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ORIGINAL CONTRIBUTION

The effect of border sprays and between-row soil tillage on *Drosophila suzukii* in organic blackberry production

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Abstract

Drosophila suzukii (Matsumura) is a major pest of soft-skinned fruit. Females have an enlarged serrated ovipositor that is used to cut into ripening fruit and lay their eggs. Larvae develop inside infested fruit, rendering fruit unmarketable. Previous research has indicated that *D. suzukii* can move from adjacent woodlands into cultivated fields. Furthermore, multiple generations can occur in a single season as a result of fallen, infested fruit in the fields. Our hypothesis was that border sprays and soil tillage of field aisles can reduce *D. suzukii* presence in commercial blackberry fields (*Rubus* spp.). To test our hypothesis, we conducted split-plot field trials in organic blackberry fields for 3 and 4 weeks in 2014 and 2015, respectively. Treatments were border sprays (whole plot, pyrethrins + azadirachtin) and tillage (subplot, ~15 cm). We evaluated adult *D. suzukii* in both years and berry infestation and natural enemies in 2015 only. We found that plots with border treatments had fewer *D. suzukii* (larvae and adults) than plots without border sprays. Tilling the soil between rows of blackberry bushes did not have a significant effect on adult captures or larval infestation of fruit. Natural enemies were unaffected by the border spray and tillage treatments. Our results confirmed our hypothesis that border sprays can be utilized to reduce populations of *D. suzukii* in organic blackberry fields, while maintaining populations of natural enemies. However, the effect of soil tillage is unclear and requires further investigation. Additional research should investigate the timing of border sprays and their effect on high infestations of *D. suzukii* as well as quantify fruit fall and depth of burial to reduce *D. suzukii* emergence using soil tillage.

Introduction

Drosophila suzukii (Matsumura) (Diptera: Drosophilidae) is an invasive fruit fly pest of small and stone fruits that has spread throughout much of North America and Europe (Walsh et al. 2011; Burrack et al. 2012; Cini et al. 2012). The female *D. suzukii* has a modified ovipositor with large serrations that allows her to cut into the skin of uninjured (due to physical or pest injury), ripening fruits and deposit an egg under the skin surface (Lee et al. 2011, 2015a). The larvae hatch and feed on the fruit flesh and associated yeasts (Starmer and Aberdeen 1990; Walsh et al. 2011; Hamby et al. 2012), causing fruit to become unmarketable. Economic losses have been significant in blueberries, caneberries, cherries and strawberries in fruit-producing regions of North America as a result of direct crop damage and increase costs of control (Bolda et al. 2010; Goodhue et al. 2011; eFly 2012).

Drosophila suzukii, also known as the spotted wing drosophila (SWD), is highly mobile and will migrate in search of resources and suitable environmental conditions (Mitsui et al. 2010, Klick et al. 2016). Many berry farms in Florida are surrounded by unmanaged, semi-natural habitats that contain non-crop hosts with fleshy, thin-skinned fruits that *D. suzukii* may utilize in addition to its commercial hosts (Iglesias, Liburd and Grunwald unpublished, Gilbert and Stys 2004). *Drosophila suzukii* has been known to infest wild blackberry (*Rubus* spp.) and grape (*Vitis* spp.), black elderberry (*Sambucus nigra*), honeysuckle (*Lonicera* spp.), and black nightshade (*Solanum nigrum*) (Poyet et al. 2014; Lee et al. 2015b; Arnó et al. 2016; Kenis et al. 2016). Non-crop hosts provide food, oviposition sites and protection during the non-crop season after which *D. suzukii* moves from adjacent unmanaged habitats into cultivated fields as resources become abundant (ripening of berries) (Liburd et al. 2015; Klick et al. 2016). Large percentages of woodland habitat in the surrounding landscape correlate with *D. suzukii* appearing earlier in cultivated fields (Pelton et al. 2016), necessitating earlier management actions be taken during the cropping season. Furthermore, in warmer geographic regions such as the south-eastern US, there is greater resource continuity, with the availability of cultivated host crops throughout most of the year (e.g. December through August in Florida). On farms where multiple host crops are grown in succession, there is potential for *D. suzukii* to move from one crop to another (e.g. blueberry to caneberry).

Control tactics that take advantage of this behaviour can contribute to a successful, long-term integrated pest management (IPM) programme for *D. suzukii*. Border sprays are selectively applied along the perimeter of a field and can be useful against pests that migrate from surrounding environments (Chouinard et al. 1992; Trimble and Solymar 1997; Blaauw et al. 2015) . This application method has been used as an alternative to cover sprays and may reduce pesticide residues on the crop, amount of pesticide applied to the field, pesticide effects on non-target organisms and fruit knock-down due to application equipment (Chouinard et al. 1992; Prokopy et al. 2003; Carroll et al. 2009; Klick et al. 2016). Border sprays have been used successfully to control plum curculio (*Conotrachelus nenuphar*) (Chouinard et al. 1992), brown marmorated stink bug (*Halyomorpha halys*) (Blaauw et al. 2015), apple maggot (*Rhagoletis pomonella*) and codling moth (*Cydia pomonella*) (Trimble and Vickers 2000) in orchard systems. As *D. suzukii* is thought to be migrating from outside the field, we hypothesize that the establishment of a pesticide border around the field will reduce *D. suzukii* in blackberry fields.

Cultural control tactics are part of an IPM programme and can be used to reduce the use of insecticides. Organic growers rely heavily on cultural controls for *D. suzukii* management due to the limited number of effective organic chemical tools registered for this pest (Bruck et al. 2011; Van Timmeren and Isaacs 2013). Currently, soil tillage has not been evaluated for *D. suzukii* management. The main goals of soil tillage are as follows: (i) enhance soil conditions for planting, (ii) manage crop residues and (iii) incorporate amendments or weeds into the soil (SSGTC 2008). *Drosophila suzukii* pupates inside or partially inside the fruit, which can rot and fall to the ground before the adult emerges (Walsh et al. 2011). Soil tillage may interrupt the life cycle of *D. suzukii* by incorporating the pupae into the soil, and ultimately reducing adult emergence.

The purpose of our study was to evaluate the effect of border sprays and between-row soil tillage on *D. suzukii* presence in commercial blackberries. *Drosophila suzukii* presence was evaluated using trapping techniques for adult flies and taking berry samples to evaluate the degree of larval infestation. Natural enemy presence is also discussed.

Materials and Methods

Field set-up

The experiments were conducted during 27 June to 16 July 2014 and 29 May to 25 June 2015. The 2014 experiment was started late in the season and therefore was only carried out for 3 weeks (4 weeks in 2015). Experimental plots were located on an organic commercial blackberry farm in Alachua County, Florida (29°35′17″N 82°5′2″W). The experiment was established in blackberry, *Rubus fruticosus* L. (Rosaceae) which was located on the south side of the farm. In years 1 and 2, the plots were adjacent to an unmanaged, woody habitat on the south side and organic southern highbush blueberries (*Vaccinium corymbosum* L. × *V. darrowi*) to the north. The plots were situated from north to south because *D. suzukii* had been captured in traps in both adjacent areas and the pressure was similar. In year 1, a water run-off area bordered the plot to the west and blackberries to the east. In year 2, the plot was adjacent to blackberries to the west and an open field to the east. The blackberry plants were 4–5 years old and planted 0.9 m apart with 3.7-m aisles between rows. Plants were trellised using the ‘V’ system with wires at heights of 1 and 2 m on which to secure canes. Plants were managed using standard grower practices that included pruning, fertilizer and irrigation (Andersen and Crocker 2014). Aisles were mowed on a regular basis as part of the grower’s management programme.

No insecticides (other than those used in the treatments) were applied to the plots during the experiments. There is a natural infestation of *D. suzukii* because this species has been captured at this farm in previous years (Liburd et al. unpublished data).

The experiment was a completely randomized two-factor split-plot design with eight replicates. The whole-plot treatment factors were with border spray or without border spray, and subplot factors were till and no till (control). Individual plot size was 0.16 ha and consisted of three to five rows of organic blackberries (var. Natchez). Whole plots were separated by a 6.1-m-wide buffer zone of unpaved road.

Insecticide applications

All applications were made using an air blast sprayer (model: storm 828, Leinbachs Inc., Rural Hall, NC). Spinosad (Entrust®, Dow AgroSciences, Indianapolis, IN) was applied one time to all plots at the manufacturer's labelled rate, 0.4 l/ha, 7 days prior to the start of the experiment. This was done to help standardize *D. suzukii* populations in each plot as the experiments were started when some ripening fruit were already present in the field. Spinosad is registered and recommended for use in organic blackberries in Florida for control of adult *D. suzukii* flies only and has a residual toxicity of 7 days (Liburd and Iglesias 2013; Van Timmeren and Isaacs 2013). Pre-experimental trap captures and fruit samples (2015 only) were collected and no differences in adult *D. suzukii* or fruit infestation were found. In border treatments, a compound consisting of azadirachtin and pyrethrins (Azera®, MGK, Minneapolis, MN) was applied three times beginning 27 June 2014 and 29 May 2015 at a 7 to 10 day interval at the manufacturer's labelled rate of 2.4 l/ha. Applications were made with only one side of the air blast sprayer active, directed into the crop. The pressure of the sprayer was adjusted so that the spray distance was approximately 3 m into the blackberry planting.

Soil tillage

A 5-ft rototiller (Howse Implement Company, Inc. East Laurel, MS) was used to till the aisles of the subplot treatments designated 'till'. The rototiller speed was ~1.6 km/min at a depth of ~15 cm. The first till was performed at the start of the experiment, and this was repeated once at 7- and 14-day intervals in 2014 and 2015, respectively. The subplots designated as 'no till' were left untilled for the entire study.

Sampling

In 2014 and 2015, traps for capturing adult *D. suzukii* were constructed using 1-l clear plastic cups with lids and 51, 4-mm holes around the centre of the cup (Iglesias et al. 2014). Traps were baited with 200 ml of yeast and sugar–water mixture. The bait was made with 4.2 g of yeast (Fleischmann's RapidRise, ACH Food Companies, Inc., Cordova, TN), 11 g white granulated sugar (Publix, Lakeland, FL), 200 ml tap water and 0.3 ml odourless dish detergent (Palmolive Pure and Clear, Colgate-Palmolive Company, New York, NY). Bait was premixed in bulk at the Small Fruit and Vegetable IPM (SFVIPM) Lab at the University of Florida and brought to the field (approximately 1 h later). Eight traps were hung randomly throughout each subplot (32 total) by securing them 1 m from the ground inside the blackberry bush. Traps were serviced weekly for three (2014) and four (2015) weeks by replacing bait content with fresh bait and transporting samples back to the SFVIPM laboratory for male and female *D. suzukii* identification.

Fruit samples were collected weekly to evaluate fruit infestation by *D. suzukii* in 2015 only. Fruit samples were not taken in 2014 due to low fruit load on the grower's farm. Approximately 100–200 g of ripe blackberries was collected from four randomly selected sample locations in each subplot. Fruit was collected before the application of the border sprays the same morning, 7 to 10 days after the previous application. Fruit samples were weighed and placed in plastic rearing containers with mesh lids (Glad, Oakland, CA) and were kept in incubators maintained at 23°C, 16 : 8 light : dark cycle and ~65% relative humidity for 2 weeks to allow *D. suzukii* adults to emerge. Male and female *D. suzukii* were identified and reported as number of *D. suzukii* emerging per kg.

Natural enemies were assessed using yellow sticky cards (15.2 by 20.3 cm, Pherocon AM, Great Lakes IPM, Vestaburg, MI) in the final week of 2015 only. Cards were established in four randomly selected locations in each subplot and were attached to the blackberry plant 2 m from the ground using a twist tie. After 7 days in the field, the cards were transported back the laboratory where pests and natural enemies were identified.

Data analysis

Data for 2014 and 2015 experiments were analysed separately. Data were transformed when necessary to normalize the distribution and homogenize the variances. Transformed data were analysed using a twoway repeated-measures ANOVA with treatment, week and treatment*week as the fixed effects. Treatment differences were separated using Tukey's honestly significant differences (HSD) test. All analyses were performed using JMP Pro Software (ver. 11.1.1, SAS Institute 2013). Differences were considered significant when $P \leq 0.05$.

Results

In the 2014 study, treatment had a significant effect on the number of adult *D. suzukii* captured (F = 4.12; d.f. = 3, 83; P = 0.0089). However, the treatment interaction with week was not significant (F = 1.64; d.f. = 6, 83; P = 0.1465). Border spray treatments, with and without the addition of tillage, captured significantly fewer *D. suzukii* than the unsprayed, no till treatment (control, fig. 1). The addition of tillage did not have a significant effect on the number of *D. suzukii* captured. In 2014, there were more female flies captured in the control than all other treatments (F = 4.48; d.f. = 3, 83; P = 0.0058) but there were no differences in male captures (F = 0.39; d.f. = 3, 83; P = 0.759, table 1).

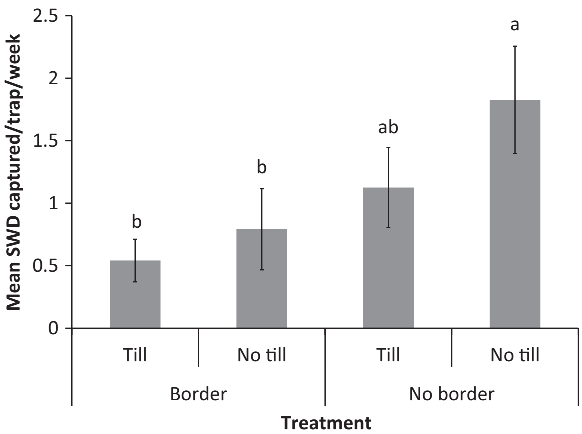

Fig. 1 The mean number of SWD captured by treatment in 2014. Bars with the same letters are not significantly different using Tukey's HSD ($P \leq 0.05$).

In 2015, treatment had an effect on the mean *D. suzukii* captured over time (F = 2.73; d.f. = 9, 112; P = 0.0065, fig. 2). The mean number of *D. suzukii* was significantly different among the treatments in week 1 (F = 4.23; d.f. = 3, 28; P = 0.0138), week 3 (F = 3.97; d.f. = 3, 28; P = 0.0178) and week 4 (F = 5.87; d.f. = 3, 28; P = 0.0031). The pattern of adult *D. suzukii* captures was similar for all 3 weeks as well as the results from the 2014 study. The mean number of *D. suzukii* in both border spray treatments was significantly lower than the unsprayed, no till treatment (control). As in 2014, the addition of tillage did not have a significant effect on the number of adult flies captured. In 2015, both female (F = 2.97; d.f. = 9, 112; P = 0.0033) and male (F = 2.09; d.f. = 9, 112; P = 0.0361) fly numbers also varied by week and treatment (table 1). The number of female flies was greater in the control than in all other treatments in week 4 (F = 6.59; d.f. = 9, 112; P = 0.0016). There were significantly more male flies captured in the control than in either of the border spray treatments in week 4 (F = 5.77; d.f. = 9, 112; P = 0.0033). The number of males in the tilled treatment without the border spray was not different than the other treatments.

In 2015, treatment had a significant effect on berry infestation by *D. suzukii* over time (F = 3.54; d.f. =

Table 1 Mean (±SE) female and male adult SWD captured in 2014 and 2015 blackberry studies

		2014	2015			
		Entire Study[†]	Week 1	Week 2	Week 3	Week 4
		Female	Female			
Border	Till	0.4 ± 0.1 b	0.0 ± 0.0	0.9 ± 0.3	0.0 ± 0.0	0.1 ± 0.1 b
	No Till	0.6 ± 0.3 b	0.0 ± 0.0	0.5 ± 0.2	0.3 ± 0.3	0.8 ± 0.3 b
No Border	Till	0.8 ± 0.3 ab	0.4 ± 0.2	0.3 ± 0.2	0.6 ± 0.3	0.8 ± 0.4 b
	No Till	1.5 ± 0.4 a	0.4 ± 0.2	0.4 ± 0.2	0.9 ± 0.4	3.6 ± 1.0 a
		Male	Male			
Border	Till	0.2 ± 0.1	0.1 ± 0.1	0.5 ± 0.4	0.0 ± 0.0	0.1 ± 0.1 b
	No Till	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0 b
No Border	Till	0.3 ± 0.1	0.3 ± 0.2	0.0 ± 0.0	0.5 ± 0.4	0.5 ± 0.3 ab
	No Till	0.3 ± 0.1	0.5 ± 0.3	0.1 ± 0.1	0.4 ± 0.2	3.4 ± 1.2 a

Values followed by different letters are significantly different across treatments within sex and year. Differences are considered significant when $P \leq 0.05$.

[†]Treatment*week interaction was not significant for female (F = 1.98; d.f. = 6, 83; P = 0.0773) or male SWD (F = 0.48; d.f. = 6, 83; P = 0.8248).

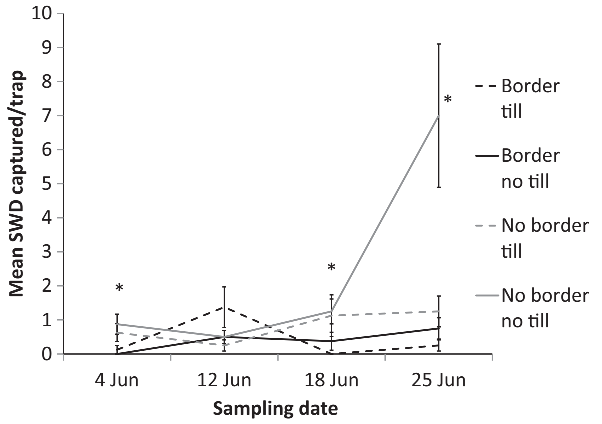

Fig. 2 The mean number of SWD captured per trap in 2015. Asterisk (*) indicates significant differences for that week (P ≤ 0.05).

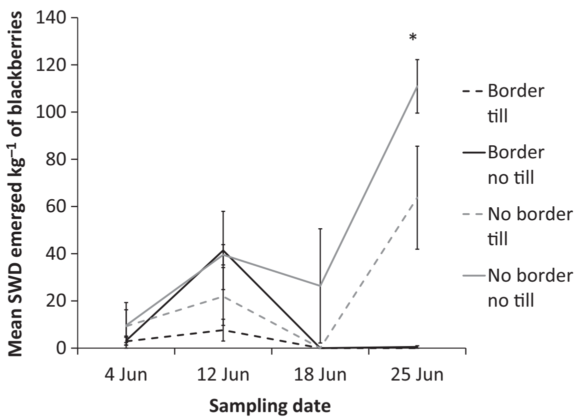

Fig. 3 The mean number of SWD emerged per kg in 2015. Asterisk (*) indicates significant differences for that week (P ≤ 0.05).

9, 47; P = 0.002, fig. 3). The mean number of emerged *D. suzukii* per kg of blackberries was significant among treatments in week 4 only (F = 71.90; d.f. = 3, 12; P < 0.0001). In week 4, both border spray treatments had significantly fewer *D. suzukii* emerge per kg than the unsprayed treatments.

Yellow sticky cards were evaluated for pests and natural enemies in 2015 only (table 2). Only 1 female *D. suzukii* was found in all treatments. More Thripidae and Aphidae were found in the tilled border treatments, but were not significant. There were significantly more Cicadellidae in the control than the tilled border treatment. A diverse array of parasitoid families was identified on the sticky card samples; the most common being Encyrtidae, Platygastridae and Aphelinidae. However, parasitoids did not differ by treatment.

Discussion

Our results confirmed our hypothesis and show that border sprays can be utilized to reduce populations of *D. suzukii* in organic blackberry fields. We found that border spray treatments, with and without the addition of soil tillage had fewer *D. suzukii* than plots without border sprays. Border sprays can be useful against pests that migrate from surrounding environments (Chouinard et al. 1992; Trimble and Solymar 1997; Blaauw et al. 2015);. Although we did not evaluate fly presence in surrounding areas or migration in this study, *D. suzukii* has been shown to utilize wild hosts in wooded areas surrounding blueberries, blackberries and raspberries (Lee et al. 2015b; Liburd et al. 2015; Briem et al. 2016) and as a result, can increase pressure on adjacent crops (Klick et al. 2016). Klick et al. (2016) found that *D. suzukii* captures were higher in raspberry fields that were adjacent to wild 'Himalaya' blackberry (*Rubus armeniacus* Focke) than fields that were not in close proximity. In unmanaged, semi-natural areas adjacent to cultivated blueberries, a decrease in *D. suzukii* adults coincided with an increase of adults in the blueberry fields (Liburd et al. 2015). Furthermore, *D. suzukii* was captured earlier in raspberry fields when adjacent to wooded areas containing wild host plants (Pelton et al. 2016).

As border sprays can target pests migrating from adjacent environments, timing of applications must be considered. Border sprays used for codling moths in apples are applied during periods when larvae are expected to be hatching in adjacent areas and adult flies are active as indicated by monitoring traps (Trimble and Vickers 2000). Applications of border sprays for control of plum curculio in apples are made during a several-week period when adults remain on the ground along the perimeter of the orchard before entering the orchard itself (Chouinard et al. 1992). Border sprays may be most effective for controlling *D. suzukii* when applied at the beginning of the season when flies are beginning to migrate into the field from adjacent areas. Early season border sprays can save effective reduced-risk insecticides with limited applications for later use such as at peak harvest when *D. suzukii* population pressure is highest and the need for insecticide application is the greatest. One of the challenges to border spray timing is that available monitoring tools using various food-based lures and cup-like traps differ in their ability to detect the first presence of *D. suzukii* in the field (Basoalto et al. 2013; Iglesias et al. 2014; Renkema et al. 2014; Burrack et al. 2015). Monitoring with current tools alone may not provide an accurate early warning of fly

Table 2 Mean (±SE) arthropods identified on yellow sticky card traps during final week of the 2015 blackberry study

		Border		No Border		
	Arthropod	Till	No Till	Till	No Till	F, P
Pests	SWD Female	0.0 ± 0.0	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	1.00, 0.436
	SWD Male	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
	SWD Total	0.0 ± 0.0	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	1.00, 0.436
	Z. indianus	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
	Other Drosophilidae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
	Cercopidae	0.5 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	3.00, 0.088
	Thripidae	38.0 ± 6.9	38.8 ± 14.3	19.0 ± 7.6	29.8 ± 12.1	0.60, 0.630
	Aleyrodidae	1.8 ± 0.3	0.8 ± 0.5	3.8 ± 1.3	3.0 ± 1.4	1.67, 0.242
	Aphidae	5.5 ± 1.8	4.0 ± 1.3	1.5 ± 0.6	0.8 ± 0.5	3.29, 0.072
	Elateridae	0.5 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	3.00, 0.088
	Cicadellidae	3.3 ± 1.7 b	4.5 ± 1.6 ab	8.3 ± 2.9 ab	13.8 ± 2.4 a	4.14, 0.042*
Natural Enemies	Anthocoridae (*Orius* spp.)	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.00, 0.436
	Aranae	1.3 ± 0.8	1.0 ± 1.0	0.5 ± 0.3	0.0 ± 0.0	0.65, 0.604
	Ceraphronidae	1.0 ± 0.4	0.3 ± 0.3	0.0 ± 0.0	0.3 ± 0.3	2.45, 0.130
	Signiphoridae	2.0 ± 0.4	0.3 ± 0.3	1.0 ± 0.6	0.3 ± 0.3	3.41, 0.066
	Encyrtidae	10.8 ± 3.2	26.3 ± 6.1	15.3 ± 5.1	13.0 ± 1.5	2.31, 0.145
	Platygastridae	15.3 ± 1.0	19.3 ± 4.2	10.5 ± 2.3	12.8 ± 4.0	1.66, 0.243
	Aphelinidae	0.5 ± 0.3	19.3 ± 11.0	1.5 ± 0.6	0.5 ± 0.5	2.74, 0.105
	Ichneumonidae	0.3 ± 0.3	0.3 ± 0.3	0.8 ± 0.8	1.0 ± 0.7	0.48, 0.705
	Trichogrammatidae	0.3 ± 0.3	0.5 ± 0.5	1.5 ± 1.2	0.5 ± 0.5	0.51, 0.683
	Mymaridae	2.0 ± 0.9	3.5 ± 1.3	3.3 ± 1.4	3.0 ± 1.7	0.65, 0.604
	Figitidae	0.8 ± 0.5	0.0 ± 0.0	0.3 ± 0.3	0.0 ± 0.0	2.25, 0.152
	Braconidae	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.0 ± 0.0	1.00, 0.436
	Perilampidae	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.0 ± 0.0	1.00, 0.436
	Diapriidae	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.5	0.0 ± 0.0	1.00, 0.436
	Unknown Parasitoids	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.5 ± 0.5	0.67, 0.590
	Total parasitoids	32.8 ± 3.5	69.5 ± 20.1	35.3 ± 8.1	31.8 ± 5.5	2.87, 0.096

Asterisk denotes significant differences ($P \leq 0.05$). Values followed by different letters are significantly different.

movement into the field. Temperature-dependent models are being developed for *D. suzukii* and can be useful for predicting when *D. suzukii* will appear (Wiman et al. 2014). Future studies investigating the use of border sprays should focus on how to better time border sprays to coincide with movement of the flies into and out of the fields.

An effective IPM programme must be sustainable, conserve natural enemies and exert little or no impact on non-target species. Some insecticides used for managing *D. suzukii* may have negative impacts on pollinators and natural enemies (Biondi et al. 2012; Barbosa et al. 2015). Border sprays serve as an insecticidal tactic that can reduce the negative impacts on beneficial insects while still providing some level of control for key pests (van Driesche et al. 1998; Klick et al. 2016). Results from our study showed that neither border sprays nor soil tillage affected the population of predators or parasitoids in the blackberry fields. Beneficial insects within the interior of the field could continue providing pollination services and natural control of other blackberry pests such as sap beetles (Nitidulidae), flower thrips (Thripidae) and scarab beetles (Scarabidae).

We chose the active ingredients pyrethrins and azadirachtin for the border spray, because this combination of compounds is labelled for organic use, has a short re-entry interval (12 h), no pre-harvest interval and can be used in rotation with other compounds for *D. suzukii* control such as spinosad (IRAC class 5). Pyrethrins (IRAC class 3A) are sodium channel modulators, a class of insecticides that have shown to be effective against *D. suzukii* in laboratory and field trials (Bruck et al. 2011; Van Timmeren and Isaacs 2013). However, most insecticides in class 3A are not approved for organic use. On their own, pyrethrins are commonly used in rotational programmes for *D. suzukii* in organic production, although with fair to good control in systems with high fly pressure (Bruck et al. 2011; Van Timmeren and Isaacs 2013). Azadirachtin (IRAC Class UN) is a botanical insecticide and a derivative of neem oil that acts as an antifeedant and insect growth regulator (Dayan et al. 2009). Neem oil has insecticidal effects on *D. suzukii* (Bruck et al.

2011; Erland et al. 2015) and has been associated with reduced lethal effects on natural enemies (Beloti et al. 2015; Gontijo et al. 2015; Nikolova et al. 2015). The combination of pyrethrins and azadirachtin can serve as an insecticide with multiple modes of action and has been shown to be effective at reducing both adult *D. suzukii* captures in the field and larval infestations in blackberries and blueberries (Iglesias and Liburd unpublished). Other approved organic insecticides could also be used in a border spray application.

Collecting and disposing of fallen fruit can be labour intensive, even for small operations. In both of our studies, tilling the aisles between the rows of blackberries to bury fallen fruit, with or without the border spray, did not have a significant effect on adult captures or larval infestation. However, data from both years of our study showed a similar pattern among the treatments. It is possible that the effect of soil tillage is minimal and was not captured in this study. Burying infested fruit in the laboratory has been effective at reducing the emergence of *D. suzukii* adults by 70–100% when buried 5–10 cm below the ground (Rodriguez-Saona and Abraham unpublished). This shallow tillage depth can be reached by standard tillers owned by most farmers. However, whether fallen fruit is fully buried using these tillage practices is unknown and should be further investigated. It is also unknown whether fallen fruit reaches the aisles or remains under the bush, where tilling is impossible.

Overall our study confirms that border sprays can be an effective method of control for *D. suzukii*. In addition, border sprays have the potential to reduce the amount of insecticide sprayed on the field, insecticide effects on natural enemies and overall cost of management. Soil tillage may be a possible method for reducing emerging *D. suzukii* populations from infested fruit in the field; however, further investigation as to its effect is needed. Border sprays should be incorporated into an IPM programme for managing *D. suzukii* populations. New questions arise that need further research, including whether border sprays are as effective in high-pressure systems and how to maximize the effect of border sprays with application timing based on *D. suzukii* movement. Furthermore, quantifying fruit fall and burial would help to elucidate the economic benefits of soil tillage vs. current grower practices of fruit removal.

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