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Using Red Panel Traps to Detect Spotted-Wing Drosophila and its Infestation in US Berry and Cherry Crops

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Abstract

Spotted-wing drosophila (SWD), *Drosophila suzukii* Matsumura (Diptera: Drosophilidae), is an invasive pest of thin-skinned fruits in the United States. Monitoring traps are an integral part of SWD integrated pest management, allowing early detection and timely management of this pest. An ideal monitoring trap should be easy to use, effective in capturing SWD, sensitive and selective to male SWD which are easy to identify due to their spotted wings, and able to predict fruit infestation from trap captures. Deli-cup-based liquid traps (grower standard), which make in-situ observations difficult, were compared with red-panel sticky traps, both baited with commercial lures (Scentry, Trécé Broad-Spectrum (BS), and Trécé High-Specificity (HS)), across several US states in blueberries (lowbush and highbush), blackberry, raspberry, and cherry crops during 2018 and 2021. Results showed that red-panel traps effectively captured SWD, were able to detect male SWD early in the season while also being selective to male SWD all season-long, and in some cases linearly related male SWD trap captures with fruit infestation. Scentry and Trécé BS lures captured similar numbers of SWD, though Trécé BS and Trécé HS were more selective for male SWD in red panel traps than liquid traps in some cases. In conclusion, due to its ease of use with less processing time, red-panel traps are promising tools for detecting and identifying male SWD in-situ and for predicting fruit infestation. However, further research is needed to refine the trap captures and fruit infestation relationship and elucidate the trap-lure interactions in berry and cherry crops.

Key words: trapping system, commercial lure, broad-spectrum lure, high-specificity lure, fruit infestation

Drosophila suzukii Matsumura (Diptera: Drosophilidae), also commonly known as spotted-wing drosophila (SWD), is an invasive pest of many soft thin-skinned small fruits in the United States (Tait et al. 2021). Initially found in the continental United States in 2008 (Hauser 2011), this drosophilid species is particularly problematic due to the female's ability to infest ripening and intact fruits with its serrated ovipositor (Atallah et al. 2014, Asplen et al. 2015, Tait et al. 2021). In addition, its wide host-range and ability to move between cultivated crops and noncrop wild hosts (Lee et al. 2015, Urbaneja-Bernat et al. 2020), allows it to survive during the off-season making it a significant pest of berry crops (Bal et al. 2017, Ballman and Drummond 2017). This pest is estimated to have caused US$56.7 million in losses in blueberries in the USA., US$174.8 million in cherries (Bolda et al. 2010), and US$39.8 million in raspberries (Farnsworth et al. 2017). Walsh et al. (2011) estimated that, assuming a 20% yield loss across all SWD-susceptive fruits, damage from this pest could cause US$511 million in economic losses in the USA. Calendar-based chemical controls are primarily used to manage SWD populations (Haviland and Beers 2012, Farnsworth et al. 2017, Iglesias and Liburd 2017, Hunter and Sial 2019), and have led to insecticide resistance in SWD populations (Diepenbrock et al. 2016). Development of monitoring tools that provide growers with an early warning of SWD infestation may reduce the need for these calendar-based insecticide applications. Thus, the integration of easy-to-use monitoring tools with effective and selective lures are important for the early detection and timely management of this pest (Landolt et al. 2012a, b, Lee et al. 2013, Cha et al. 2018, Cloonan et al. 2018).

Previous studies on SWD have focused on the development of trapping designs that can capture and retain more flies (Lee et al. 2012, 2013). However, handling the trap contents to identify and count SWD can become tedious when there is a high number of nontarget drosophilids with similar morphology to SWD (Lee et al. 2013). Moreover, it is difficult for an untrained eye to identify SWD females from other drosophilids in-situ. In contrast, SWD males have spotted wings which distinguish them from female drosophilids and other male drosophilids with no wing spots. The ease of identifying male SWD, because of this recognizable wing spot, makes them ideal for basing action thresholds on their counts. One such threshold developed for wild blueberry in Maine uses the cumulative average of male SWD captured. The cumulative average of male SWD captured is based on three Red Solo cups baited with a mixture of yeast and sugar (Drummond et al. 2019). Growers can use the cumulative average of males captured at a given site to predict the probability of having infestation the following week. For example, a cumulative average of 3.5 or 7 males results in a 10% or 25% chance of having infestation, respectively, the following week.

Currently, a liquid trap (32-oz deli-cup) is primarily used to monitor SWD in small fruit crops (Tait et al. 2021). These traps utilize an attractant such as a fermenting bait solution or synthetic lure pouch to attract SWD and a soapy-water drowning solution (Lee et al. 2012, Burrack et al. 2020, Tait et al. 2021). However, it is difficult to make in-situ counts with these liquid traps because of the drowning solution (Burrack et al. 2020). This has led to the development of alternative trap types such as panel traps with a sticky surface that attracts and captures flies without a drowning solution making in-situ counting easier (Kirkpatrick et al. 2017, 2018).

Currently, SWD monitoring traps, including red panel traps, use commercially available lures, such as Scentry (Scentry from hereon; Scentry Biologicals, Inc., Billings, MT), Trécé Broad-Spectrum (Trécé BS from hereon; Trécé Inc., Adair, OK), and Trécé High-Specificity (Trécé HS from hereon; Trécé Inc.), as olfaction cues (Burrack et al. 2015, Cha et al. 2018). However, a direct comparison between the standard liquid traps and red panel traps with these different lure-types has not been studied across different fruit-types.

Thus, the aim of this study was to compare the red-panel traps with the grower's standard liquid trap baited with different commercial lures (Scentry, Trécé BS, and Trécé HS) in several berry and cherry crops throughout the US. Traps were evaluated for their 1) ability to detect male SWD populations during early season and season-long, 2) selectivity to male SWD compared to nontarget captures, and 3) ability to relate male SWD captures with fruit infestation.

Materials and Methods

Study Sites and Experimental Design

This study was conducted across multiple cropping systems (blueberry: *Vaccinium* spp., (Ericales: Ericaceae) blackberry, *Rubus* spp. (Rosales: Rosaceae), raspberry: *Rubus* spp., (Rosales: Rosaceae); and cherry: *Prunus avium*, (Rosales: Rosaceae)) in five US states (NC, NJ, OR, NY, and ME) in 2018 (total of 16 field sites) and 11 US states (NC, NJ, NY, OR, ME, VA, MD, NH, MI, GA, and FL) in 2021 (total of 27 field sites) (Table 1). The studies started two weeks before harvest, continued for four weeks during harvest, and ended two weeks after harvest. Although we aimed to keep our methods as consistent as possible across states, the number of sites, treatments, replications, sampling frequency, start and end dates, and fly counts (male SWD, female SWD, and/or other drosophilids) differed among states, crops, and years due to differences in crop phenology, site size and availability, and other unforeseen factors (Table 1).

Trap Designs

Liquid traps were constructed with a 32-oz (~ 1 liter) deli cup with equally spaced 12 entry holes on the side of the cup (Kirkpatrick et al. 2017). The drowning solution was made by mixing 0.1% of unscented detergent soap (unscented Seventh Generation soap; www.seventhgeneration.com, Burlington, VT, USA) in 210 ml of tap water. Red panel traps were obtained from Trécé Inc and measured 14 × 25 cm^2 with sticky surfaces on both sides. In contrast to traps used in 2021, red panel traps used in the 2018 study had reduced sticky surface area around the edges of the trap (i.e., had no glue on 1–2 cm from edge to center). Both liquid and red panel traps were hung 0.5–1 m above the ground using a twist tie and placed in the middle of the canopy of the plant for all the crops except for lowbush blueberry where traps were placed above the plant canopy. All traps were spaced at least 10 m apart. In liquid traps, lures were hung inside of the lid that goes on the cup, and in red panel traps lures were hung on the upper nonsticky surface. However in 2021-GA blueberry lures were hung on the lower side of the trap. Trap contents were collected and traps replaced weekly by collecting and labeling the drowning solutions in a 16-oz (473 ml) deli cup and wrapping the red-panel traps with transparent plastic to facilitate processing at a later date. Lures were replaced every 4–5 wk.

Lure Types

Lures used in both trap types (liquid and panel traps) contained the four-component blend consisting of acetic acid, ethanol, acetoin, and methionol (Cha et al. 2012, 2013, 2014, 2015, 2017). However, concentrations and ratios of the formulation and dispensing technology differed among lures (undisclosed proprietary information). For instance, the Scentry lure consists of a clear plastic pouch (9 × 7 cm^2) with a yellowish formulation inside and volatiles are emitted from all sides of the pouch. Similarly, the Trécé BS lure also consists of a plastic pouch (7 × 7 cm^2); however, the volatiles are

Table 1. Site information, crop type, and sampling dates of SWD trap during 2018 and 2021

State	Crop	Sites	Treatments	Replicates	Dates (sampling frequency)
2018					
NC	Blackberry	1	4	5	21 June–27 July (6)
NJ	Blueberry[a]	4	4	4	13 June–25 July (6)
NJ	Blueberry[a]	6	2	5	13 June–18 Aug. (10)
OR	Blueberry[a]	1	4	5	28 June–8 Aug. (7)
NY	Raspberry	1	2	10	2 July–15 Aug. (6)
ME	Lowbush Blueberry	3	5	3	3 Aug.–5 Sept. (5)
2021					
VA	Blackberry	1	4	3	28 June–30 Aug. (12)
OR	Cherry	2	1	3	13 May–28 July (11)
WA	Cherry	1	6	5	28 Sept.–3 Nov. (6)
NH	Blueberry[a]	1	5	4	24 June–29 July (6)
MD	Blueberry[a]	2	4	3	27 May–12 Aug. (12)
NJ	Blueberry[a]	1	3	5	31 May–3 Aug. (10)
MI	Blueberry[a]	9	6	1	14 June–17 Aug. (8)
OR	Blueberry[a]	1	4	4	15 July–11 Aug. (4)
NY	Blueberry[a]	4	6	4	8 June–31 Aug. (13)
GA	Blueberry[b]	3	8	4	27 May–22 July (8)
FL	Blueberry[c]	1	4	4	23 Mar.–29 April (6)
ME	Lowbush Blueberry	1	6	4	15 July–17 Aug. (6)

[a] Northern Highbush.
[b] Rabbiteye.
[c] Southern Highbush.

emitted only from one side of the pouch that has the protective peel-off layer. The side where volatiles are emitted from is red-colored, adding a visual cue to the lure. In contrast, the Trécé HS lure consists of a red-colored case (9 cm^2) with three separate tablet-shaped compartments (2-cm diameter each) with the formulations inside and has a peel-off cover on one side. Because of commercial availability, in 2018 only the Scentry lure was tested, while all three lures were tested in 2021.

Sample Processing

Trap samples were brought back to the laboratory and the number of male and female SWD and other drosophilids were counted under a dissecting microscope. Liquid trap samples were first filtered through a 160-micron mesh cloth and were then transferred into a gridded Petri dish with 70% ethanol for counting. A transparent plastic sheet with a gridded or checkerboard pattern was placed on the sticky trap to conveniently count the flies under the microscope.

Ripe berries were collected from the area within 5–10 m from where traps were placed. The number of berries per sample varied between crops and states with 226 g berries in 2018-NJ-Highbush 30 berries in 2018-NC-Blackberry, 30–40 berries in 2018-NY-Raspberry, 100–250 berries in 2021-NY-Highbush, and 110–151 g berries in 2021-ME-Lowbush. Berries were taken to the lab, incubated for one week under ambient conditions, and the number of larvae and pupae were counted through the salt-extraction method (Shaw et al. 2019).

Statistical Analysis

All data were analyzed in JMP Pro v.16, SAS Institute Inc, Cary, NC, USA. Data from 2018 and 2021 were analyzed separately for each crop (Table 1).

To determine the SWD capture during early season, only the data for first week of fly captures were compared between traps in 2018, and among traps and lures in 2021 via nonparametric test, Wilcoxon/Kruskal-Wallis Test. However, in 2018-raspberry, only three male SWD were captured in the third week (16 July 2018) in liquid traps, so fourth week trap counts were used for the statistics. In 2021-cherry, although red panel traps with Trécé BS captured one male SWD in one of the OR sites in the fifth week, and two male SWD in sixth- and seventh-week data, most of the male SWD occurred after the seventh week, so eighth week data were used for the statistics. In 2021-blackberry, second week data were used for the statistics due to no captures in the first week. Means of male and female SWD captures were compared using Tukey-Kramer HSD at alpha = 0.05.

To determine the season long SWD capture rate, male and female SWD captures were pooled over weeks and analyzed with a mixed model using trap as a fixed effect in 2018 and traps and lures as fixed effects in 2021. Random effects were state, field, site, and block. Data were fit to several distribution models (Normal, Poisson, Negative binomial, and zero-inflated Poisson and Negative binomial) and the best model was chosen based on least AICC value. In some instances where neither of the above-mentioned models fit to the data, data were $\log(x + 1)$ transformed. When there were significant differences between treatments, means were separated with Tukey's Honestly Significant Difference (HSD) means separation test at alpha = 0.05. In 2021-blackberry and cherry, because of low fly captures, the effects of traps and lures on male and female SWD captures were analyzed through a nonparametric test, Wilcoxon/Kruskal-Wallis Test. In 2021, because there was no trap effect, male SWD captures in cherry and female SWD captures in blueberry were pooled over trap and tested for the lure effect.

To determine the selectivity of traps and lures to SWD male and female, the proportions of male and female SWD and non-SWD flies were derived by dividing the respective values with the total drosophilids (sum of male SWD, female SWD, and non-SWD). Then, the proportions of male and female SWD were regressed upon week in a linear model for highbush blueberry, lowbush blueberry, and raspberry in 2018 (weeks: 1–8) and blackberry, blueberry (highbush and rabbiteye), cherry, and lowbush blueberry in 2021 (weeks: 1–14). ANCOVA was used to compare the coefficients of regression model parameters (intercepts and slopes) between liquid and red panel traps by crop in 2018 and by crop and lure in 2021. Male SWD (%) were fitted in a linear model with trap (grouping variable) and week (continuous variable) as fixed effects. Here, the continuous variable 'week' is a covariate. For the intercepts and slopes to be significantly different between the traps, there should be significant effect of trap and the interaction of trap and week, respectively.

To determine the relationship between male SWD trap captures and fruit infestation, number of SWD males in the trap, and the number of SWD immatures from fruits collected on the same day/week of trap collection, were regressed in a linear model for highbush blueberry, blackberry, and raspberry in 2018 and highbush and lowbush blueberry in 2021. ANCOVA was used to compare the coefficients of regression model parameters (intercepts and slopes) between liquid and red panel traps. SWD immatures from fruit samples were fitted in a linear model with trap (grouping variable) and trap captures (continuous variable) as fixed effects. Here, the continuous variable 'week' is a covariate. For the intercepts and slopes to be significantly different between the traps, there should be significant effect of trap and the interaction of trap and trap captures, respectively.

Results

SWD Captures During Early Season

In 2018, only the Scentry lure was tested. In lowbush (Fig. 1a) and highbush (Fig. 1b) blueberry, both liquid and red panel traps captured male and female SWD similarly, in the first week of trap captures. In blackberry, liquid traps captured more male and female SWD than red panel traps (Fig. 1c, female: $\chi^2_1 = 6.14$, $p = 0.01$; male: $\chi^2_1 = 5$, $p = 0.02$). In raspberry, liquid traps captured more male SWD than red panel traps (Fig. 1d: $\chi^2_1 = 5.05$, $p = 0.01$) and both liquid and red panel traps captured similar female SWD.

In 2021, red panel traps captured more male and female SWD than liquid traps in lowbush blueberry when baited with the Scentry lure (Fig. 2a) (female: $\chi^2_1 = 8.6$, $p = 0.03$; male: $\chi^2_1 = 10.9$, $p = 0.01$). However, trap catches were similar between liquid and red panel traps when baited with the Trécé BS lure. In cherry (WA) liquid traps captured more female SWD than red panel traps with both Scentry and Trécé BS lures (Fig. 2b) (Scentry: $\chi^2_1 = 7.81$, $p = 0.005$; Trécé BS: $\chi^2_1 = 5.48$, $p = 0.02$), whereas red panel traps captured more male SWD than liquid traps when baited with the Trécé HS lure ($\chi^2_1 = 5.98$, $p = 0.01$); male SWD captures were similar between two traps with Scentry lures. In cherry (OR), although red panel traps captured male and female SWD with the Scentry lure and only female SWD with the Trécé BS lure, there were no trap counts from liquid traps to compare with. In blackberry (Fig. 2d) and blueberry (Fig. 2e), liquid and red panel traps captured male and female SWD similarly with Scentry, Trécé BS, and Trécé HS lures.

Season-Long SWD Captures

In 2018, liquid traps captured more female SWD than red-panel traps in lowbush blueberry (Fig. 3a: $F_{1,50} = 6.98$, $p = 0.01$), blackberry (Fig. 3b: $F_{1,50} = 6.98$, $p = 0.01$), highbush blueberry (Fig. 3c: $F_{1,214} = 51.62$, $p < 0.0001$). In lowbush blueberry (Fig. 3a) and blackberry (Fig. 3b), liquid and red panel traps captured similar male SWD, whereas in highbush blueberry (Fig. 3c) and raspberry (Fig. 3d), liquid traps captured more male SWD than red panel traps (highbush: $F_{1,662} = 17.44$, $p < 0.0001$; raspberry: $F_{1,80} = 4.99$, $p = 0.028$).

In 2021, there was a trap lure interaction in male and female SWD captures in lowbush blueberry (Fig. 4a) (trap × lure: female: $F_{1,87} = 9.04$, $p = 0.003$; male: $F_{1,88} = 11.93$, $p = 0.0009$), female SWD captures in cherry (Fig. 4b) (trap × lure: female: $F_{1,180} = 23.28$, $p < 0.0001$), and male SWD captures in blueberry (Fig. 4d) (trap × lure: male: $F_{2,1308} = 5.5$, $p = 0.004$). In lowbush blueberry, red panel traps captured more male and female SWD than liquid traps with the Scentry lure (Fig. 4a) (Tukey HSD, $\alpha = 0.05$), whereas the captures were similar between liquid and red panel traps with the Trécé BS lure (Fig. 4a). In cherry, liquid traps captured more female SWD than red panel traps with the Scentry lure (Fig. 4b) (Tukey HSD, $\alpha = 0.05$), whereas all other captures between liquid and red panel traps were similar with Scentry, Trécé BS, and Trécé HS lures (Fig. 4b). Among lures in cherry, Scentry captured more male SWD than Trécé BS and Trécé HS lures (Fig. 4b) ($\chi^2_2 = 117.26$, $p < 0.0001$). In blackberry, liquid traps captured more female SWD than red panel traps with the Trécé BS lure (Fig. 4c) ($\chi^2_1 = 8.28$, $p < 0.004$) and similar numbers of males between the liquid and red panel traps. The Scentry lures in blackberry on captured male and female flies in the liquid traps (Fig 4c).In blueberry, red panel traps captured more male and female SWD than liquid traps with the Scentry and Trécé BS lures (Fig. 4d) (Tukey HSD, $\alpha = 0.05$), whereas trap captures were similar between liquid and red panel traps with the Trécé HS lure (Fig. 4d).

Selectivity to Male SWD Over Week

In 2018, in highbush blueberry, red panel traps had significantly higher selectivity (intercept, 60.69 ± 23.77 %, *t*-ratio = 2.55, $p = 0.01$) than liquid traps during early week (ANCOVA: $F = 127.17$, df = 1, $p < 0.001$, Fig. 5) and the selectivity of red panel traps remained similar over the week (Slope, 2.77 ± 4.67 %, *t*-ratio = 0.59, $p = 0.56$). In lowbush blueberry, only liquid trap captures were available, and the selectivity of liquid traps increased linearly from zero, at a rate of 8.85 ± 2.79 % (*t*-ratio = 3.17, $p = 0.004$) increase each week (Fig. 5). In raspberry, the selectivity of both liquid and red panel traps increased linearly with similar intercepts (ANCOVA: $F = 2.3$, df = 1, $p = 0.13$) and slopes (ANCOVA: $F = 0.34$, df = 1, $p = 0.56$) (Fig. 5).

In 2021, in blackberry, the selectivity of red panel traps was significantly higher (45.26 ± 6.63, *t*-ratio = 6.83, $p < 0.0001$) than liquid traps during early week when baited with the Trécé BS lure (ANCOVA: $F = 88.08$, df = 1, $p < 0.0001$), The selectivity of red

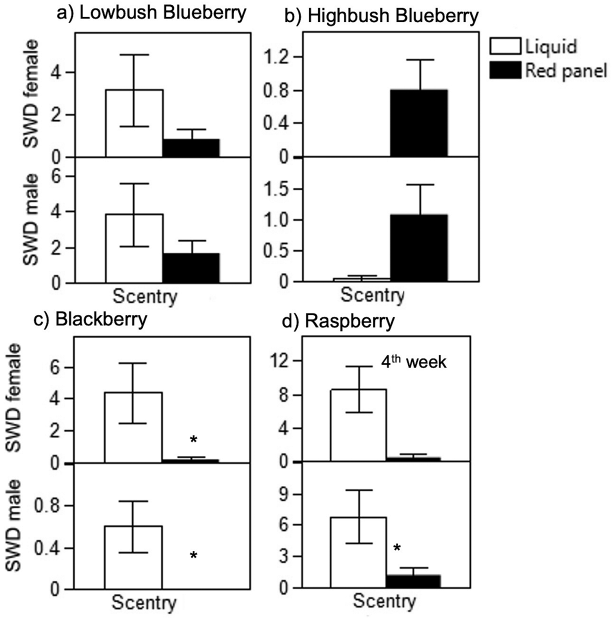

Fig. 1. Trap captures of male and female SWD (mean ± SE) during early week on liquid and red panel traps with Scentry lure in a) lowbush blueberry, b) highbush blueberry, c) blackberry, and d) raspberry fields in 2018. Asterisk signs indicate significant difference (Tukey-Kramer, $\alpha = 0.05$).

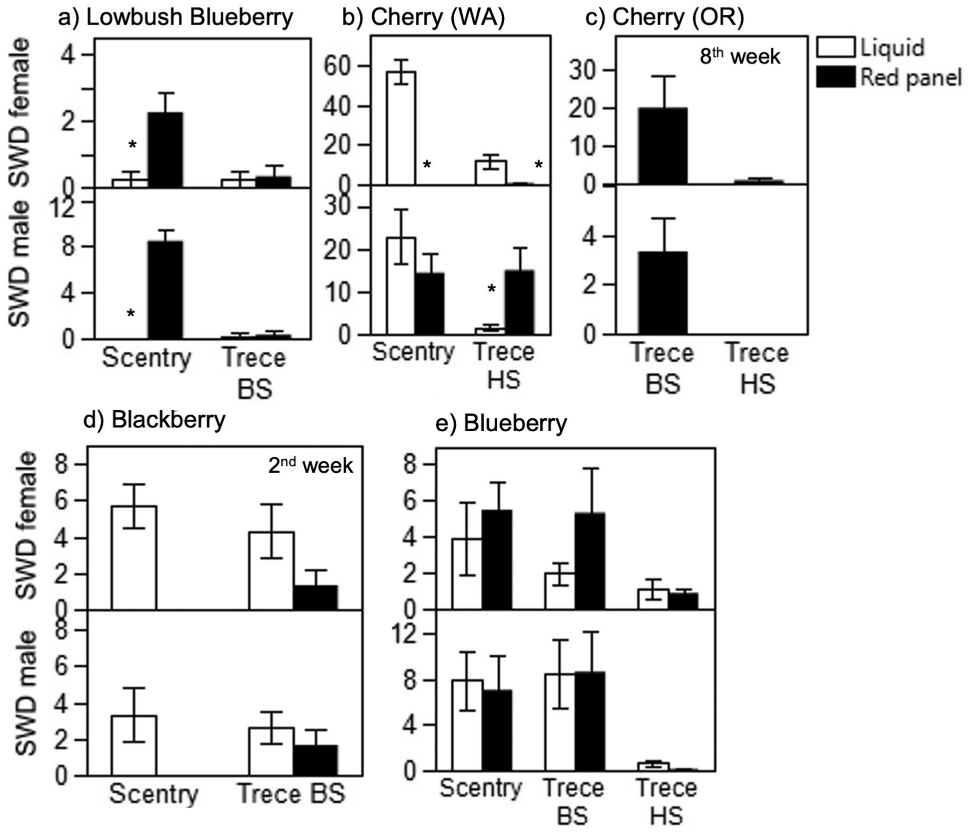

Fig. 2. Trap captures of male and female SWD (mean ± SE) during early week on liquid and red panel traps with Scentry, Trécé BS, and Trécé HS lures in a) lowbush blueberry, b) cherry, c) blackberry, and d) highbush and rabbiteye blueberry fields in 2021. Asterisk signs indicate significant difference (Tukey-Kramer, α = 0.05).

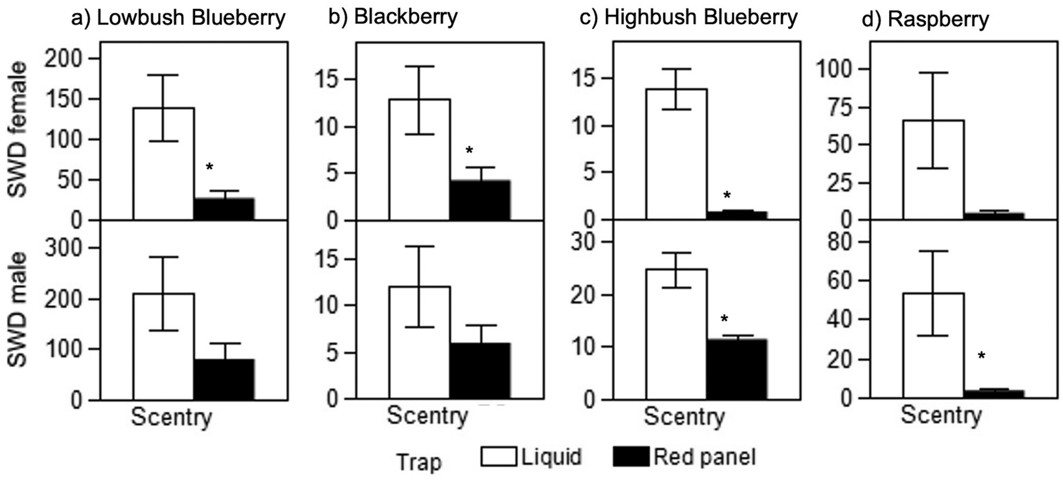

Fig. 3. Season-long trap captures of male and female SWD (mean ± SE) on liquid and red-panel traps baited with Scentry lure in a) lowbush blueberry, b) blackberry, c) highbush blueberry, and d) raspberry fields in 2018. Asterisk signs indicate significant difference (Tukey-HSD, α = 0.05).

panel traps with the Trécé BS lure decreased at a rate of −2.65 ± 1.07 % (*t*-ratio = −2.48, $p = 0.02$) each week, however, the selectivity of red panel traps was never below liquid traps throughout the season (Fig. 6a).

In blueberry (Fig. 6b), although liquid and red panel traps with the Scentry lure had zero selectivity during the first week, ANCOVA showed red panel traps had higher selectivity than liquid traps during early season ($F = 16.69$, df = 1, $p<0.0001$) and the selectivity of two traps increased linearly with similar rates throughout the season ($F = 3.57$, df = 1, $p = 0.06$). Whereas red panel traps with the Trécé BS lure had significantly higher selectivity than liquid traps during early season (ANCOVA: $F = 65.51$, df = 1, $p < 0.0001$),) and the rate of increase of selectivity over the season was significantly higher in red panel traps than liquid traps (ANCOVA: $F = 5.88$, df = 1, $p = 0.01$). Red panel traps with the Trécé HS lure showed no significant linear relationship between selectivity and week, whereas liquid traps with

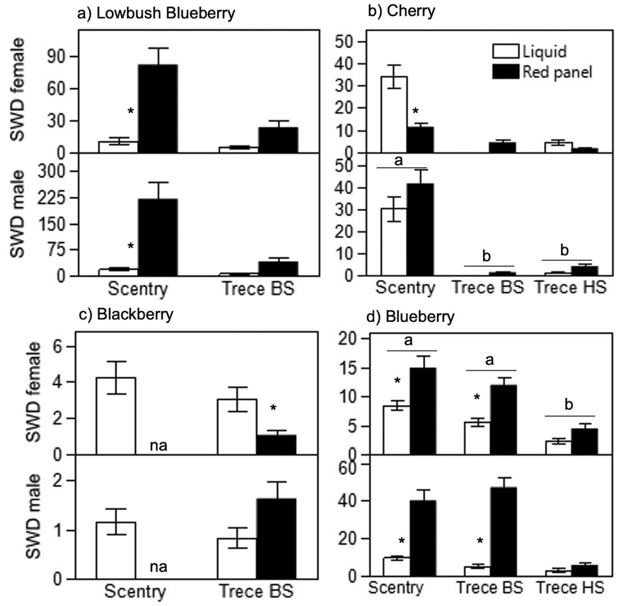

Fig. 4. Season-long trap captures of male and female SWD (mean ± SE) on liquid and red-panel traps baited with Scentry, Trécé BS, and Trécé HS lures in a) lowbush blueberry, b) cherry, c) blackberry, and d) blueberry fields in 2021. Asterisk signs indicate significant difference (Tukey-HSD/Tukey-Kramer, α = 0.05).) Horizontal lines represent pooled result and the lines with different letters are significantly different (Tukey-HSD, α = 0.05).

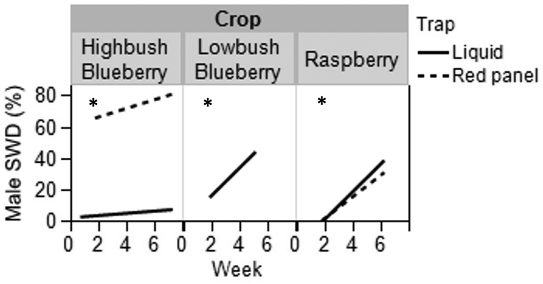

Fig. 5. Linear relationship of % male SWD captures relative to total *Drosophila* captured (selectivity) in liquid and red-panel traps with Scentry lure over 1–8 wk in a) highbush blueberry, b) lowbush blueberry, and c) raspberry fields in 2018. Asterisk signs indicate the regression line(s) are significant.

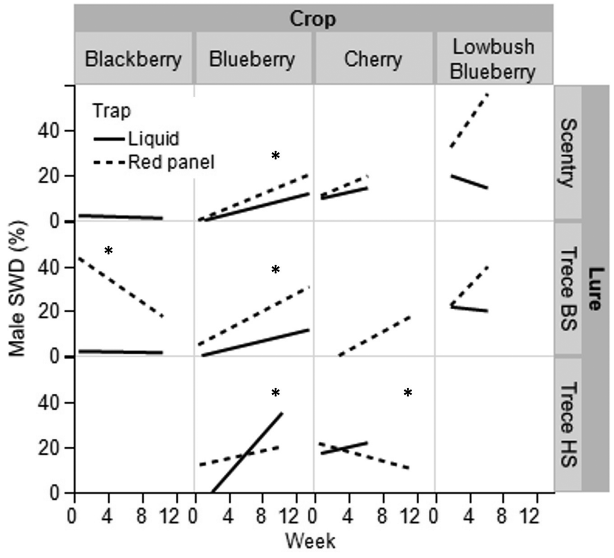

Fig. 6. Linear relationship of % male SWD captures relative to total *Drosophila* captured (selectivity) in liquid and red-panel traps with Scentry, Trécé BS, and Trécé HS lures over 1–14 wk in a) blackberry, b) highbush blueberry, c) cherry, and d) lowbush blueberry fields in 2021. Asterisk signs indicate the regression line(s) are significant.

the Trécé HS lure had a significant increase in selectivity over the week (Slope, 4.22 ± 1.51: *t*-ratio = 2.79, $p = 0.008$) from zero percent in the first week ($p = 0.39$).

In cherry (Fig. 6c), only red panel traps with Trécé BS and Trécé HS lures showed a significant linear relationship between selectivity and week. Red panel traps with the Trécé BS lure had selectivity below zero percent during the first week but increased linearly during the later season at a rate of 2.07 ± 0.37 % (*t*-ratio = 5.66, $p < 0.0001$) each week. In red panel traps with Trécé HS lure, the selectivity was high during the first week (Intercept: 22.22 ± 5.32, *t*-ratio = 4.18, $p < 0.0001$) and the selectivity remained similar throughout the week (Slope: −1.03 ± 0.86, *t*-ratio = −1.19, $p = 0.24$).

In lowbush blueberry (Fig. 6d), due to high variation, a significant linear relationship could not be established for selectivity over week.

Relation of Fruit Infestation with Male SWD Captures

In 2018-highbush blueberry, only red panel traps in 'Marucci In' site in NJ showed a significant linear relationship between male SWD captures and fruit infestation, where number of immatures in fruits increased at a rate of 0.40 ± 0.00 (*t*-ratio = 56.25, $p = 0.0003$) immatures for each male SWD in red panel traps (Fig. 7a). In blackberry (Site = Sandhills), only liquid traps showed a significant linear relationship where number of immatures in fruits increased at a rate of 0.54 ± 0.07 (*t*-ratio = 8.00, $p < 0.0001$) immatures for each male SWD (Fig. 7b).

In raspberry (Site = Tomions), both liquid and red panel traps showed a significant linear relationship. In liquid traps, SWD immatures increased linearly with male SWD captures at a rate of 0.89 ± 0.36 (*t*-ratio = 2.45, $p < 0.02$) immatures for each male SWD. Whereas the linear relationship was much stronger ($r^2 = 0.89$) in red panel traps than liquid traps ($r^2 = 0.2$), where SWD immatures increased at a rate of 7.99 ± 0.58 (*t*-ratio = 13.78, $p < 0.0001$) immatures for each male SWD. The intercept (ANCOVA-trap: $F = 12.49$, df = 1, $p = 0.0009$) and slope (ANCOVA-treatment*male SWD: $F = 34.13$, df = 1, $p < 0.0001$) of lines of red panel traps were significantly higher than liquid traps (Fig. 7c). In 2021-highbush (Site = Gands) and lowbush blueberry (Site = Mont.), there was no significant relationship between SWD immatures and male SWD captures with either lure type (Fig. 7d and e).

Discussion

In this study, red panel traps performed similar to liquid traps in their early detection of male SWD across most of the crops tested. Moreover, an increase in male SWD captures in red panel and liquid traps corresponded to increases in fruit infestation in highbush blueberry and raspberry, and increases in male SWD captures in the red panel traps corresponded with fruit infestation in raspberry.

Although red panel traps were more selective to male SWD than liquid traps, the selectivity was variable between crop and lure type, as has been previously reported in liquid traps (Cloonan et al. 2019). For example, during early weeks, red panel traps with the Scentry lure had selectivity as high as 60% in highbush blueberry, whereas for the same trap-lure combination, it was close to zero selectivity in

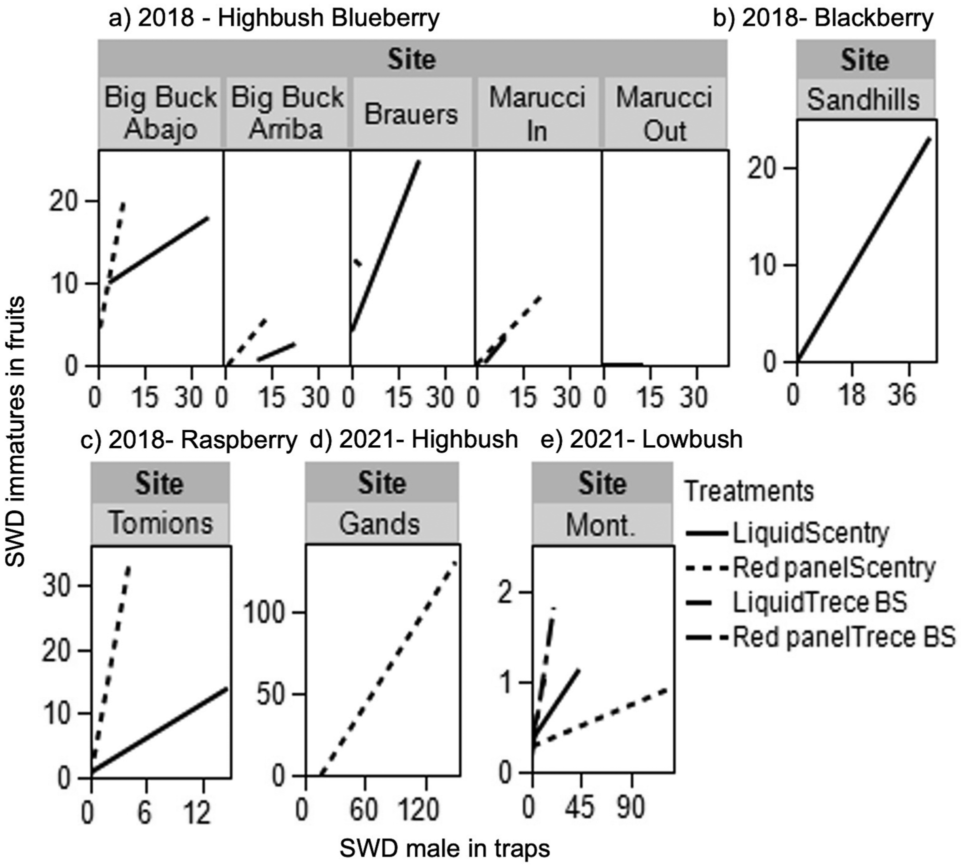

Fig. 7. Linear relationship of SWD immatures in fruits with SWD male in liquid and red panel traps with Scentry and Trécé BS lures collected from the same field sites in a) highbush blueberry, b) blackberry, and c) raspberry fields in 2018, and in d) highbush blueberry and e) lowbush blueberry in 2021. Asterisk signs indicate the regression line(s) are significant.

blueberry (highbush and rabbiteye). During early weeks, red panel traps with the Trécé BS lure had selectivity of 45% in blackberry, whereas the same trap-lure combination in blueberry had selectivity close to zero during early weeks. The red panel-Trécé HS lure combination had poor selectivity in blueberry whereas the same combination in cherry had selectivity of 22% during early weeks. These results indicate the selectivity to male SWD is crop and time-specific, and that combinations of red-panel traps with Scentry or Trécé BS lures are more selective to male SWD in blueberry, red-panel-Trécé BS lure combination in blackberry, and red-panel-Trécé HS lure combination in cherry.

Since the liquid and red-panel traps function differently, there was an interaction effect between trap designs and lure types on SWD captures by crop type. The reason for differences in capture rates might be because the amount of volatilization of the chemicals depends on the material matrix of the lure, the placement of the lure (inside or outside of the trap), surface area exposed, environmental conditions (temperature and humidity), and crop types (Jaffe et al. 2018, Burrack et al. 2020). Therefore, further research is needed to determine the effect of biotic and abiotic conditions in the trap-lure interactions to capture SWD in these crops.

The volatiles in the commercial lures are released at a constant rate throughout the season with modern dispensing technology (Cha et al. 2013). Therefore, the increase in male SWD captures as the season progresses does not necessarily mean that the ability of a lure to attract male SWD increases over the season. The increase in selectivity over the week may instead be due to an increase in overall SWD population in the berry field, and the lures were effective in differentiating the population change. This change in selectivity could also be caused by behavioral changes dependent on the time of year.

In blackberry, although liquid trap captures predicted fruit infestation with fewer male captures, the selectivity of liquid traps with either lure type was poor. Whereas red panel traps with the Trécé BS lure was highly selective for male SWD season-long. In this study, every two male SWD captures in red panel traps corresponded to one SWD immature in blueberries and blackberries collected from a sampling area of 5–10 m. In raspberry, every two male SWD captures in red panel traps corresponded to ~15 SWD immatures in berries from a given sampling area. However, these relationships will need to be further studied before red-panel traps can be fully integrated into an SWD monitoring program in US berry crops.

In our current study fruit infestation increased with increasing male SWD trap captures in some of the blueberry, blackberry, and raspberry sites, though this correlation was not consistent across blocks within each state or between states. This low correlation may be due to few fruits collected from the field, or low SWD infestation in the field. Thus, rigorous research is needed in each fruit type, in each state, developing specific threshold models using male SWD capture as a correlation to fruit infestation. However, due to the ease of handling the red panel traps compared to the liquid traps, and the results presented in this study showing that liquid traps and red panel traps capture similar numbers of male SWD over the entire season, red panel traps can be used as an alternative to liquid traps for general SWD population monitoring.

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