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

Lauren M. Diepenbrock, Jesse A. Hardin, Hannah J. Burrack

North Carolina State University, Department of Entomology and Plant Pathology, United States

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Abstract

Drosophila suzukii is an invasive insect pest which impacts small fruit production throughout much of the world. Current management programs use regular applications of broad-spectrum insecticides which must be rotated for resistance management. This study examines the efficacy of rotational treatment programs designed to meet the needs of commercial growers in the southeastern United States, a region which experiences frequent rainfall during the growing season. In bioassays, all insecticides in our programs killed at least 50% of all female flies. Despite this good efficacy and weekly applications, infestation still occurred within fields. Our findings demonstrate the necessity of a comprehensive management strategy for blackberries, requiring additional efforts to current chemical-intensive management regimes, including cultural management practices such as pruning, harvest frequency, and post-harvest cooling.

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 and stone fruits. Originating from Asia, *D. suzukii* has now become widespread throughout Europe and the Americas (Asplen et al., 2015; Calabria et al., 2012; Cini et al., 2014, 2012; Deprá et al., 2014; Hauser, 2011; Lee et al., 2011b). Unlike many drosophilids common to North America, whose larvae feed upon overripe or rotting substrates, *D. suzukii* females prefer to lay eggs in ripe and ripening fruit (Kinjo et al., 2013; Lee et al., 2011b; Swoboda-Bhattarai and Burrack, 2016), and possess a large, heavily sclerotized ovipositor which enables their oviposition into these substrates (Atallah et al., 2014; Hauser, 2011). In North America, *D. suzukii* infestation results in hundreds of thousands of dollars in crop losses from rejected harvested fruit from host crops including blueberries, cherries, caneberries (raspberries and blackberries), grapes, and strawberries (Cini et al., 2012; Goodhue et al., 2011; Vilela and Mori, 2014), and its management adds significantly to production costs of these fruit (Diepenbrock et al., 2016a; Goodhue et al., 2011).

D. suzukii has been detected throughout the United States, with much research effort devoted towards the management of this pest. Previous management studies have been performed in raspberries and cherries on the west coast (Beers et al., 2011; Bruck et al., 2011), in blueberry in the Great Lakes region (Van Timmeren and Isaacs, 2013), and in blueberry in the southeast (Diepenbrock et al., 2016a). To date, none have explored management programs in blackberry (*Rubus spp.*), arguably the most impacted host crop in the southeastern United States (eFly Working Group, 2014). In North Carolina, blackberry producers grow either floricanefruiting or floricanefruiting and primocane fruiting varieties of blackberry. Floricanefruiting varieties (e.g. 'Navajo', 'Ouachita', 'Natchez') produce fruit from mid-June until the end of July, while

floricane and primocane-fruiting varieties (e.g. Prime-Ark ® 45) will bear fruit until the first freeze. Because blackberry is highly susceptible to *D. suzukii* infestation, growers must proactively protect their fruit once it becomes vulnerable, as they begin to ripen (Swoboda-Bhattarai and Burrack, 2016). These conservative management practices represent an increase in insecticide use of at least 90% compared to the period before *D. suzukii* detection, but significant crop losses still occur (eFly Working Group, 2014). Diamides, organophosphates, pyrethroids, and spinosyns are the most effective insecticide classes against *D. suzukii* (Bruck et al., 2011; Diepenbrock et al., 2016a). There is significant concern about potential effects on non-target organisms with increased use of these primarily broad-spectrum insecticides. There are also limitations to insecticide based management programs for *D. suzukii* that make them challenging for growers to implement, including seasonal application restrictions, long pre-harvest intervals, and potential trade barriers due to insecticide residue tolerances.

Relatively few insecticides effective against *D. suzukii* are labelled in blackberry, and creating management programs that rotate mode of action to reduce risk of resistance development while also adhering to seasonal application restrictions is challenging. Our overall goal was to evaluate season-long insecticide rotations for *D. suzukii* in blackberry crops in the southeastern U.S. We compared three management programs designed to minimize insecticide residue levels on marketable fruit, maximize efficacy and residual activity, and reduce risk to beneficial insects by using insecticides considered to be less toxic to these organisms (Roubos et al., 2014a; Roubos et al., 2014b). To evaluate these programs, we compared the efficacy of individual treatments within rotational programs in laboratory bioassays, and monitored adult fly presence, infestation rates, and pesticide residues from field plots.

2. Experimental Methods

2.1. Experimental design

Field experiments were conducted at one grower-cooperator farm during 2014 and two farms during 2015 in the piedmont region of North Carolina (NC). The 2014 experimental location consisted of Prime-Ark ® -45, a floricanne and primocane-fruited variety (Clark and Perkins-Veazie, 2011). In 2015 one location had a pure stand of the floricanne-fruited ‘Navajo’ (Moore and Clark, 1989) and the other location had a mixed planting of the floricanne-fruited varieties ‘Navajo’ and ‘Ouachita’ (Clark et al., 2005) (Table 1). None of the plantings were under covers or high tunnels. All fields were picked at regular 2-4 d intervals depending on labor availability, and damaged fruit were left to decay on the ground in row centers, standard practice in the region. Treatments were replicated within sites and randomly assigned to plots ranging from 0.16-0.45 ha. Treatments were applied using grower equipment, and replicated 3-4 times per site in a randomized complete block. During 2014, materials were applied every 7 d, and every 6 d during 2015. Cost for the three programs we compared ranged from \$319-\$447 (USD) per ha for a 6 week period (Table 2).

Treatments consisted of insecticide programs, which were designed to address marketing, harvest interval, non-target risk, and input cost concerns (Table 2). The first, “export-friendly”, treatment (Export) consisted of insecticides for which major trading partners have established Maximum Residue Levels (MRL), the second treatment incorporated all three modes of action (MaxMOA) currently possible in U.S. blackberry production systems, and the third program utilized only non-organophosphate insecticides (Non-OP). Blackberries are harvested every 2-3 days, so all insecticides used had a one day post-harvest interval (PHI) to enable growers to maintain their tight picking schedules. All insecticides were applied using grower owned

equipment (Table 2) and every row was sprayed on both sides by running the sprayer through every row-middle at the maximum label rate for *D. suzukii* management in North Carolina (Table 3). Our work necessitated large plots available only on commercial farms. Because blackberry is a preferred host for *D. suzukii* (Burrack et al., 2013; Diepenbrock et al., 2016b), and there are high local populations of the pest (Swoboda-Bhattaria, *Unpub. data*), we could not include an untreated control. The goal of our project was to make comparisons among treatment programs, and all of the locations we conducted experiments have high naturally occurring *D. suzukii* populations.

2.2. Data collection

2.2.1. Single product efficacy bioassays

Bioassays using field treated material were performed to assess acute toxicity, which is not feasible to measure in the field due the small size and mobility of *D. suzukii*. A single branch with at least 3 leaflets and 3 ripe berries from the exterior edge of canes were collected from the center of each plot for use in bioassays (adapted from Diepenbrock et al., 2016a; Van Timmeren and Isaacs, 2013). Bioassay samples were taken immediately after insecticide application (0 DAT) and 6-7 days after treatment (DAT). 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 30 ml plastic cup (Dart Container Corporation, Mason, MI) (Burrack et al., 2013; Diepenbrock et al., 2016a; Van Timmeren and Isaacs, 2013). Containers 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; Diepenbrock et al., 2016a) and supplemental water.

Ten reproductively mature adult *D. suzukii* (5 male, 5 female) from laboratory colonies (Burrack et al., 2013; Dalton et al., 2011; Diepenbrock et al., 2016a) were placed into each chamber. Observations were made at 24 h to assess mortality and were left in containers for an additional 48 h, 72 h in total. Mortality at 24 h (acute mortality) is presented as it is unlikely that flies would remain in continuous contact with treated plants for up to 72 h. After 72 h, flies were removed from containers and fruit were held for an additional 48 h after which they were dissected to count larvae.

2.2.2 Adult trapping

One trap was suspended approximately 1.5 m from the ground on trellis posts 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 a 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. Flies per plot per week and total fly capture for the entire season were computed.

2.2.3 Larval infestation

Ripe, marketable berries were collected from the center of each field plot prior to insecticide applications to determine infestation. Forty berries were collected 6 DAT and held in 266 ml plastic containers (up and up brand, Target®, Raleigh, NC) at 20°C for 168 h. Containers were vented on the bottom with a fine mesh (white organza) to allow liquid from

decomposing fruit to drain (Burrack et al., 2013). Berries were then dissected under a stereomicroscope, and all *Drosophila spp.* larvae and pupae counted. Larvae present per plot per week and season-long infestation were computed.

2.2.4 Pesticide residue sampling

Marketable blackberries were sampled weekly 7 (2014) or 6 (2015) DAT from the center of each plot. 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 -20°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).

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, mortality data were arcsine-square root transformed. Offspring production, weekly infestation data, and trap capture values did not require transformation for analysis, but season-long field infestation data were log transformed for normality and to correct heteroscedasticity. Where significant effects were observed, means were separated using the Tukey-Kramer adjustment for multiple comparisons in all cases except season-long field infestation comparisons where LSD was employed. The interaction of week and treatment were analyzed to show efficacy of individual insecticides within treatments, and when appropriate, pooled across the season to detect season-long trends in programs.

3. Results

3.1 Single product efficacy bioassays

There was no statistical difference between mortality for male *D. suzukii* than female flies across all sites and years (24 hour mortality in 0 DAT assays pooled across sites and years: mean male mortality = 68%, mean female mortality = 56%; $t_{204, 204} = 1.13$, $p = 0.384$). Because female *D. suzukii* are directly responsible for fruit damage, we present female mortality and offspring production in the following sections (Diepenbrock et al., 2016a).

3.1.1 Prime-Ark-45 ® (2014)

Mortality was similar in weekly 0 DAT bioassays among all treatments (Table 4), with the exception of week 5 in which the Export program had much higher mortality than the MaxMOA program despite the same insecticide being applied in both programs. In the first three weeks of treatment application, all programs killed 70% or more female flies within 24 hours in 0 DAT bioassays, however in the final three weeks, only 50% or fewer females died within 24 hours with the exception of the Export program in week 5. Offspring production in these assays was similar across weeks and treatments (Table 4), with the exception of the MaxMOA program during week 5 in which an average of 56.25 larvae were recovered from treated fruit in bioassays. It is possible that the fruit in these assays did not receive good insecticide coverage. Female mortality 7 DAT was less than 50% in all bioassays, suggesting that there is limited residual activity for all materials (Data pooled across programs for 6 weeks: $F_{2,69} = p = 0.329$; Supplementary Table 1).

3.1.2. Floricane-fruited varieties: Ouachita, Navajo (2015)

At site 1, a mixed variety planting, female mortality in 0 DAT bioassays was similar across programs with the exceptions of weeks 3 and 5 (Table 5). In week 3, different insecticides were applied in each program, with 93% female mortality achieved in the Export program and only 20% in the Non-OP program with mortality in the MaxMOA program intermediate at 67%.

The same insecticide, zeta-cypermethrin, resulting in low mortality in the Non-OP program in week 3 also had low mortality (27%) in week 5. This insecticide was used several other times with higher mortality rates, so other factors likely impacted efficacy of this material during these weeks. Offspring production was variable (Table 5) but generally low with less than 12 offspring recovered in most bioassays. In weeks 1 and 4, greater numbers of offspring were produced in the Export program bioassays than in any other assays (35.33 ± 23.46 and 19.00 ± 11.53 respectively). Offspring production was not as high in other weeks when those materials were applied (Table 5). Similar to 2014, residual efficacy was low in all programs (Supplementary Table 2) with one exception. In week 3 of the Non-OP program (zeta-cypermethrin), 80% of female flies died within 24 hours of treated plant materials 6 DAT. Resulting offspring production was numerically, but not significantly, lower than other treatments.

At site 2, a 'Navajo' planting, female mortality in 0 DAT bioassays was similar across programs within most weeks (Table 6), but was low. For example, during week 6 there was no difference between programs, with mortality less than 15%. The same material was applied in all programs that week, and caused higher mortality in other weeks. In weeks 3 and 4, the MaxMOA program had higher mortality than the other two programs; however in week 4, mortality was only 33% in this program. Offspring production was low in all programs during each week (Table 6). Similar to the previous trials, there was very low residual efficacy (Supplementary Table 3), with a maximum of 53% mortality in week 4 of the MaxMOA program. Offspring production was similarly low in all programs each week (Table 6) despite differences in female mortality.

3.2 Adult SWD trapping

Previous research has shown that trapping of adult *D. suzukii* does not correlate with fruit damage (Burrack et al., 2015), therefore trapping was performed primarily for the purpose of confirming the presence of adult *D. suzukii* within crop fields. Flies were trapped at all locations included in this study (Supplementary Table 4). More flies were trapped in 2014 than in 2015 ($F_{1,16}=16.71$, $p<0.001$), but there was no difference in the total number of flies trapped by treatment ($F_{2,16}=1.56$, $p=0.24$).

3.3 Field infestation

Because our experiments were conducted on commercial farms, leaving any fruit unprotected was not acceptable. In nearby untreated research station plantings, infestation in ‘Ouachita’ and ‘Von’ cultivars peaked at 33 larvae per berry in 2014 (Swoboda-Bhattarai, *unpub. data*) and over 25 larvae per berry in July 2015 (Diepenbrock and Burrack, 2016). Even weekly insecticide applications, frequent harvest, and standard commercial pruning practices did not prevent infestation in any of sites in either year (Table 7). When larvae per plot were totaled across the entire harvest period, infestation was higher in 2014 than 2015 ($F_{1,16}=15.90$, $p=0.001$). There were differences in infestation rates between treatments within each year ($F_{2,16}=4.77$, $p=0.024$), but these differences were not consistent. The MaxMOA program had the highest cumulative infestation rate in 2014, and the NonOP program having the highest amount of infestation in 2015.

3.3.1. Prime-Ark-45 ® (2014)

We also analyzed weekly larval infestation observations within each site. Infestation was not detected until the third week of the experiment and was the same across all treatments (data not shown, $F_{2,8}=1.51$, $p=0.277$). With the exception of week 6, infestation remained below 2

larvae per berry. In week 6, all plots received spinetoram, with the MaxMOA treatment having double the amount of infestation in either of the other treatments.

3.3.2. Floricane-fruited varieties: Ouachita, Navajo (2015)

Weekly infestation rates at site 1 were less than 1 larva per berry, and no larvae were detected in weeks 1 and 3. Infestation at site 1 did not differ between treatments (data not shown, $F_{2,60} = 1.10$, $p = 0.340$). Infestation was similarly low at site 2 and was not detected until week 6. Fewer than 1 larva per berry were found in weeks 6 through 8 at site 2 and also did not differ between treatments (data not shown, $F_{2,19} = 0.03$, $p = 0.967$).

3.4 Chemical residues

Chemical residues for all three insecticides used in our programs were within the Maximum Residue Limits for the United States (Table 8). In 2015, the average amount of malathion residue detected was frequently over the limit for the European Union, while in 2014 all averages were within the limit. Residue samples were taken 7 DAT in 2014, but 6 DAT in 2015, which may have caused a higher amount of residue to be detected in 2015. Average spinetoram residues were over the limit for the European Union at one site in 2015, but remained within acceptable limits for all target markets in 2014 and in our other site in 2015. At present, Canada has no set tolerance for zeta-cypermethrin, so any detection of this material is not permissible. All programs, even those where zeta-cypermethrin was not included, had detectable levels of this chemical, suggesting that contamination either via drift during application or handling may have occurred. Samples were taken from the center of each plot to minimize the potential for drift. However with plots adjacent to one another, it is possible that more drift occurs than expected. It is also possible that some pesticide remained in tanks between treatments despite thorough rinsing procedures.

4. Discussion

In this study, we documented the efficacy of season-long insecticide programs with weekly applications to protect fruit from *D. suzukii* in conventional blackberry fields. Insecticide applications incur costs to growers depending on their needs (e.g. export markets) and can cut short the duration of their growing season due to strict limitations on the amount of each active ingredient permitted to be applied to each crop annually. Several blackberry varieties can produce for longer than 6 weeks, with few remaining applications [per label regulations](#) available after this period.

Weekly insecticide treatments did not prevent infestation at any of our sites during either year. The presence of a single larva in a shipment of fruit can cause that entire shipment to be rejected. With zero tolerance for infestation in fruit (Bruck et al., 2011; Burrack et al., 2015; Van Timmeren and Isaacs, 2013), growers may still experience crop loss even when using an intensive chemical-based management regime. Some growers are able to sell these fruit to other markets (e.g. processing), but for a lower price (LMD, Personal Communication).

Although insecticide programs did not prevent infestation, we confirmed that the materials used were toxic to *D. suzukii* as applied. After 24 h of exposure, mortality of female flies in bioassays was generally 50% or greater (Tables 4-6), with consistent, though variable, offspring production (Tables 4-6). However, there were several instances where the same materials differed significantly in mortality, sometimes when applied during the same week. We did not observe this high degree of variability within treatments of the same material in a previous study conducted in blueberries (Diepenbrock et al., 2016a). Blackberries grow vigorously in the southeastern US, and produce a dense, hedge-like canopy which previous work by our laboratory has demonstrated facilitates higher *D. suzukii* infestation rates (Diepenbrock

and Burrack, 2016). Differences in spray coverage and penetration likely influenced both field infestation levels and bioassay results. If the plant material used in bioassays was not fully covered by insecticide, then it is possible that flies could avoid direct interaction with the chemicals and lead to high variability in mortality under bioassay conditions. These observations highlight the challenges of managing *D. suzukii* in blackberry production in particular. Blackberries are a highly preferred host crop (Lee et al., 2011a) and several varieties fruit during the latter half of the growing season in the southeastern United States, when *D. suzukii* populations are very high.

There **was essentially** no residual effects on female mortality or offspring production evident from bioassays conducted on materials collected 6-7 DAT (Supplementary tables 1-3). Heavy rain events and constant humid growing conditions in our region (State Climate Office of North Carolina) likely reduced the residual efficacy of programs under field conditions. Previous studies on the efficacy of individual chemicals applied to blueberry, a less preferred host than blackberry (Burrack et al., 2013), found that none of the tested chemicals had residual impacts on adult mortality following a significant rain event ((Diepenbrock et al., 2016a; Van Timmeren and Isaacs, 2013). Because the majority of insecticides available for *D. suzukii* management in blackberry do not remain effective after rain events, growers in the southeast often need to apply insecticides more frequently than in drier areas of the country (Caprile et al., 2011; Isaacs et al., 2013), which treat every 7-10 d upon detection. Because *D. suzukii* is a highly mobile species (Hauser, 2011; Mitsui et al., 2010) that is capable of moving between crop and non-crop hosts (Diepenbrock et al., 2016b; Klick et al., 2014) and has a wide variety of potential non-crop hosts (Lee et al., 2015; Poyet et al., 2015), a lack of residual efficacy is a concern for growers. With limited insecticide treatment options in blackberry, and minimal residual efficacy under

southeastern North American growing conditions, growers may need to shorten their already short (7-10 d) application intervals.

Reliance on insecticides for management of *D. suzukii* has led to both grower and marketer concerns about pesticide residues (Diepenbrock et al., 2016a; Haviland and Beers, 2012). Berries found to be over the maximum residue level (MRL) for their intended market cause the entire shipment to be rejected. Similar to management studies conducted in cherries (Haviland and Beers, 2012) and blueberries (Diepenbrock et al., 2016a), mean residue levels for spinetoram were generally within limits for domestic sale and export (Canada, European Union; Table 7), however malathion residues were occasionally over the limit for export to the EU. Canada does not have an established MRL for zeta-cypermethrin, so any detectable amount will cause fruit to be rejected. Zeta-cypermethrin is a highly persistent material, and residues were detected for up to 4 weeks on fruit after application and in plots where the material was not directly applied. Blackberries are harvested for 6-8 weeks, and growers do not always know where fruit will be shipped, limiting the use of this material in rotations. Due to its high persistence and likely drift or carry-over between treatments, it would be risky for growers potentially marketing blackberries to Canada to use zeta-cypermethrin even on other crops on their farms during harvest.

Recent research efforts have focused on the biology of *D. suzukii*, describing its wide host range (Lee et al., 2015; Mitsui et al., 2010; Rota-Stabelli et al., 2013), host preferences (Bellamy et al., 2013; Burrack et al., 2013; Diepenbrock et al., 2016b), global spread (Asplen et al., 2015; Cini et al., 2014; Hauser, 2011; Walsh et al., 2011), and within-host variability of infestation (Diepenbrock and Burrack, 2016). Using this information, researchers and pest management practitioners are focused on how to best exploit the ecology of this pest such that

we can create optimized integrated pest management practices. One such practice is the adoption of post-harvest cold storage (Aly et al., 2017), whereby offspring survival in fruit intended for sale can be reduced by storage in temperatures of 5°C or below for a minimum of 24 hours. Other practices include educating harvest teams on fruit removal (Diepenbrock and Burrack, 2016) and pruning practices that improve spray coverage and reduce preferred fly habitat. Eradication of a polyphagous mobile pest is unlikely (reviewed in Diepenbrock et al., 2016a), so creating viable integrated management options for *D. suzukii* is an important, ongoing project requiring collaboration among growers and researchers to enable successful production of vulnerable fruit crops. The insecticide-based management programs presented here provide a tool for growers to meet their immediate pest management needs as researchers work to progress the science leading to comprehensive, integrated management practices which incorporate the ecology and biology of this pest.

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Table 1

Field site and application rate. Maximum label rates were applied every 7 days.

Year	Location	Variety	Treatment replications	Plot size (ha)	Application Equipment	Application rate (l/ha)
2014	Cleveland County, NC	Prime- Ark®-45	4	0.16-0.18	Jacto Arbus 400 Airblast	487
2015	Cleveland County, NC	Navajo	3	0.43-0.45	Durand Wayland 557 Airblast, top nozzles off	935
2015	Cleveland County, NC	Navajo and Ouachita	3	0.19-0.31	Tifone Airblast 882	692

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

Treatment	Active ingredient	cost per hectare (6 week rotation) ^a
Export friendly (Export)	malathion, spinetoram	\$447
Maximum Modes of Action (MaxMOA)	zeta-cypermethrin, malathion, spinetoram	\$319
Non-Organophosphate (Non-OP)	zeta-cypermethrin, spinetoram	\$381

6 weeks is the general duration of floricane harvest; insecticides within each program were rotated

* Cost estimates rounded up the nearest dollar on a survey of three pesticide dealers in NC

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Table 3

Insecticide application rates, Reentry, and Preharvest intervals

Insecticide (trade name)	Maximum application rate	REI/PHI
malathion (Malathion 8F)	2.34 ml/ha	12 h/ 1 day
spinetoram (Delegate 25WG)	170 g/ha	4 h/ 1 day
zeta-cypermethrin (Mustang Max 0.8SC)	118 ml/ha	12 h/ 1day

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Table 4 2014 Single product efficacy bioassays: Proportion of female *D. sukukii* dead after 24 hours of exposure to treated plant materials and mean number of offspring produced (0 DAT). Values within a column followed by same letter are not significantly different via mean comparison using the Tukey-Kramer adjustment ($\alpha = 0.05$).

	Week 1 6/17/2014	Week 2* 6/26/2014	Week 3 7/4/2014	Week 4 7/10/2014	Week 5 7/17/2014	Week 6 7/25/2014
<i>Treatment</i>	female mortality					
Export	0.90 ± 0.20 a ¹	0.70 ± 0.20 a ³	0.95 ± 0.10 a ¹	0.45 ± 0.34 a ³	0.80 ± 0.23 a ¹	0.45 ± 0.25 a ³
MaxMOA	0.80 ± 0.23 a ²	0.75 ± 0.19 a ¹	0.85 ± 0.19 a ³	0.49 ± 0.23 a ²	0.15 ± 0.19 b ¹	0.50 ± 0.20 a ³
Non-OP	0.80 ± 0.28 a ²	0.70 ± 0.35 a ³	0.59 ± 0.43 a ²	0.49 ± 0.37 a ³	0.45 ± 0.34 ab ²	0.50 ± 0.20 a ³
df	2,9	2,9	2,9	2,9	2,9	2,9
F	0.25	0.14	1.77	0.06	5.34	0.06
p	0.785	0.872	0.224	0.940	0.030	0.938
<i>Treatment</i>	offspring production					
Export	15.00 ± 17.34 a ¹	3.00 ± 3.56 a ³	3.25 ± 2.75 a ¹	9.75 ± 8.38 a ³	7.75 ± 7.93 b ¹	4.00 ± 4.76 a ³
MaxMOA	0.75 ± 1.50 a ²	4.75 ± 8.22 a ¹	7.00 ± 1.83 a ³	1.75 ± 2.06 a ²	56.25 ± 19.72 a ¹	5.00 ± 7.39 a ³
Non-OP	1.25 ± 2.50 a ²	1.50 ± 3.00 a ³	15.75 ± 17.21 a ²	7.00 ± 8.29 a ³	5.5 ± 2.08 b ²	7.00 ± 2.58 a ³
df	2,9	2,9	2,9	2,9	2,9	2,9
F	3.13	0.27	1.86	1.70	24.02	0.64
p	0.093	0.769	0.210	0.236	< 0.001	0.551

*week 2 data were taken at 48 hours

¹malathion, ²zeta-cypermethrin, ³spinetoram

Table 5 2015 Single product efficacy bioassays: Proportion of female *D. suzukii* dead after 24 hours of exposure to treated plant materials and mean number of offspring produced in mixed planting (0 DAT). Values within a column followed by same letter are not significantly different via mean comparison using the Tukey-Kramer adjustment ($\alpha = 0.05$).

		Week 1 6/12/2014	Week 2 6/19/2014	Week 3 6/26/2014	Week 4 7/3/2014
<i>Treatment</i>		female mortality			
Export		0.60 ± 0.20 a ¹	0.93 ± 0.12 a ³	0.93 ± 0.12 a ¹	0.60 ± 0.20 a ³
MaxMOA		0.60 ± 0.20 a ²	0.73 ± 0.23 a ¹	0.67 ± 0.23 ab ³	0.80 ± 0.20 a ²
Non-OP		0.40 ± 0.35 a ²	0.60 ± 0.20 a ³	0.20 ± 0.20 b ²	0.67 ± 0.23 a ³
	df	2,6	2,6	2,6	2,6
	F	0.91	2.29	9.63	0.94
	p	0.453	0.182	0.013	0.441
<i>Treatment</i>		offspring production			
Export		35.33 ± 23.46 a ¹	6.33 ± 7.77 a ³	10.67 ± 18.48 a ¹	19.00 ± 11.53 a ³
MaxMOA		2.67 ± 3.06 b ²	2.33 ± 2.52 a ¹	9.50 ± 0.71 a ³	1.33 ± 2.31 b ²
Non-OP		6.33 ± 8.39 b ²	11.00 ± 5.20 a ³	4.00 ± 1.73 a ²	0.00 ± 0.00 b ³
	df	2,6	2,6	2,5	2,6
	F	4.58	1.81	0.27	7.32
	p	0.062	0.243	0.776	0.025
		Week 5 7/14/2014	Week 6 7/20/2014	Week 7 7/29/2014	
<i>Treatment</i>		female mortality			
Export		0.93 ± 0.12 a ¹	0.73 ± 0.46 a ³	0.80 ± 0.00 a ¹	
MaxMOA		0.87 ± 0.12 a ¹	0.73 ± 0.23 a ³	0.67 ± 0.23 a ¹	
Non-OP		0.27 ± 0.23 b ²	0.47 ± 0.42 a ³	0.87 ± 0.12 a ²	
	df	2,6	2,6	2,6	
	F	8.17	0.81	1.5	
	p	0.019	0.487	0.297	
<i>Treatment</i>		offspring production			
Export		3.33 ± 5.77 a ¹	6.67 ± 5.51 a ³	0.00 ± 0.00 a ¹	
MaxMOA		2.00 ± 2.65 a ¹	2.33 ± 2.52 a ³	2.33 ± 3.22 a ¹	
Non-OP		0.00 ± 0.00 a ²	1.67 ± 1.15 a ³	0.00 ± 0.00 a ²	
	df	2,6	2,6	2,6	
	F	0.63	1.75	1.58	
	p	0.565	0.253	0.281	

¹malathion, ²zeta-cypermethrin, ³spinetoram

Table 6 2015 Single product efficacy bioassays: Proportion of female *D. suzukii* dead after 24 hours of exposure to treated plant materials and mean number of offspring produced in ‘Navajo’ (0 DAT). Values within a column followed by same letter are not significantly different via mean comparison using the Tukey-Kramer adjustment ($\alpha = 0.05$).

		Week 1 6/3/15	Week 2 6/10/15	Week 3 6/16/15	Week 4 6/25/15
<i>Treatment</i>		female mortality			
Export		0.73 ± 0.23 a ¹	0.40 ± 0.40 a ³	0.20 ± 0.35 ab ¹	0.07 ± 0.12 b ³
MaxMOA		0.60 ± 0.20 a ²	0.53 ± 0.50 a ²	0.77 ± 0.25 a ³	0.33 ± 0.12 a ²
Non-OP		0.67 ± 0.23 a ²	0.33 ± 0.31 a ³	0.13 ± 0.23 b ²	0.07 ± 0.12 b ³
	df	2,6	2,6	2,6	2,6
	F	0.44	0.19	4.18	3.92
	p	0.663	0.836	0.073	0.082
<i>Treatment</i>		offspring production			
Export		0.00 ± 0.00 a ¹	10.33 ± 8.50 a ³	65.33 ± 60.14 a ¹	26.00 ± 27.40 a ³
MaxMOA		0.33 ± 0.58 a ²	15.67 ± 26.27 a ¹	8.33 ± 1.15 a ³	23.00 ± 13.23 a ²
Non-OP		0.00 ± 0.00 a ²	8.00 ± 5.00 a ³	19.33 ± 21.20 a ²	36.00 ± 26.21 a ³
	df	2,6	2,6	2,6	2,6
	F	1.00	0.64	3.10	2.00
	p	0.422	0.562	0.119	0.216
		Week 5 7/2/15	Week 6 7/15/15	Week 7 7/22/15	Week 8 7/27/15
<i>Treatment</i>		female mortality			
Export		0.53 ± 0.50 a ¹	0.13 ± 0.12 a ³	0.53 ± 0.31 a ³	0.60 ± 0.35 a ¹
MaxMOA		0.47 ± 0.46 a ¹	0.07 ± 0.12 a ³	0.60 ± 0.20 a ³	0.80 ± 0.20 a ¹
Non-OP		0.67 ± 0.42 a ²	0.13 ± 0.23 a ³	0.47 ± 0.12 a ³	1.00 ± 0.00 a ²
	df	2,6	2,6	2,6	2,5
	F	0.11	0.18	0.27	1.37
	p	0.897	0.840	0.772	0.336
<i>Treatment</i>		offspring production			
Export		0.00 ± 0.00 a ¹	0.33 ± 0.57 a ³	14.67 ± 19.50 a ³	0.67 ± 1.54 a ¹
MaxMOA		2.33 ± 4.04 a ¹	15.33 ± 14.01 a ³	3.33 ± 1.53 a ³	0.67 ± 1.54 a ¹
Non-OP		5.33 ± 5.03 a ²	0.33 ± 0.57 a ³	6.33 ± 9.29 a ³	0.50 ± 0.71 a ²
	df	2,6	2,6	2,6	2,5
	F	0.13	1.03	1.40	0.02
	p	0.885	0.412	0.317	0.982

¹malathion, ²zeta-cypermethrin, ³spinetoram

Table 7 Average season-long infestation totals per treatment in weekly samples, 40 berry samples collected per plot. Values within a column followed by same letter are not significantly different via LSD ($\alpha = 0.05$).

Year	Treatment	Total infestation
2014	Export-Friendly	186.75 $\pm$ 47.14 b
	Maximum Modes of Action (MOA)	336.50 $\pm$ 89.49 a
	Non-organophosphate	139.00 $\pm$ 11.87 b
2015	Export-Friendly	4.67 $\pm$ 3.16 e
	Maximum Modes of Action (MOA)	4.00 $\pm$ 1.69 de
	Non-organophosphate	6.83 $\pm$ 2.51 cd
df		2,16
F		4.77
<i>p</i>		0.024

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Table 8 Minimum, mean, and maximum insecticide residues detected on fruit 6-7 DAT.

Year	Site	Treatment	Malathion			Spinetoram			Zeta-Cypermethrin		
			min	mean	max	min	mean	max	min	mean	max
2014	NC-1	Export	0.000	0.015	0.052 ^c	0.006	0.046	0.135 ^c	0.000	0.003 ^b	0.036 ^b
		MaxMOA	0.000	0.009	0.037 ^c	0.000	0.027	0.137 ^c	0.000	0.028 ^b	0.092 ^b
		Non-OP	0.000	0.000	0.000	0.000	0.041	0.200 ^c	0.000	0.035 ^b	0.108 ^b
2015	NC-2	Export	0.000	0.084 ^c	0.269 ^c	0.001	0.053	0.152 ^c	0.000	0.017 ^b	0.160 ^b
		MaxMOA	0.000	0.076 ^c	0.288 ^c	0.000	0.046	0.209 ^c	0.019 ^b	0.061 ^b	0.197 ^b
		Non-OP	0.000	0.001	0.004	0.000	0.051 ^c	0.225 ^c	0.030 ^b	0.086 ^b	0.197 ^b
2015	NC-3	Export	0.003	0.034 ^c	0.115 ^c	0.002	0.021	0.085 ^c	0.000	0.019 ^b	0.100 ^b
		MaxMOA	0.000	0.026 ^c	0.125 ^c	0.000	0.007	0.054 ^c	0.015 ^b	0.068 ^b	0.208 ^b
		Non-OP	0.000	0.003	0.023 ^c	0.000	0.009	0.050	0.000	0.074 ^b	0.243 ^b

Letters indicate that residue limits were exceeded for: United States^a, Canada^b, European Union^c