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Research

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Interpreting Temporal and Spatial Variation in Spotted-Wing Drosophila (Diptera: Drosophilidae) Trap Captures in Highbush Blueberries

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Abstract

Integrated pest management (IPM) programs for the spotted-wing drosophila *Drosophila suzukii* (Diptera: Drosophilidae) rely on insecticide applications to reduce adult populations and prevent fruit infestation. Although monitoring traps are used for early *D. suzukii* adult detection to time the start of insecticide applications, it remains unclear whether trap counts can be used to determine the efficacy of these programs and predict the risk of fruit infestation. To address this, a 2-yr study (2016–2017) was conducted in highbush blueberries in New Jersey (USA) to interpret *D. suzukii* trap count variation in relation to the frequency of insecticide applications and proximity to forest habitats. We also correlated trap counts with fruit infestation and used traps to determine the maximum dispersive distance traveled by *D. suzukii* adults within blueberry fields by using mark-release-capture studies. Using a trapping network across nine farms, we demonstrated that insecticide applications reduce *D. suzukii* trap counts, but this varied according to seasonality, and that traps placed closer to forest habitats within farms had higher fly counts than those placed in farm interiors. Moreover, blueberry fields that had zero fruit infestation also had predictably lower trap counts than fields with infested fruit, and the maximum dispersive distance for *D. suzukii* within blueberry fields was 90 m. In summary, while *D. suzukii* trap counts in blueberry farms could predict the frequency of insecticide applications and fruit infestation, the predictive power of our trap data was too variable across the blueberry harvest period to make it a reliable tool.

Key words: monitoring, insecticide use, fruit infestation, mark-release-recapture, maximum dispersal

Integrated pest management (IPM) programs rely on the development of effective monitoring tools to reduce unnecessary pesticide applications (Van den Bosch and Stern 1962). Monitoring methods are used to prevent pests from reaching damaging thresholds in crops that could otherwise result in economic losses to farmers (Stern 1973, Pedigo et al. 1986). However, existing IPM programs are constantly being challenged by invasive pests since they are usually not considered major pests in their country of origin and as a result often arrive to new areas without reliable monitoring protocols (e.g., Ragsdale et al. 2011, Weber et al. 2017). A lack of monitoring techniques can be problematic for highly mobile, generalist invasive pests that use and become abundant in a wide variety of hosts, including noncrop hosts, and that could, thus, become unpredictable in space and time (Mazzi and Dorn 2012), resulting in more intense agrochemical use.

The spotted-wing drosophila *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) is a vinegar fly native to Southeast Asia that was first detected in the continental United States in California in 2008 (Hauser 2011). Since then, *D. suzukii* has spread rapidly throughout the world and is now present in most of the United States (Walsh et al. 2011) as well as in Canada, Mexico, South America, and many countries across Europe (Arriaga 2011, Burrack et al. 2012, Cini et al. 2012, Deprá et al. 2014). Unlike most of its drosophilid relatives who are only capable of oviposition on overripe and rotting fruit, *D. suzukii* females are equipped with a large serrated ovipositor, which enables them to use healthy and ripening fruit (Atallah et al. 2014). *Drosophila suzukii* attacks a large variety of crops, including blueberries, raspberries, blackberries, cherries, and strawberries, but is also able to use many wild hosts, including dogwood, pokeweed, crab apple, and wild rose (Walsh et al. 2011, Lee et al. 2015). As a result, *D. suzukii* has become a major pest of the small fruit industry, causing major revenue losses. For example, researchers in the Pacific production areas (California, Washington, and Oregon) of the United States estimated potential crop losses of over $500 million annually (Bolda et al. 2010). In the Trento province (Northern Italy), losses to small fruit crops were estimated at €500,000 and €3 million in 2010 and 2011, respectively (Cini et al. 2012). These values do not take into account increases in monitoring, sanitation, insecticide, insecticide application, and other production costs that can be significant (De Ros et al. 2015).

Although progress is being made in other aspects of IPM (e.g., Cloonan et al. 2018, Lee et al. 2019), current recommendations to manage *D. suzukii* rely heavily on preventive weekly applications of broad-spectrum insecticides, including organophosphates, carbamates, and pyrethroids, in rotation (Beers et al. 2011, Van Timmeren and Isaacs 2013). These insecticide applications usually begin as soon as the fruit ripens and becomes susceptible, and continues throughout the fruiting period. Because a single infested fruit can cause the rejection of an entire shipment, there is a zero-tolerance threshold for *D. suzukii* larvae in fresh market fruit or frozen products (Aly et al. 2017). Thus, early detection of adult activity in crops is critical to reduce fruit infestation risks. Monitoring traps can be used to detect early fly activity and time the start of insecticide applications. Several trap designs (Lee et al. 2012, Basoalto et al. 2013, Kirkpatrick et al. 2018a) and bait formulations (Cha et al. 2012, Landolt et al. 2012, Burrack et al. 2015, Cloonan et al. 2019) have been tested to capture *D. suzukii* adults. In New Jersey (USA) highbush blueberries (*Vaccinium corymbosum* L.), initiation of spray programs begins across the state as soon as *D. suzukii* become present in monitoring traps (Michel et al. 2015). However, the possibility of using trap counts to evaluate the effectiveness of *D. suzukii* management programs and for predicting fruit infestation in highbush blueberries and other crops has thus far remained an open question.

In several small fruit crops, *D. suzukii* adults disperse into fields from bordering noncrop habitats (Klick et al. 2016a, Pelton et al. 2016, Ballman and Drummond 2017, Leach et al. 2019). This is also the case in highbush blueberries in New Jersey, where *D. suzukii* uses nearby forest habitats, likely as refugia and overwintering sites, and exploits wild blueberries in the understory (Urbaneja-Bernat et al. 2020). Their ability to overwinter in wooded areas suggests that they may move into fields from those locations early in the season (Ballman and Drummond 2017, Leach et al. 2019). As a result, fields that border wooded areas may be more at risk for *D. suzukii* occurrence and would be targets for early insecticide sprays (Klick et al. 2016b). Thus, understanding the role of noncrop habitats on *D. suzukii* trap counts and the maximum distance traveled by flies within crops may help optimize current trapping methods to better time insecticide applications and identify where treatments are most needed (i.e., border sprays; Klick et al. 2016b) in agroecosystems.

In the present 2-yr study (2016–2017), in the highbush blueberry agroecosystem in southern New Jersey, we investigated how *D. suzukii* adult trap counts are influenced by the intensity of insecticide inputs throughout the fruiting season and their placement relative to noncrop habitats. We also correlated trap counts with fruit infestation and used traps to determine the maximum distance traveled by *D. suzukii* adults within blueberry fields by using mark-release-recapture studies. Specifically, we asked the following questions: 1) Does the frequency of insecticide sprays reduce *D. suzukii* trap counts and, if so, when (based on seasonality)? 2) Does proximity to forest edges increase *D. suzukii* trap counts? 3) Are trap counts correlated with fruit infestation? 4) What is the range of attraction of the traps? Addressing these four interlinked questions is essential to improve our interpretation and for the optimization of current *D. suzukii* trapping methods.

Materials and Methods

Drosophila suzukii Colony

The *D. suzukii* colony used in this study was maintained at the Rutgers P.E. Marucci Center (Chatsworth, NJ) by methods used by Rodriguez-Saona et al. (2019). The colony was initiated in 2013 from adults emerging from infested fruit collected from commercial blueberry farms located in Atlantic Co., NJ, it was maintained on an artificial Drosophila diet modified from Jaramillo et al. (2015), and held in a growth chamber (Percival Scientific, Perry, IA) at 25°C, 55% relative humidity, and a photoperiod of 16:8 (L:D) h. Field-collected flies were added to the colony annually to maintain genetic diversity. Flies used in the mark-release-recapture experiments were 3–6 d old.

Study Sites

Our trapping experiments were conducted in 2016–2017 in nine conventional practice commercial highbush blueberry (*V. corymbosum*) farms located in the Pinelands region of southern New Jersey (Fig. 1). Highbush blueberry is a native perennial deciduous shrub that is grown commercially in this region and is harvested from early June through mid-August. Eight of the farms were sampled in 2016 (farms 1–8; Fig. 1) and six were sampled in 2017 (five used in 2016 + farm 9). These farms were located in Burlington and Atlantic counties (six farms in Atlantic Co. and three farms in Burlington Co.), covering a total of 538 ha of blueberry plantings (~7% of the total blueberry-producing area in the state; Supp Table 1 [online only]). Farms were selected to include a representative range of farm sizes, locations, and management practices within the state. Individual farm size varied from 6.2 to 256.1 ha (mean ± SE = 59.8 ± 24.5 ha; Supp Table 1 [online only]). All farms contained the two major blueberry varieties grown in New Jersey and in the Northeastern United States (Gallardo et al. 2018), namely 'Duke,' an early-season variety, and 'Bluecrop,' a midseason variety. In New Jersey, 'Duke' is harvested from early June through mid-July, whereas 'Bluecrop' is harvested from mid-June through the end of July. All farmers followed standard local pest management practices, and insecticide records were collected after each growing season from all farms. Only insecticides applied during fruit maturation to target fruit-feeding insects like *D. suzukii* were used in data analyses, and the records were used to calculate the number of insecticides applied for each field throughout the season in the sampled farms.

The mark-release-recapture studies were conducted in two highbush blueberry farms. In 2016, the study was conducted in four field-blocks in a farm (Farm A) located in Burlington Co., NJ (39°49′41.10″N, 74°27′15.11″W). In 2017, the study was conducted in one field-block in a farm (Farm B) located in Atlantic Co., NJ (39°38′9.42″N, 74°44′8.80″W). All five field-blocks were ~1 ha, and no insecticides were sprayed in these sites for the duration of the studies. Marked *D. suzukii* were released either before harvest (June 2016) or after harvest (October 2017) to: 1) avoid releasing flies when susceptible fruit was present and, thus, maximize fly

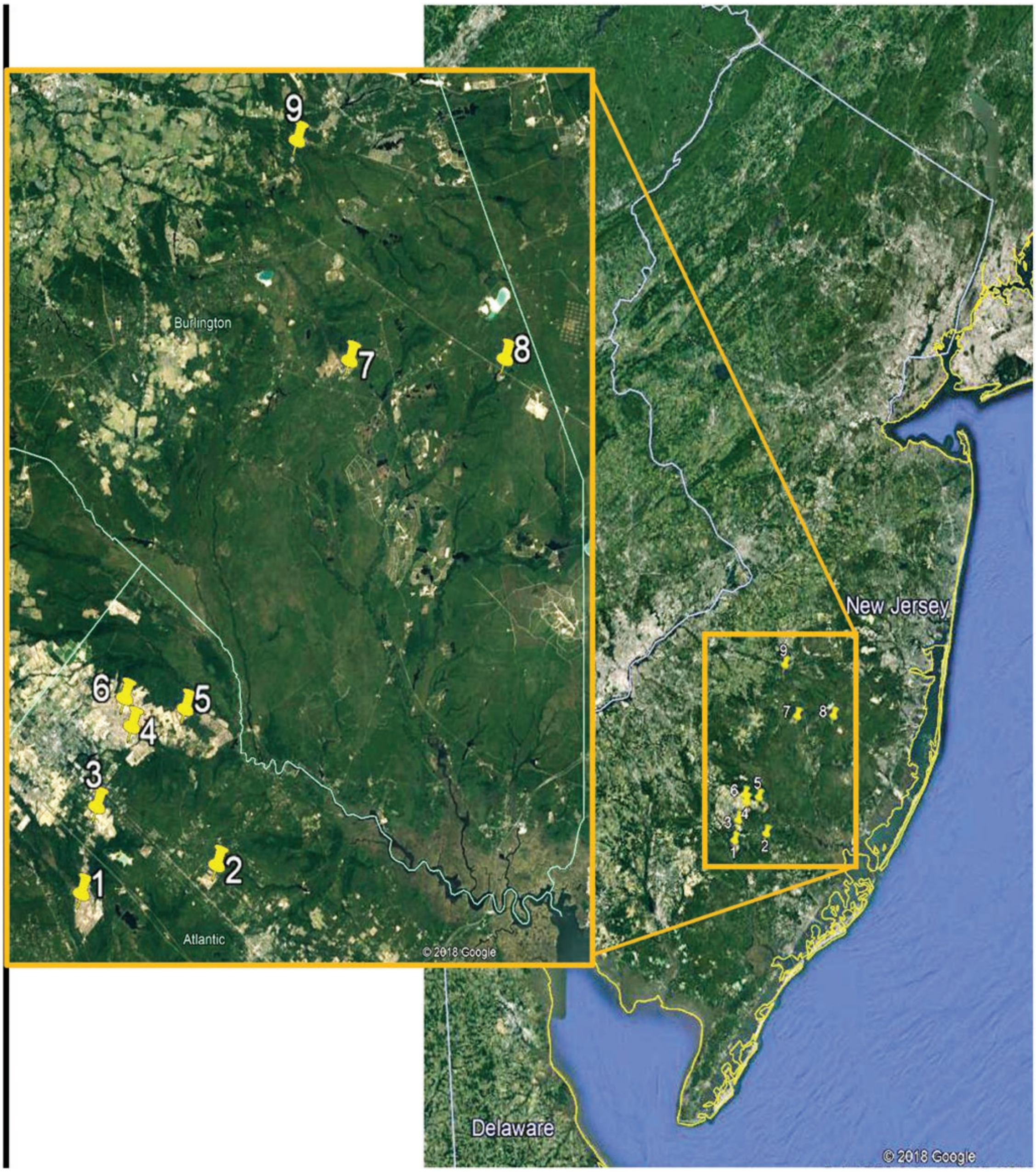

Fig. 1. Location of the nine commercial highbush blueberry farms (yellow pushpins) in southern New Jersey (USA) monitored for *Drosophila suzukii* adults in traps (2016–2017) and fruit infestation (2017). Left panel shows with more detail the locations of each of the farms. See Supp Table 1 (online only) for details on farm size and geographic coordinates. Six farms are located in Atlantic County (Farms 1–6), and the other three are located in Burlington County (Farms 7–9).

movement within the fields; and 2) prevent exposure of marked flies to insecticides applied by growers.

Trapping Network

We established a trapping network across the nine farms to determine whether *D. suzukii* trap counts are influenced by the intensity of insecticide inputs and their placement relative to noncrop habitats. The study was done in all 'Duke' and 'Bluecrop' fields in these farms. In total, 147 and 118 traps were placed across all farms in 2016 and 2017, respectively (Supp Table 1 [online only]). Traps within farms were placed at a density of 1–2 per field (1–4 per ha, Supp Table 1 [online only]), depending on the size of the field, with more traps in bigger fields. To account for farm size, about a third of the traps were placed along the farm borders facing wooded habitats or other nonblueberry crop ecosystems (i.e., within 200 m from field edges), while the rest were placed in the farm interior (Rodriguez-Saona et al. 2018). This ensured that farms with longer peripheral borders (especially smaller farms) had higher edge-to-interior ratio of traps.

Traps were made using 946-ml clear deli-cups (Michel et al. 2015), baited with a commercial *D. suzukii* lure (Spotted Wing Drosophila Lure, Product no. L962, Scentry Biologicals Inc., Billings, MO), and monitored weekly for ~12 wk from the first week in June through the end of August of each year. Ten holes were placed around the upper portion of the cup, evenly spaced two-thirds of the way around the cup leaving a gap through which the trap contents could be poured out. Plastic-coated paperclips were used to hang the lures above a drowning solution. The drowning solution consisted of water with unscented soap (4 ml of soap per gallon of water). Traps were hung directly on the blueberry bushes in the bottom third of the canopy (~1–1.5 m above ground). Lures were replaced every 4 wk, as recommended by the company. The number of *D. suzukii* adults (males and females) captured in traps was counted under a stereomicroscope (Nikon SMZ-U, Tokyo, Japan). Subsampling was used in 2017 samples for traps with >500 flies; one-fourth of the samples were processed by volume, and absolute numbers were estimated. The location of traps was mapped using a Trimble hand-held GPS device and digitally marked as point source data with appropriate geographic coordinates (GPS Pathfinder Office 3.10; Trimble Navigation Ltd). High-resolution orthophoto imagery for all farms and surrounding areas were downloaded from the New Jersey Department of Environmental Protection Land Use/Land Cover information (http://www.nj.gov/dep/gis/lulc07shp.html). These data were used to calculate the distance from each trap to the nearest forest patch.

Fruit Sampling

To determine whether *D. suzukii* trap counts correlate with fruit infestation, fruit samples were taken from both 'Duke' and 'Bluecrop' varieties during the 8-wk harvest period (5 June–28 July of 2017; with samples covering a total of 6 wk for each variety: 'Duke' from 5 June to 14 July; 'Bluecrop' from 19 June to 28 July). Fruit samples were collected from the same fields where *D. suzukii* traps were placed and were >2 m away from traps. Two samples were taken from 40 fields of each variety across all farms, for a total of 960 samples (80 fields × 6 wk × 2 samples). Each sample was ~230 g (8 ounces) of fruit, taken randomly from multiple bushes near the trap area and from all areas of the bush (top, middle, and bottom). Fruit samples were placed in labeled (farm, field, date, and sample number) plastic bags and incubated at room temperature for 10 d to ensure that any eggs present in the fruit would develop into larvae that could easily be counted using the salt float method to extract the larvae from fruit (Shaw et al. 2019). Fruit samples were submerged in ~600 ml of a salt/water solution (1 cup of salt per gallon of warm water) for 24 h to extract any larvae present and then the larvae were collected by filtering through a fine mesh screen. The number of *D. suzukii* larvae in each sample was then counted under a stereomicroscope.

Mark-Release-Recapture Study

In 2016 and 2017, studies were conducted to assess the maximum dispersive distance of *D. suzukii* flies in highbush blueberries. The methods followed those similar to Kirkpatrick et al. (2018b). On the morning of each release date, colony-reared flies were lightly anesthetized with CO_2 to facilitate handling and counting. Glass powder blowers (model 119; DeVilbiss Healthcare, Port Washington, NY) were used to apply fluorescent dusts (DayGLO Color Corporation, Cleveland, OH) to the flies before release. This method has successfully been used for marking *D. suzukii* in previous mark-release-recapture studies without any effects on fly movement (Rice et al. 2017, Kirkpatrick et al. 2018b, Drummond et al. 2019a). Flies (approximately 1:1 male:female) for each release distance were marked with a different color of fluorescent dust, with the same color used for the same distance in each field-block (replicate). The five colors used were Horizon Blue (A-19), Signal Green (A-18-N), Aurora Pink (A-11), Blaze Orange (A-15-N), and Saturn Yellow (A-17-N). A different powder blower was used for each color of fluorescent dust. To mark the flies, fluorescent dusts were lightly puffed to groups of 10 or 20 anesthetized flies placed into standard 50-ml polystyrene Drosophila vials (Genesee Scientific, San Diego, CA). Marked flies were held in the vials for up to 8 h in the laboratory before they were released in fields, and their status checked prior to release to ensure they were healthy.

At Farm A (2016), release points were flagged in the four cardinal directions from the central monitoring trap at 10, 20, 30, 40, and 50 m, for a total of four replicates (one replicate in each field-block). A replicate was done on 17 June, another on 21 June, and two on 24 June. At Farm B (2017), methods were the same as in 2016, but release points were at 15, 30, 45, and 60 m from the central trap for one replicate (on 31 October). In 2016, for each replicate, the number of marked flies released at each point was 100, for a total of 400 flies released at each distance. In 2017, the number of marked flies released at each point was 100, 150, 220, and 300 from the closest to the farthest distance, for a total of 400, 600, 880, and 1,200 flies released at each distance. We adjusted the numbers of marked flies released at each distance in 2017 so that more flies were released at the greater than nearer distances to ensure captures at most of the distances. For all replicates, flies were released from 4:00 to 6:00 p.m. To release flies, the vials were placed on the ground and their tops opened, allowing flies to fly out on their own. In total, 8,000 and 3,080 marked *D. suzukii* flies were released in 2016 and 2017, respectively.

In each field, a single 14 × 23-cm double-sided, sticky, red panel trap (Great Lakes IPM, Vestaburg, MI) baited with a *D. suzukii* Scentry lure (Kirkpatrick et al. 2018a) was placed in the bottom third of the canopy of a bush at the center of the field. A 0.5-cm hole in each corner of a panel enabled it to be hung from a branch with twist ties, and a similar hole in the center of the trap allowed the lure to be attached with a twist tie. Traps were checked daily for a total of 7 d, and the sticky panels with any captured flies were replaced. Panels with captures were examined in the laboratory under a 45.7-cm 15 W Fluorescent Tube (Black Light; Amscan Inc., Toronto, Canada) to determine the color of the powder marks. The lure was not replaced during the 1-wk duration of the experiment and new lures were used in 2016 and 2017.

Data Analyses

For the trapping data, the number of *D. suzukii* flies was averaged to obtain the mean weekly number of flies per trap per field. These data were then divided into four 'seasons,' according to *D. suzukii* population size and insecticide inputs (see Results), with each season lasting about 2–4 wk. Three of these seasons covered the ~2 mo harvest period, namely 'early' (June 01–June 18; when only 'Duke' was fruiting), 'mid' (June 19–July 11; when both 'Duke' and 'Bluecrop' were fruiting), and 'late' (July 12–July 25; when only 'Bluecrop' was fruiting), with relatively low, medium, and high population sizes, respectively. In addition, we trapped flies after harvest: 'post' (July 26–August 31). Prior to analyses, male and female *D. suzukii* trap catches were totaled because previous studies showed no differences between sexes in their response to the Scentry lure (Kirkpatrick et al. 2017), and data were checked for normality and equal variances.

We used generalized linear models to determine the effect of number of insecticide applications on the number of *D. suzukii* captures in traps. The full (three-way) model included the following independent variables: 'sprays' (number of insecticide applications), 'season' (early, mid, late, and post), 'farm,' and the two- and three-way interactions among them. Data were log(x+1)-transformed to fit model requirements. Tukey HSD tests were conducted to determine mean differences across sprays and seasons. In addition, we performed Kruskal–Wallis chi-squared tests to assess for differences in insecticide applications across seasons. Data were analyzed separately for each year.

Generalized linear models were also used to determine the effect of trap location (distance from the forest) on the number of *D. suzukii* captures in traps for each of the years. The full (three-way) model included the independent variables: 'location' ('edge' versus 'interior'), season (early, mid, late, and post), farm, and the two- and three-way interactions among them. We considered an edge trap if it was located ≤200 m from a forest habitat (this distance was used conservatively based on previous studies indicating that the maximum distance *D. suzukii* flies can travel is ca. 90–120 m; Kirkpatrick et al. 2018b, Drummond et al. 2019a), whereas traps located >200 m from the forest were considered interior. Welch two-sample *t*-tests were used to separate edge versus interior means across seasons. Data were analyzed separately for each year.

Two analyses were done to determine whether *D. suzukii* trap counts correlate with fruit infestation. First, we performed a logistic regression with trap counts as a predictor of infestation. Infestation was used as a binomial variable with values of 0 or 1 representing the absence or presence of larvae in fruit, respectively. This is because there is a zero-tolerance threshold for larva-infested fruit in the fresh market (Aly et al. 2017) and, thus, the presence of larvae rather than their absolute number guide management decisions. Second, we compared trap counts of fields with fruit infestation (values = 1) versus those without infestation (0) by using Welch two-sample *t*-tests. This latter analysis was conducted only for the mid and late seasons because the numbers of infested fruit during early-season and postharvest were too low.

For the mark-release-recapture study, the daily number of marked *D. suzukii* flies captured on traps was summed to obtain a weekly total; this total number was then divided by the number of released flies to calculate the proportion of *D. suzukii* recaptured for each distance. These data were combined for both years to graph the two following plots according to Kirkpatrick et al. (2018b): 1) an untransformed plot of the proportion of *D. suzukii* recaptured versus distance of release from the central trap (this untransformed plot shows whether the release distances are appropriately spaced and whether the line fitted to the graph is smoothly concave and approaches the x-axis asymptotically) (Miller et al. 2015) and 2) the proportion of *D. suzukii* recaptured × annulus area versus distance of release from the central trap (Miller plot). A second-order polynomial curve was fitted to the Miller plot data; the point at which this curve crosses the x-axis estimates the maximum dispersive distance for 95% of the responding population (Adams et al. 2017, Kirkpatrick et al. 2018b). Preliminary analysis showed no differences between years in our estimate of maximum dispersive distance, so data from both years were pooled to create the final plots.

All analyses were performed in R software version 3.4.3 (R Development Core Team 2017) using the packages 'lubridate,' 'ggplot2,' 'dplyr,' and 'WVPlots.'

Results

Does the Frequency of Insecticide Sprays Reduce *D. suzukii* Trap Counts?

In both years (2016–2017), *D. suzukii* trap captures were significantly reduced by the number of insecticide applications in blueberry farms (Figs. 2 and 3; Table 1). As few as one insecticide spray per season was sufficient to reduce trap counts in some instances (i.e., mid and late seasons in 2016), and 2–4 insecticide applications reduced trap counts in mid season (both years) and late season (2016). However, in no circumstance did increasing numbers of sprays from 2 to 4 per season affect trap counts. As expected, time of the year

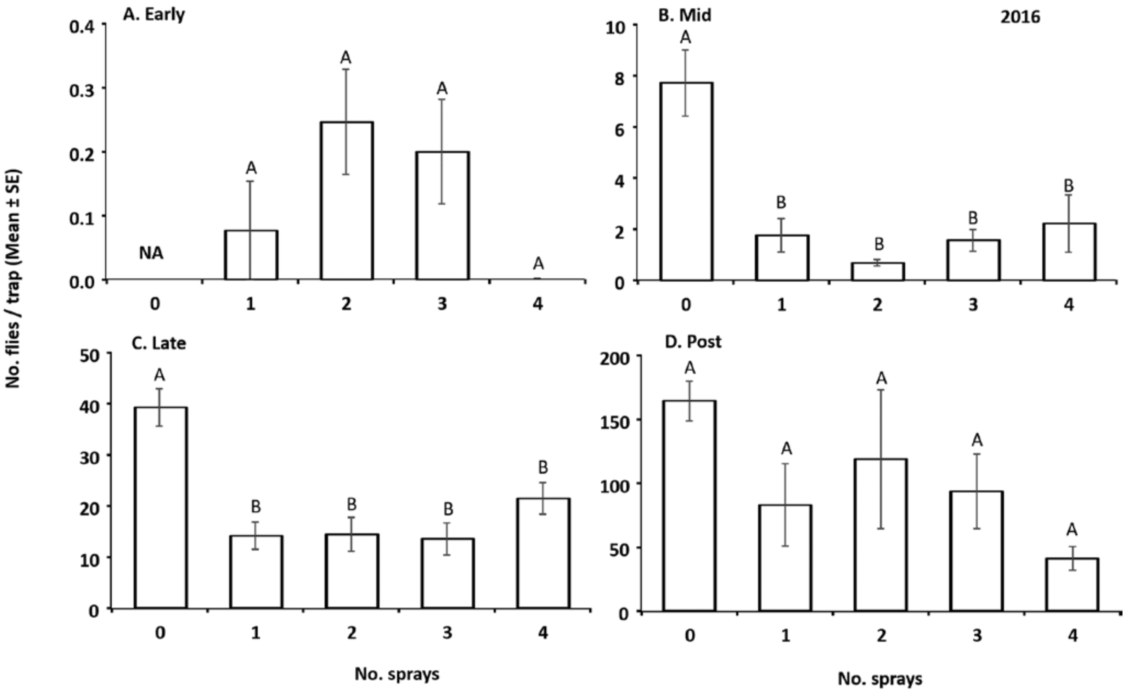

Fig. 2. Effects of the frequency of insecticide applications on the mean (± SE) weekly number of *Drosophila suzukii* adults captured per trap in highbush blueberry farms in 2016. Data were analyzed separately for each season: (A) early (June 01–June 21), (B) mid (June 21–July 12), (C) late (July 13–August 03), and (D) post (August 03–August 24). Different letters indicate significant differences in the number of fly captures among insecticide regimes (α = 0.05; Tukey HSD tests). NA (not available) = no trap captures.

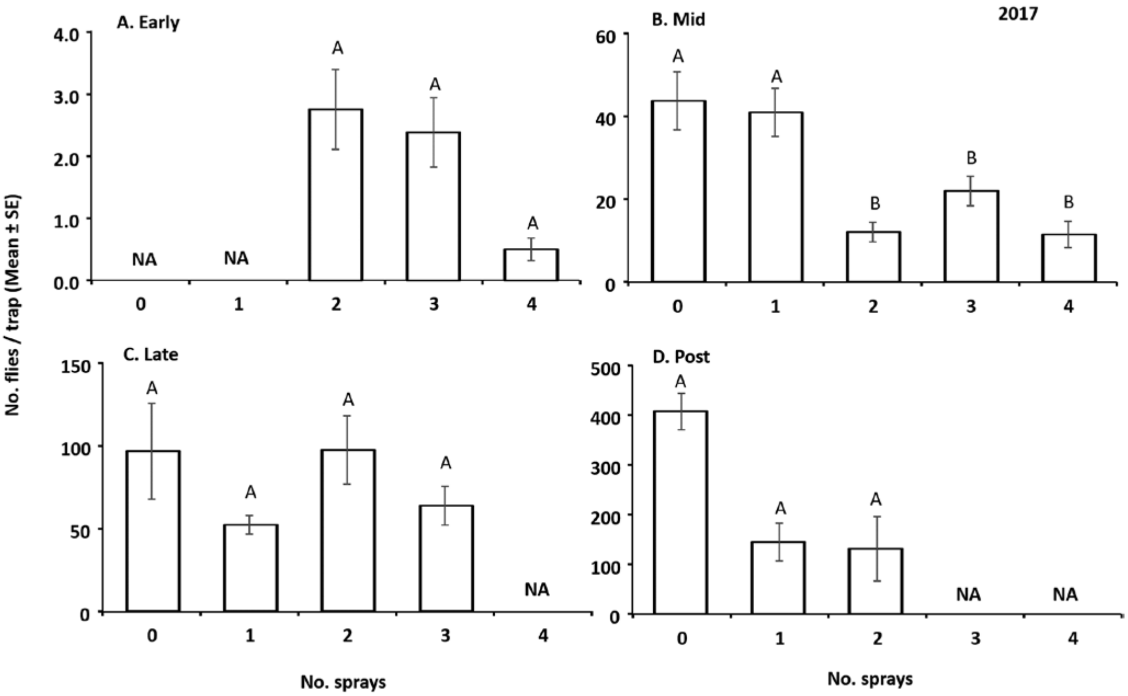

Fig. 3. Effects of the frequency of insecticide applications on the mean (± SE) weekly number of *Drosophila suzukii* adults captured per trap in highbush blueberry farms in 2017. Data were analyzed separately for each season: (A) early (June 01–June 21), (B) mid (June 21–July 12), (C) late (July 13–August 03), and (D) post (August 03–August 24). Different letters indicate significant differences in the number of fly captures among insecticide regimes ($\alpha = 0.05$; Tukey HSD tests). NA (not available) = no trap captures.

Table 1. Results from generalized linear models determine the effect of the frequency of insecticide applications on the number of *Drosophila suzukii* captures in traps in 2016 and 2017

Year	Factors[a]	df	*F*	*P*-value
2016	Sprays	4	21.03	**<0.001**
	Season	3	17.03	**<0.001**
	Farm	7	1.95	0.059
	Sprays × season	11	0.43	0.941
	Sprays × farm	21	1.24	0.213
	Season × farm	20	0.15	1.000
	Sprays × season × farm	22	0.09	1.000
	Residuals	892		
2017	Sprays	4	37.49	**<0.001**
	Season	3	18.38	**<0.001**
	Farm	5	6.74	**<0.001**
	Sprays × season	9	1.97	**0.040**
	Sprays × farm	11	4.12	**<0.001**
	Season × farm	12	0.20	0.998
	Sprays × season × farm	5	0.05	0.998
	Residuals	790		

[a] Sprays = number of insecticide applications; season = time of year (early, mid, late, and post).

(season) also influenced *D. suzukii* trap counts (Table 1), with more flies captured as the growing season progressed (Figs. 2 and 3). In 2017, there was a significant sprays-by-season interaction (Table 1), indicating that the effect of the number of insecticide applications on trap counts varied by seasonality. Two or more insecticide applications significantly reduced trap counts in mid season but not in any other seasons in 2017 (Fig. 3). In both years, more insecticides were applied in the early and mid seasons than in the late and post seasons across all farms (2016: Kruskal–Wallis χ^2 test = 104.92, df = 3, $P < 0.001$; 2017: Kruskal–Wallis χ^2 test = 111.25, df = 3, $P < 0.001$; Supp Fig. 1 [online only]).

Does Proximity to Forest Edges Increase *D. suzukii* Trap Counts?

In both years, the location of traps relative to forest habitats significantly influenced *D. suzukii* trap counts, with ~45% more flies caught in traps near forest habitats than those placed in the interior of farms (Fig. 4; Table 2).

Are Trap Counts Correlated With Fruit Infestation?

Our first analysis indicated that *D. suzukii* trap count data were strongly correlated with fruit infestation (Fig. 5). The model was able to predict fruit infestation based on trap counts with 86.4% accuracy across all seasons. However, the high accuracy of this model was likely driven by the fact that most fruit samples had zero infestation. For this reason, we conducted a second analysis that compared the number of trap counts in fields with and without infested fruit during the mid and late seasons. During the mid-season, traps in noninfested fields had 65.6% lower fly captures than traps in infested fields ($t = -3.8$, df = 29.8, $P < 0.001$); although significant ($t = -1.84$, df = 91.89, $P = 0.034$), this difference was only 24.6% in the late season (Fig. 6), indicating that trap counts are 2.7 times better predictors of fruit infestation early in the season when the *D. suzukii* population size is low.

What Is the Range of Attraction of Traps?

An average of ~3% of the released flies were recaptured across all five replicates. The untransformed plot shows that *D. suzukii* fly captures decreased with increasing distance from the central trap and

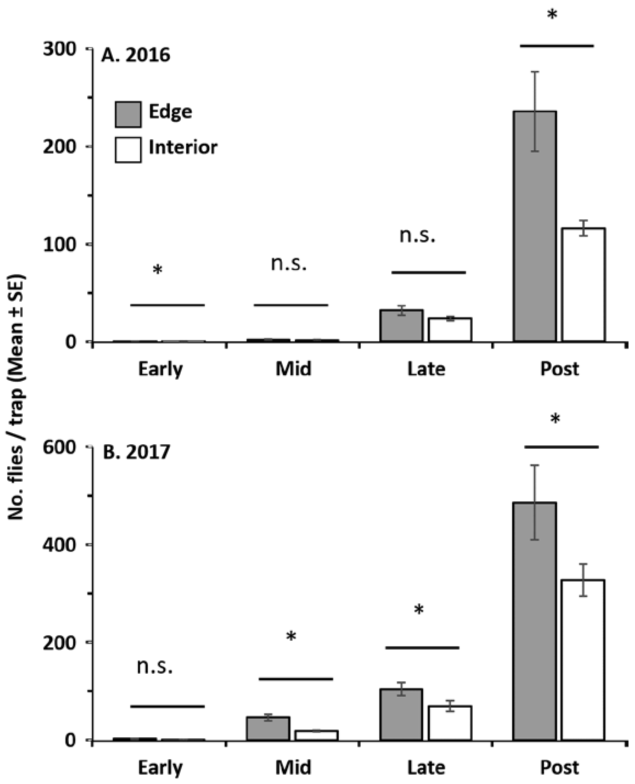

Fig. 4. Effect of trap location relative to a forest habitat (edge vs interior) on the mean (± SE) weekly number of *Drosophila suzukii* captures in traps in 2016 (A) and 2017 (B). Seasons were divided into early (June 01–June 21), mid (June 21–July 12), late (July 13–August 03), and post (August 03–August 24). An asterisk indicates significant differences in the number of fly captures between locations for each season; n.s. = not significant ($\alpha = 0.05$; Welch two-sample *t*-tests).

approached the x-axis asymptotically (Fig. 7A). The percentage of flies caught at the closest distance of 10 m from the central trap was 5.7%, whereas the percent caught decreased to 0.7% at a farthest distance of 60 m. On average, *D. suzukii* flies traveled 28.8 m ± 0.8 (mean ± SE) per day. Based on the Miller plot, the maximum dispersive distance for 95% of the *D. suzukii* population was estimated at ~90 m (Fig. 7B).

Discussion

Current IPM programs for *D. suzukii* rely on effective insecticide applications to reduce adult populations and prevent fruit infestation; however, it remains unclear whether trap counts can be used to predict the efficacy of these programs and associated risks of infestation. Here, we demonstrated that 1) insecticide applications in highbush blueberries reduced *D. suzukii* trap counts, but this depended on time of the year (i.e., seasonality); 2) trap location matters—traps placed near noncrop forest habitats within farms had higher fly counts than those placed in farm interiors; 3) fields with zero fruit infestation had predictably lower trap counts than those with infested fruit; and 4) the maximum net dispersive distance for *D. suzukii* within highbush blueberry fields was estimated at 90 m.

In New Jersey as well as in other U.S. states, traps for *D. suzukii* are used mostly to determine the initiation of fly activity, i.e., as an early warning to begin chemical control measures (Michel et al. 2015, Cloonan et al. 2018, Kirkpatrick et al. 2018a), which raises questions on the value of subsequent trap counts. For instance, a study in highbush blueberries found no differences in *D. suzukii* trap captures between conventional and organic management practices (Van Timmeren and Isaacs 2013). Similarly, management practices (organic and conventional) did not directly affect trap captures of flies in lowbush (wild) blueberries (*Vaccinium angustifolium* Aiton) (Drummond et al. 2019b), but the authors found that the frequency of insecticide applications did have an effect. In this study, we showed that *D. suzukii* trap counts are consistently reduced by the frequency of insecticide applications during the middle of the harvest period (mid-season) of highbush blueberries, which may provide growers guidance on the effectiveness of their management programs. The amount of insecticide used across all farms during this period was one of the highest of the entire harvest period in both years, only comparable to that of the early season. These results suggest that trap counts can serve as indicators of effective management programs mainly when those programs use insecticides heavily. Although insecticide applications were also high during the early season, the number of flies caught on traps was very low in all fields (<5 flies per trap), including those that were unsprayed. In the late season, the results were variable between years—insecticide applications reduced the numbers of flies per traps in 2016 but not in 2017. A key difference between these years was *D. suzukii* abundance—fly numbers were higher in 2017 than in 2016. Thus, whether trap counts can provide information about the effectiveness of management programs varies depending on *D. suzukii* fly density. According to our results, when fly counts reach numbers above 50 per trap, the data become too variable and inaccurate to make any predictions based on the intensity of management programs. Another important finding was that trap counts were not affected, for the most part, by increasing numbers of insecticide applications. This was surprising, as we expected the numbers of flies in traps to decrease with an increasing frequency of applications. It is unlikely that the insecticide residues from one or two applications lasted for an entire season, so it is unclear why trap counts remained low under such low insecticide inputs.

Besides their use for assessing seasonal fluctuations of *D. suzukii* flies, monitoring traps can be used to determine the spatial distribution of

Table 2. Results from generalized linear models to determine the effect of trap location (distance from the forest) on the number of *Drosophila suzukii* captures in traps in 2016 and 2017

Year	Factors[a]	df	*F*	*P*-value
2016	Location	1	5.46	**0.019**
	Season	3	1,010.88	**<0.001**
	Farm	7	9.18	**<0.001**
	Location × season	3	0.74	0.526
	Location × farm	7	4.00	**<0.001**
	Season × farm	20	1.51	0.069
	Location × season × farm	13.2	0.68	0.839
	Residuals	946		
2017	Location	1	45.01	**<0.001**
	Season	3	618.53	**<0.001**
	Farm	5	14.19	**<0.001**
	Location × season	3	1.29	0.277
	Location × farm	5	6.39	**<0.001**
	Season × farm	14	4.09	**<0.001**
	Location × season × farm	14	0.69	0.785
	Residuals	810		

[a] Location = trap position within farms relative to a forest patch (edge vs Interior); season = time of year (early, mid, late, and post).

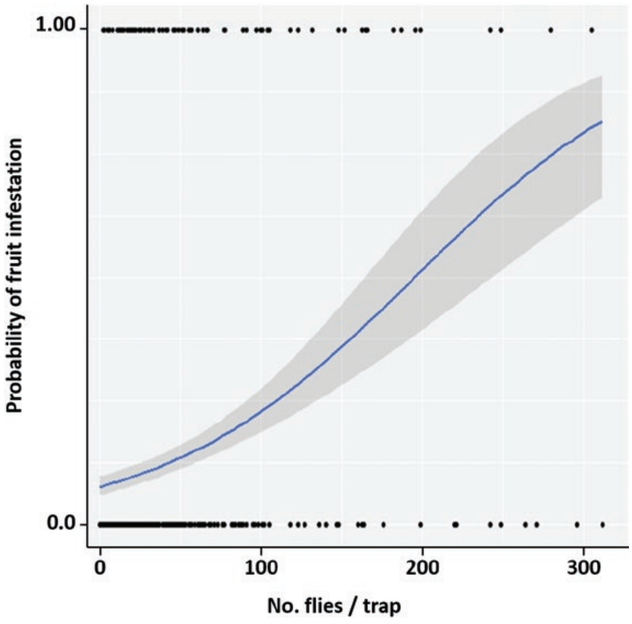

Fig. 5. Relationship between the probability of blueberry fruit being infested and the number of *Drosophila suzukii* in traps. Each dot represents an individual trap and whether fruit was either infested (y = 1) or not infested (y = 0) by *D. suzukii* larvae. The regression line is the result of a model output using the log-transformed mean trap counts.

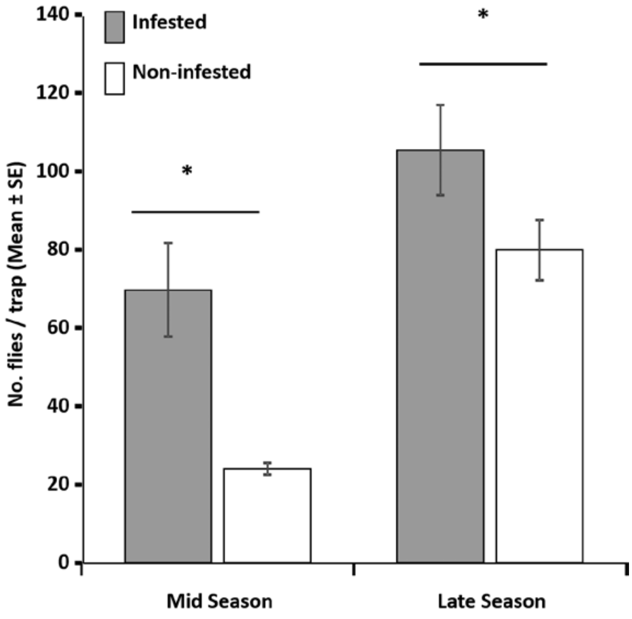

Fig. 6. Mean (± SE) number of *Drosophila suzukii* captures per trap in blueberry fields with and without infested fruit during the mid and late seasons of 2017. An asterisk indicates significant differences in the number of fly captures between treatments for each season ($\alpha = 0.05$; Welch two-sample *t*-tests).

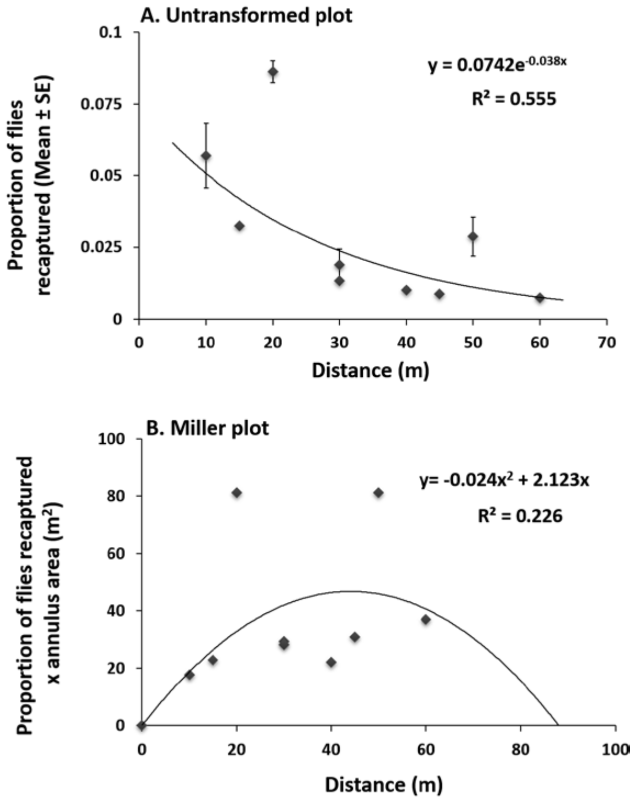

Fig. 7. (A) Mean (± SE) probability of *Drosophila suzukii* fly capture versus distance of release from a single, central trap. (B) Miller plot transformation for the *D. suzukii* releases.

flies within farms to better deploy monitoring and management strategies. In fact, there is strong evidence that noncrop habitats, and the wild fruits therein, serve as potential sources of *D. suzukii* adults to neighboring cropping systems because they provide resources such as food, as well as nesting and overwintering sites (Lee et al. 2015, Arno et al. 2016, Briem et al. 2016, Kenis et al. 2016, Klick et al. 2016a, Pelton et al. 2016, Ballman and Drummond 2017, Little et al. 2017, Thistlewood et al. 2018, Tonina et al. 2018, Leach et al. 2019). In New Jersey, wild blueberries (*Vaccinium* spp.) growing in the forest understory are used by *D. suzukii* for oviposition and larval development (Rodriguez-Saona et al. 2019). We also showed recently that these wild blueberries mature at the same time as the commercial highbush blueberries and are infested by *D. suzukii* throughout the entire harvest period of the crop (Urbaneja-Bernat et al. 2020). Higher levels of wild fruit infestation in the surrounding habitats have been shown to correlate with higher levels of *D. suzukii* trap captures in commercial lowbush blueberry fields (Ballman and Drummond 2017). Haro-Barchin et al. (2018) also found that the number of *D. suzukii* in traps increases with the amount of forest surrounding highbush blueberry fields. Building on this previous knowledge, we showed that, within highbush blueberry farms, traps placed near forest habitats capture more *D. suzukii* flies than those placed in the farm interiors. Our results, together with those reported previously (e.g., Swoboda-Bhattarai and Burrack 2020), indicate that forests may provide *D. suzukii* resources and protection from pesticide applications, and thus serve as a constant source of flies moving into the blueberry crop during the entire harvest period.

We were able to predict a higher probability of *D. suzukii* fruit infestation with increases in fly trap captures. According to our mid-season data, no fruit infestation was seen in blueberry fields when trap counts were ~20 flies/trap; however, mean trap counts of 60–70 flies indicated a high probability of infestation. In the late season, fields with trap captures of ~80 flies/trap recorded no infested fruits, whereas those with more than 100 flies/trap had infested fruit. Similar to the frequency of insecticide applications, the power of trap counts as predictors of fruit infestation seem to vary by seasonality—their power is higher in early-mid season (before mid-July in New Jersey) when trap counts are low, i.e., below 50 flies/trap. A correlation between *D. suzukii* trap counts and fruit infestation was also reported in lowbush blueberries (Drummond et al. 2019b), and this information was used to develop action thresholds. Whether *D. suzukii* trap counts can guide decisions on insecticide use in highbush blueberries needs investigation.

The capture rates of released flies of about 3% from our mark-release-recapture studies were comparable to 2.2–5.7% reported by Drummond et al. (2019a) and were higher than those (<2%) reported by Kirkpatrick et al. (2018b). We estimated a maximum dispersive distance of approx. 90 m for *D. suzukii* flies in highbush blueberries, which is similar to that traveled in Michigan tart cherry orchards (Kirkpatrick et al. 2018b). Slightly farther maximum traveled distances were estimated for *D. suzukii* flies in pruned (107 m, mean of three trials) and fruit-bearing (120 m) lowbush blueberries in Maine (Drummond et al. 2019a). The lowbush blueberry canopy is much different (substantially shorter) than that of highbush blueberries and cherries, which may account for these differences in fly dispersal. Vacas et al. (2019) reported a daily flight distance below 100 m for *D. suzukii* in a mixed orchard area containing various citrus varieties. Drummond et al. (2019a) estimated that *D. suzukii* travels at a rate of 0.1–30 m per day in lowbush blueberries, which agrees with our average traveled distance of ~29 m in highbush blueberries. Our mark-release-recapture experiment was conducted before and after harvest, when limited fruit susceptible to *D. suzukii* was present in fields, and under variable environmental conditions. Although there are expected methodological differences between our study and previous studies, it appears that, irrespective of cropping system, crop phenological stage, and environmental conditions, a *D. suzukii* fly can travel a maximum distance of 90–120 m. Drummond et al. (2019a) reported no differences in dispersal rate between male and female *D. suzukii*. In a flight mill study, Wong et al. (2018) showed that physiological (feeding) status can affect *D. suzukii* flight capacity. However, whether the physiological status of flies (i.e., mating status, degree of starvation) influences their dispersal capacity under field conditions remains unknown.

In conclusion, our data indicate that under certain circumstances monitoring traps for *D. suzukii* can predict the efficacy of management programs in highbush blueberries but, because of high seasonal variability, their predictive power may not be very reliable. Although trap counts could also predict fruit infestation, this prediction was more accurate under a relatively low population size. Based on our data, proximity to forest was the most reliable predictor of high *D. suzukii* numbers in traps, suggesting a constant pressure of flies moving from noncrop forest habitats into highbush blueberry fields. Our dispersal data were consistent with those previously reported and could be used for future monitoring and management recommendations, such as establishing trap densities (Kirkpatrick et al. 2018b) or for border spray tactics (Klick et al. 2016b). Although significant progress has been made in improving current trapping systems for *D. suzukii* (Cloonan et al. 2018), this study highlights the challenges of developing action thresholds and making management decisions based on trap counts for an invasive pest that has a zero tolerance for larval infestation in crops such as highbush blueberries.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

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