent rain events, which may have reduced the acute impacts of individual chemicals. However, it is likely that there were sufficient residues remaining on plants to kill flies with prolonged exposure. Specific components of each program still had higher mortality at 120 h relative to the control (Table 10; 1DAT) than at 24 h relative to the control (Table 9). These include cyantraniliprole (Reduced Risk, week 6), malathion (Short PHI weeks 2, 4 and 6), phosmet (Export 3, week 6), spinetoram (Reduced Risk, week 5), and zeta-cypermethrin (Short PHI, week 5) (Table 10, 1 DAT). Following heavy rain events at the research farm, zeta-

cypermethrin and malathion (Short PHI) had higher percentages of mortality than the control at 120 h (Table 10, 1 DAT weeks 1 and 2), suggesting that these materials remain active on plants through rainy weather. All programs tested at a conventional grower site provided similar level of mortality (acute and long-term exposure) indicating that they were equally effective against *D. suzukii*.

There were no differences in acute or long-term exposure mortality between programs for trials conducted at a conventional blueberry grower's farm (Supporting Information Table 3). For trials conducted at commercial sites, growers requested to not include an untreated control; therefore programs tested at these locations can only be compared to one another.

3.2 Adult SWD trapping (NC sites only)

3.2.1 NC 2013

Trap captures of adult *D. suzukii* were low in all programs, averaging less than one fly per trap per day. After harvest and treatments ceased, the number of adult flies captured increased to an average of 45 flies per trap per day (Site 1, 16 Jul-23 Jul) and 270 flies per trap per day (Site 2, 23 Jul-30 Jul). There were no differences between treatments at either site for post-harvest trap capture (data pooled across season, Site 1 $F_{3,35} = 0.43$, $p = 0.7298$; Site 2 $F_{3,72} = 1.39$, $p = 0.2527$).

3.2.2 NC 2014

The number of adult flies trapped did not differ between treatments (data pooled across season, $F_{4,75} = 1.75$, $p = 0.1479$). Two or fewer flies per trap per day were captured prior to berries ripening. Trap capture increased to an average of 29 flies per trap per day as fruit matured, then declined quickly until 4 September, at which point there were few fruit remaining in the field.

3.3 Larval infestation

3.3.1 North Carolina- 2013

Fruit infestation was low and did not differ between treatments (data pooled across season, Site 1 $F_{3,24} = 0.58$, $p = 0.6336$; Site 2 $F_{3,24} = 1.73$, $p = 0.1880$). At both locations, infestation developed after treatments ceased at the end of the commercial harvest. At Site 2, all programs had less post-harvest infestation than the control (data pooled across treatments during postharvest, $F_{1,24} = 27.24$, $p < 0.0001$), with no differences between treatments. This suggests that sufficient insecticide residue remained on the treated plants to deter infestation for several weeks after weekly application ceased.

3.3.2 North Carolina- 2014

Fruit infestation was low, with no difference between programs (Supporting Table 4; data pooled across season, $F_{4,30} = 1.23$, $p = 0.3204$). Low amounts of infestation occurred after the final treatment applications on 30 July, with significantly higher infestation in the untreated control at 2 and 4 weeks after applications ended, suggesting a residual effect of programs.

3.3.3 Georgia- 2014

Infestation was low in southern highbush and rabbiteye harvest seasons across all treatments at all locations (data pooled across season, Southern Highbush: Research Farm $F_{3,120} = 0.83$, $p = 0.4772$, Grower $F_{3,40} = 0.80$, $p = 0.5061$; Rabbiteye: Research Farm $F_{3,180} = 1.64$, $p = 0.1830$, Grower $F_{2,40} = 0.52$, $p = 0.6033$).

3.4 Chemical Residues

Across all replications, chemical residues were within the Maximum Residue Limits (MRL) established by the United States and two of its major trading partners, Canada and Japan with the exception of one instance of zeta- cypermethrin (GA 1- Short PHI) and one of

fenpropathrin (NC 3- Export 2) exceeding those limits (Supporting Table 5). Individual components of each program were frequently over the limit for export to countries in the European Union, which has low tolerance levels for all chemical residues. It should be noted that Canada currently does not have a set MRL for zeta-cypermethrin, and berries that are intended for shipment there are not currently treated with this material.

There were several instances where residues over MRL limits were detected within untreated controls, suggesting contamination of samples. It is possible that contamination occurred via drift, which we tried to control for by taking samples from the center of each plot or human error during the collection, preparation, and/or shipping of samples to the analytical laboratory.

4. Discussion

This study documents the efficacy of season-long insecticide programs with weekly applications for control of *D. suzukii* in conventional blueberry growing systems. At 24 h exposure, bioassays using plant materials collected within 1 DAT from treated plots had a higher percentage of adult mortality than those from control plots (Tables 4, 5, 6, 7). Residual effectiveness was evident at 3 DAT (GA Research Farm; Table 8) and 5 DAT (GA grower sites; Supporting Information Tables 2, 3). However, by 7 DAT in the field, there were no residual effects (Tables 7, 9). *D. suzukii* is a highly mobile species (Hauser, 2011; Mitsui et al., 2010) that is capable of moving between crop and non-crop hosts (Klick et al., 2014) where they may find temporary refuge from insecticide applications, making it important to know that programs both work upon contact shortly after application, and for several days afterwards. With limited

residual efficacy of currently available insecticides, fruits become vulnerable to infestation in a matter of days and growers may have to shorten their already short application intervals.

Heavy rain events occur regularly during the blueberry harvest season in the southeastern US, and likely reduced the residual effectiveness of programs in the field. Previous studies on the efficacy of individual chemicals found that none had residual impacts on adult mortality after a significant rain event (Van Timmeren and Isaacs, 2013). This highlights the importance of considering rainfastness of specific insecticide components within spray programs for areas with frequent precipitation. Some chemicals may remain effective after rain events, but the majority of the chemicals available for *D. suzukii* management in blueberries do not appear to do so. Because of this, growers in the southeast need to apply insecticides more frequently than in drier areas of the country where insecticides remain effective up to 14 DAT (Beers et al., 2011; Van Timmeren and Isaacs, 2013). Increased insecticide applications can become costly to growers depending on their needs (e.g. export markets, use of reduced risk materials, short pre-harvest interval). For growers in NC and GA marketing for export, we tested 3 rotational programs that range in cost from \$52-\$67 per ha for a 6 week period (Table 2). The short PHI programs cost \$22-\$26 per ha, and programs comprised of reduced risk materials range from \$99 to \$160 per ha.

Specific components within programs were more effective against *D. suzukii* adults in bioassays than others. These include phosmet and malathion (organophosphates) and zeta-cypermethrin and fenprothrin (pyrethroids). Two materials, zeta-cypermethrin and cyantraniliprole, also reduced the number of offspring produced in 1 DAT bioassays (Table 6; Supporting Information Table 1). One material in the Reduced Risk program, cyantraniliprole, did not kill a high percentage of adults upon contact, but did reduce infestation. Prolonged

contact with this material resulted in significant mortality in bioassays (Tables 8, 10) and may minimize repeated adult interactions with fruit in a field setting. The potential for this insecticide to reduce infestation may offset the high price tag associated with using a reduced risk rotation of insecticides (Table 2), particularly for growers interested in using chemicals that are less toxic to beneficial insects (Liu et al., 2012).

All programs reduced field infestation relative to the untreated control (Supporting Table 4, post-application infestation) and local presence of adults (NC baited monitoring traps) even after treatment applications had ceased. This suggests that residual effects from programs for a period of time after treatment applications ceased. It is likely that some insecticide residues remain on plant materials in sufficient quantities to deter local *D. suzukii* activity within plots. It should be noted that in recent years, there has been an increase in the amount of pesticides used in crops susceptible to *D. suzukii* (eFly Working Group 2013). This has led to grower and marketer concerns about pesticide residues (Haviland and Beers 2012, LMD *pers. comm. with growers*). Berries intended for export that are over the MRL limit for their intended market cause the entire shipment to be rejected, incurring additional costs to growers in lost yield. For this study, all insecticides were applied at the maximum label rate so we had the greatest chance of detecting residues in berry samples. Similar to residue levels detected from insecticide trials in cherries (Haviland and Beers, 2012), mean residue levels for most insecticides tested were generally within limits for domestic sale and export to any major trading partners (Canada, Japan, European Union; Supporting Information, Table 5). However, similar to data from Haviland and Beers (2012), pyrethroid residue levels were variable, and the mean level of detection was occasionally over the MRL throughout several trials and consistently over the limit for the EU in 2013 at NC site 2. This class of insecticides degrades more slowly than others

labelled for use in small fruits to control *D. suzukii*, and can be detected for a long period after application (Haviland and Beers, 2012). At this site, the grower made a pre-harvest aerial application of fenpropathrin, and residues remained on the plants for several weeks into our trials. Insecticide residues may also impact the efficacy of subsequent pesticide applications. Such impacts were seen in 2013 at NC site 2. The pre-harvest application of fenpropathrin resulted in greater mortality in semi-field bioassays for three weeks after treatment, with residues of this material being detected in all three of these weeks.

Eradication of *D. suzukii* is unlikely due to its wide host range (Bellamy et al., 2013; Lee et al., 2015; Mitsui et al., 2010; Rota-Stabelli et al., 2013), high dispersal capability (Asplen et al., 2015; Cini et al., 2014; Hauser, 2011; Walsh et al., 2011b), and the potential to spread into new regions via trade routes (Hulme, 2009; Hulme et al., 2008; Westphal et al., 2008). Current management goals aim to minimize crop damage by reducing local populations and deterring oviposition. At present, insecticides are the primary option for achieving this. To reduce the risk of pests developing resistance to active ingredients, it is important that modes of action are rotated in chemically-based programs (Sparks and Nauen, 2015; Tabashnik, 1989). Long-term use of any broad-spectrum insecticide is not a sustainable management option due to the potential for insects to develop resistance (Haviland and Beers, 2012; Mallet, 1989), unintended impacts on non-target organisms (Bridges, 2000; Epstein et al., 2000; Pimentel, 1995), and the increased cost of production (Bolda et al. 2010, Goodhue et al. 2011, eFly Working Group 2013), but is a viable short-term strategy as researchers continue to develop targeted management options.

Chemical control for *D. suzukii* is one of the necessary tools for creating a robust integrated pest management (IPM) program and should be the last line of defense once a

program is developed (Pedigo and Rice, 2009). Creating a robust IPM program requires knowledge of the pest's biology and ecology, which are currently being investigated globally. Recent projects have focused on building the knowledgebase for creating sustainable control options. These includes studies on monitoring (Burrack et al., 2015; Lee et al., 2012), modeling population dynamics based on environmental conditions (Wiman et al., 2014), understanding the role of non-crop hosts (Lee et al., 2015), determining how adults locate hosts (Keesey et al., 2015) and searching for potential agents of biological control (Chabert et al., 2012). All of these, as well as chemical control options, are necessary to create a sustainable integrated pest management strategy for the control of this invasive, polyphagous pest.

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Tables

Table 1. Field site and application rates. Maximum label rates for each state were applied every 7-10 days.

Year	Location	Cultivar/Variety	Treatment replications	Application equipment	Application rate (l/ha)
2013	Bladen County, NC (grower)	Southern highbush, var. Duke	3	Airtech air cannon trailer mounted	468
2013	Sampson County, NC (grower)	Southern highbush, var. Legacy	3	Airblast Jacto Arbus 1000 trailer mounted	682
2014	Sampson County, NC (grower)	Rabbiteye, var. Tiff Blue	4	Airblast Jacto Arbus 1000 trailer mounted	664
2014	Bacon County, GA (research farm)	Southern highbush, var. Star	4	Airblast Jacto Arbus 400 (top two nozzles and the bottom nozzles were closed)	468
2014	Bacon County, GA (research farm)	Rabbiteye var. Climax, Powderblue and Brightwell	3	Airblast Jacto Arbus 400 (top two nozzles and the bottom nozzle were closed)	468
2014	Bacon County, GA (grower)	Southern highbush, var. Star, V1	3	Airblast	468
2014	Bacon County, GA (grower)	Rabbiteye, var. Brightwell, Powderblue, Premier	3	Airblast	468

Table 2. Season-long insecticide programs for the control of *D. suzukii* in blueberries

Treatment	Active ingredient	Locations and years tested	Cost per hectare (6 week rotation)*
Export-friendly 1; maximum modes of action (Export1)	phosmet, malathion, spinetoram, fenpropathrin	NC, 2013 and 2014 GA 2014	\$52(NC) \$54 (GA)
Export-friendly 2; maximum modes of action (Export2)	methomyl, malathion spinetoram, fenpropathrin	NC, 2014	\$60 (NC) \$63 (GA)
Export-friendly 3; maximum modes of action (Export 3)	spinetoram, novaluron, phosmet	GA, 2014	\$67
Short pre-harvest interval (ShortPHI)	zeta-cypermethrin, malathion	NC, 2013 and 2014 GA 2014	\$22 (NC) \$26 (GA)
Reduced Risk (Reduced Risk)	spinetoram, acetamiprid (NC 2013), cyantraniliprole (all 2014)	NC, 2013 and 2014 GA 2014	\$99 (NC 2013) \$160 (all 2014)
Untreated Control (UTC)	n/a	NC, 2013 and 2014 GA 2014	n/a

*Cost estimates rounded up to the nearest dollar based on a survey of three pesticide dealers each in NC and GA during 2014. 6 weeks is the general duration of a season for both cultivars tested; insecticides within each program were rotated in the order listed here

Table 3. Insecticide application rates, Reentry, and Postharvest Intervals

Insecticide (trade name)	Maximum application rate	REI/PHI
acetamiprid (Assail 30SG)	371.3 ml/ha	12 hours/1 day
fenpropathrin (Danitol 2.4EC)	1120.9 ml/ha	24 hours/3 days
spinetoram (Delegate 25WG)	420.3 ml/ha	4 hours/3 days
cyantraniliprole* (Exirel 10SE)	1498.1 ml/ha	12 hours/3 days
phosmet (Imidan 70W)	1490.7 ml/ha	24 hours/3 days
methomyl (Lannate 2.4SL)	3362.6 ml/ha	48 hours/3 days
malathion (Malathion 8F)	2241.7 ml/ha (NC) 2802.1 ml/ha (GA)	12 hours/1 day
zeta-cypermethrin (Mustang Max 0.8SC)	292.3 ml/ha	12 hours/1 day
novaluron (Rimon 0.83EC)	876.9 ml/ha	12 hours/1 day

*Non-ionic surfactant added at GA grower locations 1169.2 mL/ha

Table 4. 2013 Semi-field bioassays, North Carolina Site 1: Percent of female *D. suzukii* dead after 24 hours of exposure to treated plant materials

<i>Treatment</i>	Week 1 6/4/13	Week 2 6/13/13	Week 3 6/19/13	Week 4 6/26/13
Export 1	91.0±9.0a ¹	63.0±23.0a ³	82.0±10.0a ⁴	60.0±20.0ab ⁶
Short PHI	58.0±15.0ab ²	89.0±6.0a ⁴	100.0±0.0a ²	100.0±0.0a ⁴
Reduced Risk	100.0±0.0a ¹	49.0±14.0ab ⁵	85.0±8.0a ¹	27.0±13.0b ⁵
UTC	7.0±7.0b	0.0±0.0b	7.0±7.0b	7.0±7.0b
df	3, 8	3, 8	3, 8	3, 8
F	19.77	7.39	36.12	10.74
<i>p</i>	<0.001	0.011	<0.001	0.004

Materials: ¹spinetoram, ²zeta-cypermethrin, ³phosmet, ⁴malathion, ⁵acetamiprid, ⁶fenpropathrin

Table 5. 2013 Semi-field bioassays, North Carolina Site 2: Percent of female *D. suzukii* dead after 24 hours of exposure to treated plant materials

<i>Treatment</i>	Week 1 5/30/13	Week 2 6/9/13	Week 3 6/14/13	Week 4 6/20/13	Week 5 6/27/13	Week 6 7/5/13
Export 1	90.0±10.0a ³	100.0±0.0a ⁴	85.0±12.0a ¹	20.0±14.0b ⁶	55.0±15.0ab ³	100.0±0.0a ⁴
Short PHI	97.0±3.0a ²	100.0±0.0a ⁴	86.0±9.0a ²	94.0±6.0a ⁴	67.0±13.0a ²	80.0±8.0ab ²
Reduced Risk	98.0±3.0a ¹	18.0±9.0b ⁵	93.0±5.0a ¹	35.0±17.0b ⁵	65.0±10.0a ¹	60.0±16.0ab ⁵
UTC	68.0±11.0a	0±0b	7.0±7.0b	0.0±0.0b	5.0±5.0b	25.0±25.0b
df	3, 11	3, 12	3, 12	3, 12	3, 11	3, 12
F	2.77	155.06	21.27	12.27	6.39	4.27
p	0.092	<0.001	<0.001	<0.001	0.007	0.028

Materials: ¹spinetoram, ²zeta-cypermethrin, ³phosmet, ⁴malathion, ⁵acetamiprid, ⁶fenprothrin

Table 6. 2014 Semi-field bioassays, North Carolina: Percent of female *D. suzukii* dead after 24 hours of exposure to treated plant materials and mean total number of offspring produced

	Week 1 6/5/14	Week 2 7/2/14	Week 3 7/14/14	Week 4 7/23/14	Week 5 7/30/14
<i>Treatment</i>	female mortality				
Export1	80.0±8.0a ¹	100.0±0.0a ⁵	80.0±14.0a ⁶	80.0±8.0a ⁷	85.0±10.0a ¹
Export2	NA	85.0±15.0a ⁴	100.0±0.0a ⁵	65.0±5.0a ⁶	95.0±5.0a ⁷
Short PHI	40.0±8.0ab ²	95.0±5.0ab ⁵	65.0±17.0a ²	90.0±6.0a ⁵	45.0±5.0b ²
Reduced Risk	25.0±15.0bc ³	70.0±13.0b ⁶	65.0±15.0a ³	60.0±14.0a ⁶	50.0±17.0b ³
UTC	0.0±0.0c	0.0±0.0c	0.0±0.0b	20.0±20.0b	0.0±0.0c
df	3,11	4,15	4,15	4,15	4,15
F	9.65	20.52	12	5.01	15.43
p	0.002	<0.0001	0.0001	0.009	<0.0001
<i>Treatment</i>	offspring production				
Export 1	0.00±0.00b ¹	0.00±0.00b ⁵	2.25±0.95b ⁶	0.00±0.00b ⁷	0.00±0.00c ¹
Export 2	-	0.00±0.00b ⁴	0.50±0.50b ⁵	0.75±0.48b ⁶	0.00±0.00c ⁷
Short PHI	0.00±0.00b ²	0.00±0.00b ⁵	1.25±0.48b ²	0.00±0.00b ⁵	1.00±0.41b ²
Reduced Risk	7.33±7.33b ³	0.25±0.25b ⁶	5.75±2.29b ³	0.25±0.25b ⁶	18.25±12.15b ³
UTC	31.67±11.46a	15.00±1.47a	32.5±13.05a	15.75±1.93a	35.50±4.77a
df	3,10	4,15	4,15	4,15	4,15
F	6.57	100.12	5.22	59.87	7.29
p	0.01	<0.0001	0.008	<0.0001	0.002

Materials: ¹phosmet, ²zeta-cypermethrin, ³cyantraniliprole, ⁴methomyl, ⁵malathion, ⁶spinetoram, ⁷fenpropathrin

Table 7. 2014 Semi-field bioassays, Georgia Research Farm (Southern Highbush): Percent of female *D. suzukii* dead at 24 hours of exposure to treated plants collected at 1, 3 and 7 days after treatment (DAT)

		Week 1 5/5/14	Week 2 5/12/14	Week 3 5/19/14	Week 4 5/27/14	Week 5 6/3/14
<i>Treatment</i>		1 DAT				
Export		25.0±5.0ab ¹	40.0±25.0a ⁵	80.0±8.0a ⁴	80.0±12.0a ⁶	65.0±13.0a ¹
Short PHI		50.0±6.0a ²	65.0±24.0a ⁴	80.0±12.0a ²	25.0±10.0b ⁴	70.0±17.0a ²
Reduce Risk		20.0±14.0ab ⁵	35.0±22.0a ³	40.0±16.0ab ⁵	10.0±6.0b ³	60.0±8.0ab ⁵
UTC		0.0±0.0b	5.0±5.0a	0.0±0.0b	0.0±0.0b	5.0±5.0b
df		3,9	3,9	3,9	3,9	3,9
F		8.46	1.51	14.41	15.84	6.73
p		0.006	0.277	0.0009	0.0006	0.011
<i>Treatment</i>		3 DAT				
Export		5.0±5.0b ¹	41.0±19.0a ⁵	30.0±13.0a ⁴	95.0±5.0a ⁶	65.0±5.0a ¹
Short PHI		35.0±5.0a ²	48.0±12.0a ⁴	45.0±10.0a ²	55.0±10.0b ⁴	45.0±5.0a ²
Reduce Risk		5.0±5.0b ⁵	39.0±22.0a ³	25.0±10.0a ⁵	35.0±17.0bc ³	25.0±19.0ab ⁵
UTC		0.0±0.0b	0.0±0.0a	15.0±10.0a	5.0±5.0c	0.0±0.0b
df		3,9	3,9	3,9	3,9	3,9
F		17.48	3.14	1.14	20.35	9.49
p		0.0004	0.08	0.383	0.0002	0.004
<i>Treatment</i>		7 DAT				
Export		10.0±6.0a ¹	50.0±21.0a ⁵	20.0±14.0a ⁴	20.0±14.0a ⁶	20.0±0a ¹
Short PHI		5.0±5.0a ²	10.0±6.0a ⁴	40.0±16.0a ²	0.0±0.0a ⁴	10.0±6.0a ²
Reduce Risk		10.0±6.0a ⁵	10.0±10.0a ³	25.0±13.0a ⁵	10.0±10.0a ³	15.0±15.0a ⁵
UTC		5.0±5.0a	15.0±15.0a	45.0±10.0a	0.0±0.0a	5.0±5.0a
df		3,9	3,9	3,9	3,9	3,9
F		0.33	1.86	0.65	1.5	1.87
p		0.802	0.206	0.603	0.28	0.305

Materials: ¹phosmet, ²zeta-cypermethrin, ³cyantraniliprole, ⁴malathion, ⁵spinetoram, ⁶fenpropathrin

Table 8. 2014 Semi-field bioassays, Georgia Research Farm (Southern Highbush): Percent of female *D. suzukii* dead at 120 hours of exposure to treated plants collected at 1, 3 and 7 days after treatment (DAT)

	Week 1 5/5/14	Week 2 5/12/14	Week 3 5/19/14	Week 4 5/27/14	Week 5 6/3/14
<i>Treatment</i>	1 DAT				
Export	95.0±5.0a ¹	85.0±10.0a ⁵	90.0±10.0a ⁴	100.0±0.0a ⁶	100.0±0.0a ¹
Short PHI	90.0±10.0a ²	75.0±25.0a ⁴	95.0±5.0a ²	95.±0.05a ⁴	95.0±5.0a ²
Reduce Risk	95.0±5.0a ⁵	55.0±20.0a ³	90.0±10.0a ⁵	90.0±6.0a ³	100.0±0.0a ⁵
UTC	20.0±6.0b	15.0±10.0a	10.0±6.0b	15.0±5.0b	10.0±6.0b
df	3,9	3,9	3,9	3,9	3,9
F	14.46	3.16	17.26	35.21	45.63
<i>p</i>	0.0009	0.079	0.0004	<.0001	<.0001
<i>Treatment</i>	3 DAT				
Export	95.0±5.0a ¹	65.0±21.0a ⁵	50.0±21.0ab ⁴	100.0±0.0a ⁶	95.0±5.0a ¹
Short PHI	90.0±6.0ab ²	80.0±8.0a ⁴	100.0±0.0a ²	95.0±5.0a ⁴	85.0±5.0ab ²
Reduce Risk	45.0±13.0b ⁵	55.0±17.0ab ³	60.0±8.0ab ⁵	85.0±15.0a ³	70.0±6.0b ⁵
UTC	15.0±10.0c	5.0±5.0b	20.0±14.0b	50.0±10.0b	0.0±0.0c
df	3,9	3,9	3,9	3,9	3,9
F	15.01	4.02	7.18	7.4	41.11
<i>p</i>	0.0002	0.016	0.009	0.008	<.0001
<i>Treatment</i>	7 DAT				
Export	90.0±6.0a ¹	60.0±18.0ab ⁵	30.0±13.0b ⁴	65.0±24.0a ⁶	75.0±13.0a ¹
Short PHI	75.0±10.0a ²	65.0±13.0a ⁴	85.0±10.0a ²	20.0±14.0a ⁴	50.0±13.0ab ²
Reduce Risk	15.0±10.0b ⁵	30.0±6.0ab ³	45.0±15.0ab ⁵	55.0±13.0a ³	20.0±14.0b ⁵
UTC	25.0±15.0b	20.0±14.0a	35.0±10.0ab	5.0±5.0a	5.0±5.0b
df	3,9	3,9	3,9	3,9	3,9
F	11.94	4.81	3.46	3.57	6.54
<i>p</i>	0.002	0.029	0.038	0.060	0.012

Materials: ¹phosmet, ²zeta-cypermethrin, ³cyantraniliprole, ⁴malathion, ⁵spinetoram, ⁶fenprothrin

Table 9. 2014 Semi-field bioassays, Georgia Research Farm (Rabbiteye): Percent of female *D. suzukii* dead at 24 hours of exposure to treated plants collected at 1, 3 and 7 days after treatment (DAT)

	Week 1*	Week 2*	Week 3	Week 4	Week 5	Week 6
	6/9/14	6/16/14	6/23/14	6/30/14	7/7/14	7/14/14
<i>Treatment</i>	1 DAT					
Export	0.0±0.0a ⁵	0.0±0.0a ⁶	0.0±0.0b ¹	27.0±13.0a ⁵	20.0±12.0a ⁶	60.0±20.0a ¹
Short PHI	0.0±0.0a ²	7.0±7.0a ⁴	27.0±7.0a ²	20.0±12.0a ⁴	53.0±24.0a ²	53.0±30.0a ⁴
Reduce Risk	7.0±7.0a ⁵	7.0±7.0a ³	0.0±0.0b ⁵	13.0±7.0a ³	20.0±12.0a ⁵	13.0±13.0a ³
UTC	0.0±0.0a	0.0±0.0a	0.0±0.0b	0.0±0.0a	7.0±7.0a	0.0±0.0a
df	3,6	3,6	3,6	3,6	3,6	3,6
F	1	0.57	53.17	1.07	2.22	3.43
p	0.455	0.654	0.0001	0.429	0.187	0.093
<i>Treatment</i>	3 DAT					
Export	27.0±18.0a ⁵	7.0±7.0a ⁶	7.0±7.0ab ¹	0.0±0.0a ⁵	7.0±7.0a ⁶	27.0±18.0a ¹
Short PHI	33.0±24.0a ²	0.0±0.0a ⁴	47.0±13.0a ²	7.0±7.0a ⁴	7.0±7.0a ²	27.0±0.07a ⁴
Reduce Risk	20.0±0.0a ⁵	7.0±7.0a ³	7.0±7.0ab ⁵	7.0±7.0a ³	13.0±7.0a ⁵	0.0±0.0a ³
UTC	20.0±12.0a	7.0±7.0a	0.0±0.0b	0.0±0.0a	0.0±0.0a	7.0±7.0a
df	3,6	3,6	3,6	3,6	3,6	3,6
F	0.06	0.25	7.1	0.57	1	2.93
p	0.977	0.859	0.021	0.654	0.455	0.121
<i>Treatment</i>	7 DAT					
Export	0.0±0.0a ⁵	0.0±0.0a ⁶	0.0±0.0a ¹	0.0±0.0a ⁵	7.0±7.0b ⁶	7.0±7.0a ¹
Short PHI	7.0±7.0a ²	0.0±0.0a ⁴	13.0±13.0a ²	0.0±0.0a ⁴	87.0±7.0a ²	33.0±18.0a ⁴
Reduce Risk	0.0±0.0a ⁵	0.0±0.0a ³	0.0±0.0a ⁵	7.0±7.0a ³	20.0±12.0b ⁵	13.0±7.0a ³
UTC	0.0±0.0a	0.0±0.0a	0.0±0.0a	0.0±0.0a	7.0±7.0b	7.0±7.0a
df	3,6	3,6	3,6	3,6	3,6	3,6
F	1	-	1	1	8.96	0.65
p	0.455	-	0.455	0.455	0.012	0.609

Materials: ¹phosmet, ²zeta-cypermethrin, ³cyantraniliprole, ⁴malathion, ⁵spinetoram, ⁶novaluron

*Heavy rain in weeks 1 and 2

Table 10. 2014 Semi-field bioassays, Georgia Research Farm (Rabbiteye): Percent of female *D. suzukii* dead at 120 hours of exposure to treated plants collected at 1, 3, and 7 DAT

	Week 1* 6/9/14	Week 2* 6/16/14	Week 3 6/23/14	Week 4 6/30/14	Week 5 7/7/14	Week 6 7/14/14
<i>Treatment</i>	1 DAT					
Export	0.0±0.0b ⁵	0.0±0.0c ⁶	73.0±27.0a ¹	60.0±23.0ab ⁵	33.0±18.0b ⁶	87.0±7.0a ¹
Short PHI	20.0±0a ²	67.0±18.0a ⁴	53.0±27.0a ²	80.0±12.0a ⁴	100.0±0.0a ²	100.0±0.0a ⁴
Reduce Risk	7.0±7.0ab ⁵	60.0±12.0ab ³	13.0±7.0a ⁵	60.0±12.0ab ³	100.0±0.0a ⁵	40.0±12.0b ³
UTC	0.0±0.0b	7.0±7.0bc	7.0±7.0a	0.0±0.0b	7.0±7.0b	0.0±0.0c
Df	3,6	3,6	3,6	3,6	3,6	3,6
F	8	8.85	2.95	6.95	27.4	38.49
<i>P</i>	0.016	0.013	0.121	0.022	0.0007	0.0003
<i>Treatment</i>	3 DAT					
Export	40.0±20.0a ⁵	7.0±7.0a ⁶	60.0±23.0ab ¹	7.0±7.0a ⁵	13.0±13.0a ⁶	93.0±7.0a ¹
Short Phi	73.0±27.0a ²	27.0±17.0a ⁴	87.0±13.0a ²	13.0±7.0a ⁴	47.0±13.0a ²	73.0±13.0ab ⁴
Reduce Risk	53.0±18.0a ⁵	47.0±7.0a ³	7.0±7.0c ⁵	26.0±13.0a ³	60.0±12.0a ⁵	53.0±24.0ab ³
UTC	20.0±12.0a	13.0±13.0a	13.0±7.0b	0.0±0.0a	7.0±7.0a	13.0±7.0b
Df	3,6	3,6	3,6	3,6	3,6	3,6
F	1.85	1.52	12.49	1.34	4.16	4.71
<i>P</i>	0.240	0.302	0.005	0.348	0.065	0.050
<i>Treatment</i>	7 DAT					
Export	0.0±0.0b ⁵	7.0±7.0a ⁶	26.0±26.0a ¹	7.0±7.0a ⁵	13.0±7.0b ⁶	47.0±13.0a ¹
Short PHI	27.0±7.0a ²	0.0±0.0a ⁴	20.0±12.0a ²	13.0±13.0a ⁴	80.0±12.0a ²	67.0±24.0a ⁴
Reduce Risk	7.0±7.0ab ⁵	13.0±13.0a ³	7.0±7.0a ⁵	20.0±12.0a ³	13.0±7.0b ⁵	33.0±7.0a ³
UTC	0.0±0.0b	0.0±0.0a	7.0±7.0a	0.0±0.0a	7.0±7.0b	7.0±7.0b
Df	3,6	3,6	3,6	3,6	3,6	3,6
F	7.77	0.6	0.33	0.71	7.87	3.81
<i>P</i>	0.017	0.640	0.808	0.579	0.017	0.077

Materials: ¹phosmet, ²zeta-cypermethrin, ³cyantraniliprole, ⁴malathion, ⁵spinetoram, ⁶novaluron