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Partial Budget Analysis of Exclusion Netting and Organic-certified Insecticides for Management of Spotted-wing *Drosophila* (Diptera: Drosophilidae) on Small Farms in the Upper Midwest

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Abstract

Drosophila suzukii Matsumura (Diptera: Drosophilidae), or spotted-wing drosophila, is an invasive pest first detected in the United States in 2008. Although *D. suzukii* can use many cultivated fruit as hosts, raspberries are considered ‘most at risk’ for infestation. Conventional broad-spectrum insecticides are proven effective *D. suzukii* controls and can be economically profitable when combined with integrated pest management (IPM) on large-scale commercial raspberry farms. It remains unclear, however, whether organic controls are cost-effective strategies, particularly for farms operating on a small-scale seasonal basis, as is common in the Upper Midwest. The purpose of this paper is to explore the efficacy of two organic *D. suzukii* controls—exclusion netting for high tunnels and organic insecticides for open plots using data available from different field trials—and to ascertain whether any economic benefits of the organic controls outweigh treatment costs for small-scale raspberry operations under different risk scenarios. The field trials suggest that the organic treatments are effective controls for *D. suzukii* infestation and economically profitable. The exclusion netting treatment produced positive net returns compared to the alternative of no treatment and economically outperformed the organic-certified insecticide treatment for several yield, price and infestation scenarios. As *D. suzukii* infestation rates increased, net returns improved for both organic treatments. The economic results were robust across a range of yields and prices, suggesting that in almost all scenarios small scale organic raspberry growers benefit economically from the application of exclusion netting on high tunnels and insecticides for open plots.

Key words: economics, physical exclusion, integrated pest management, organic, raspberry

Drosophila suzukii Matsumura (Diptera: Drosophilidae) or spotted-wing drosophila is an invasive agricultural pest to North America first detected in the United States in California in 2008 (Farnsworth et al. 2017). *Drosophila suzukii* prefer soft-skinned fruits and can damage a variety of hosts including raspberries, blackberries, blueberries, strawberries, cherries, and grapes (Bellamy et al. 2013). *Drosophila suzukii* eggs develop into larvae and destructively feed on the interior of the fruit (Kanzawa 1939), rendering the fruit unmarketable at the time of harvest or shortly after harvest.

In the Upper Midwest, mid-season and fall-bearing raspberries are considered ‘most at risk’ with infestation rates ranging from 2 to 100% making it difficult for growers to balance the multiple of goals of integrated pest management (IPM) including pest control, pollinator benefits, economic sustainability and profitability (Rogers et al. 2016, DiGiacomo et al. 2019, Gullickson et al. 2019).

The majority of IPM research to date has accounted for *D. suzukii* yield loss using visual inspection of larvae from crushed fruit at the time of harvest to identify and cull fruit that has detectable (second

or third instar) larvae. This approach may underestimate *D. suzukii*-related losses or overestimate gains from treatment as undetectable infestation (eggs and first instar larvae) can be significant. Using microscopes, *D. suzukii* eggs and early-instar larvae have been identified in otherwise marketable fruit several days postharvest (Del Fava et al. 2017, Leach et al. 2018, Gullickson, 2020). Retailers maintain zero-tolerance standards for *D. suzukii* and will destroy or return contaminated fruit to growers who must then bear the full costs of production and marketing. Post-harvest losses due to rejected fruit can be substantial (Yeh et al. 2020) and are reportedly more common for organic versus conventional raspberries (Goodhue et al. 2011). Approximately 23% of Swiss cherry growers surveyed in 2016 reported at least one fruit delivery rejected by buyers due to *D. suzukii* infestation (Mazzi et al. 2017).

Since the arrival of *D. suzukii*, fruit growers who previously relied on limited, low-cost IPM tools to manage crop quality have begun investing in annual controls to manage *D. suzukii* (Asplen et al. 2015). Growers use a variety of cultural and chemical treatment strategies for *D. suzukii* management, with the most effective considered to be broad-spectrum conventional insecticides and, to a lesser degree, organic insecticides (Van Timmeren and Isaacs 2013, Asplen et al. 2015, Mazzi et al. 2017). However, organic insecticides tend to cost more, have shorter residual activities, and are less effective against *D. suzukii* compared to conventional insecticides (Gullickson et al. 2019, Sial et al. 2019), indicating the need for additional management options beyond chemical control.

In addition to, and as an alternative to insecticides in both organic and conventional systems, some growers have begun using exclusion netting to prevent *D. suzukii* infestation. Exclusion netting is plastic insect netting with mesh that is too small for certain insects to pass through and can be used to prevent pests from contact with the susceptible plant. An 80 g netting, which has a mesh size of 1.0 mm × 0.6 mm, is required to exclude *D. suzukii* from passing through the mesh openings (Cormier et al. 2015).

High tunnels retrofitted with fine mesh netting have effectively reduced *D. suzukii* infestation (Cormier et al. 2015, Leach et al. 2016, Rogers et al. 2016), and improved small fruit yield (Demchak 2009, Yao and Rosen 2011, Hanson et al. 2016). In floricane (summer-bearing) red raspberry production, high tunnels equipped with exclusion netting had 82% fewer *D. suzukii* eggs and 74% fewer larvae infested fruit and the first instance of infestation was six days later compared to open field production (Leach et al. 2016). Sixty-three percent of Swiss growers who used exclusion netting were satisfied with its effectiveness as a single control measure for *D. suzukii* compared to 56% of growers who used insecticides (Mazzi et al. 2017).

From an economic, whole farm perspective that accounts for the costs and benefits of *D. suzukii* control (e.g., Mitchell and Hutchison 2009, Onstad and Crain 2019), the results are inconclusive. To date, the impact of *D. suzukii* on farm revenue has been quantified by combining detectable yield loss from infestation with production values to estimate economic damage (Bolda et al. 2010, De Ros et al. 2015, Yeh et al. 2020) and by quantifying material and labor costs incurred for *D. suzukii* prevention and control (Goodhue et al. 2011, Burrack 2012, De Ros et al. 2015, Mazzi et al. 2017, Farnsworth et al. 2017).

Using these methods, several studies suggest that the material and labor costs associated with conventional insecticide applications outweigh the yield benefits for soft-skinned fruit crops, resulting in negative net returns for *D. suzukii* control (Lee et al. 2011, Del Fava et al. 2017, Yeh et al. 2020). However, other studies indicate that insecticides can eliminate virtually all revenue losses from *D. suzukii* resulting in positive revenue gains for large-scale conventional farms

producing high-value crops (Goodhue et al. 2011, Lee et al. 2011, Farnsworth et al. 2017). Organic insecticides cost more than conventional sprays (Goodhue et al. 2011, Farnsworth et al. 2017), yet the premium for organic berries can also be significant (USDA-Agricultural Marketing Service [AMS]), potentially outweighing the cost of treatment (Yeh et al. 2020). Preliminary research suggests that using organic insecticides to reduce *D. suzukii* yield losses can improve profitability for large-scale farms (Goodhue et al. 2011).

All economic studies to date assume growers operate at a large scale and benefit from economic efficiencies when purchasing labor and material inputs. However, most raspberry farms in the Upper Midwest are small with a median farm size of 0.20 hectares (0.50 acres) compared to farms in California, Oregon and Washington (the country's major production areas) where median farm size is 5.57 hectares (13.76 acres) (Supp Table 1 [online only]). The raspberry growing season in the Upper Midwest is short – typically lasting 4–10 wk per season depending on variety, compared to 24 wk in California (Farnsworth et al. 2017). Despite their small farm sizes and relatively short production seasons, raspberry growers in Upper Midwest states contribute significantly to state-wide produce revenue. In Minnesota, for example, growers supply approximately half of the state's seasonal (4-month) raspberry utilization (DiGiacomo et al. 2019) and demand remains strong for additional local produce.

Knapp et al. (2021) proposed that the heterogeneity of farm structure (farm size, management, crops produced) can lead to differences in perceived and actual *D. suzukii* control costs. Thus, while some organic strategies, such as insecticides and exclusion netting, show promise for controlling *D. suzukii* it remains unclear whether the economic benefits observed on large-scale farms in California are transferable to relatively small, seasonal organic farms like those found in the Upper Midwest.

In this study, we report the results from 2017 to 2019 efficacy field trials for two organic *D. suzukii* controls and uses these results to investigate the economic costs and benefits of organic control treatments for small-scale seasonal raspberry operations. The treatments explored are exclusion netting applied to the end walls of high tunnels and a chemical rotation of insecticides for open field application. Visibly detectable and undetectable *D. suzukii* are accounted for in the analysis to explore the effects of zero-tolerance standards on net returns for the small-scale seasonal grower. Results are tested for rigor using a sensitivity analysis on raspberry price and yield – two common risk factors for fruit growers.

Materials and Methods

Field trials for the efficacy experiments took place on certified organic land at the West Central Research and Outreach Center, University of Minnesota, Morris, MN. (45.5919°N, 95.9189°W). The efficacy trials compared two treatments in 2018–2019: high tunnels with exclusion netting and open plots with organic insecticide treatments. The same high tunnel and field plots were used in 2017 as controls (no treatment applied) for another experiment conducted by the same researchers with the same plants. Data from the 2017 field trial experiment were applied in this study to represent the 'no treatment' control for 2018–2019 as *D. suzukii* pest pressure at this site in 2017 was similar to pest pressure in other years at nearby MN field plots (Rogers et al. 2016).

The 2017–2019 experimental plots were 5.2 m long and plants were spaced at 0.6 m intervals within each row with four replications for each treatment. Bare-root fall-bearing raspberry plants, *Rubus idaeus* L. cv. 'Himbo Top', (Nourse Farms, Whately, MA)

were planted on 8 June 2016 and were allowed to establish for a year prior to 2017 data collection. Since primocane raspberries are pruned to the ground in the spring annually, their growth was consistent among all years.

For the high tunnel experiment, eight research-size exclusion tunnels (5.2 m length $\times$ 2.4 m width $\times$ 2.4 m height) were constructed and covered with 6 mm thick UVA clear poly. End walls were left uncovered in 2017. In 2018 and 2019, tunnel ends were covered with ExcludeNet (Berry Protection Solutions, Stephentown, NY) 80 g insect netting at the green berry stage or prior to bloom and fastened to the tunnels using Snap Clamps (Circo Innovations, Grass Valley, CA) plastic fasteners.

For the insecticide treatment field trials, raspberry plots were sprayed with a spinosad (Entrust SC Naturalyte)-erythritol (Now Foods, Bloomingdale, IL) chemical rotation in 2018 and spinosad-*Chromobacterium subtsugae* (Grandevo WDG, Marrone Bio Innovations, Davis, CA) in 2019; the change to Grandevo WDG was due to phytotoxicity experienced with Entrust in 2018 (Supp Table 3 [online only]). The maximum allowable number of applications according to the product label were made each year; a total of 4 applications in 2018 and 12 applications in 2019. During both years, spraying was initiated at the pink fruit stage, approximately 1 wk before the first harvest.

Fruit for all plots was harvested twice weekly during the 2017–2019. The harvest windows in 2017, 2018, and 2019 lasted from 8 August to 9 October, 7 September to 27 September, and 1 August to 9 October, respectively. Fruit was classified as marketable if the raspberries were fully ripe, firm, undamaged in appearance and could be sold fresh. Raspberries were classified as unmarketable if they were overripe, crumbly, had visible mold, sunscald, or reflected visibly detectable damage from *D. suzukii*. A subsample of 10 marketable berries per treatment replication were observed over the duration of one week in lab conditions to explore the presence of visually undetectable *D. suzukii* (eggs and first instar larvae). Raspberries that were infested with visually undetectable *D. suzukii* at the time of harvest (LAB_{0t}), became heavily sunken with juice pooling and often had late-instar larvae present within one week, while uninfested raspberries remained dry and intact.

To determine whether yields and approximate *D. suzukii* populations were similar between years, we used a two-way ANOVA comparing the total yields amongst treatment and year on the number of *D. suzukii* caught in traps. Field trial data on total yield (g), the number of *D. suzukii* caught in traps, and infestation rates (proportion of *D. suzukii* infested berries) for treatments were investigated for normality and then analyzed with two-way ANOVA followed by a Tukey post-hoc test ($\alpha = 0.05$). Data were analyzed using R (4.0.0., R Core Team, R Foundation for Statistical Computing, Vienna, Austria).

The field trial data were used for a cost–benefit analysis to compare the economic performance of exclusion netting and insecticides for small-scale growers of organic raspberries, 0.20 ha (0.50 acres). The cost–benefit analysis applies partial budget (PB) methods. PBs

are based on the principle that a minor change in operational management, such as spraying for *D. suzukii* or adding exclusion netting to high tunnels, can increase (or decrease) farm income.

The PB is structured as a table with two columns (Table 1) where the net change in income is represented as $NCI_{0t} = (C_0 + R_t) - (R_0 + C_t)$. The left-hand-side of the table has one column listing the negative economic effects of added costs associated with the proposed change (C_t) or new treatment and the reduced returns that would have been generated under original operations with no treatment (R_0). These added costs and reduced returns are described in the PB as ‘added outflows’. Another column on the right-hand-side of PB table lists positive economic effects or ‘added inflows’ which are represented by reduced costs associated with the original management plan where no treatment was applied (C_0) and the added returns from improved yields with the applied treatment (R_t). The difference between the two columns (net change in income or NCI_{0t}) indicates whether the proposed change (spraying with organic insecticides or adding exclusion netting) will have a positive or negative effect on profitability. When NCI_{0t} is positive, the change in income from the new treatment is greater than the alternative of no treatment.

The difference between added inflows and added outflows are used to estimate the benefit-cost ratio (BCR). This ratio is calculated as benefits divided by costs and is represented as $BCR_{0t} = (C_0 + R_t)/(R_0 + C_t)$. The BCR is a discrete way of identifying the most cost-effective control strategy and for prioritizing control strategies (Tisdell, 1995). When the BCR = 1.0, the proposed change (organic *D. suzukii* strategy) would break-even on expenses. A BCR <1.0 will lose money whereas BCR >1.0 would generate a profit or positive return on investments represented as $P_{0t} = BCR_{0t} - 1.0$, where P_{0t} represents the profit generated for every \$1 invested.

Fixed costs, for items such as buildings, land, equipment and perennial crops, are not included in the PB as these items remain unchanged when making minor changes (Dalsted and Gutierrez 2004, Tigner 2018). Accordingly, our analysis did not include material or operating costs associated with plants, plant establishment, organic certification, spray equipment, protective clothing and high tunnel structures.

The PB did account for treatment costs, harvest expenses and yield using visibly detectable and visibly undetectable *D. suzukii* infestation rates. High tunnel exclusion netting and fabric clips were valued using list prices available from Berry Protection Systems and Growers Solution, LLC and amortized over 7–10 yr. Time for field tasks was measured by researchers and verified with growers (personal communication with Harry Hoch, MN and Dale-Ila Riggs, NY). The time for annual installation and removal of netting on four tunnels (8.53 m $\times$ 28.04 m or 24 ft $\times$ 92 ft each) was estimated at 18–24 h. Installation rates vary depending on the fastening system used, grower experience and snow loads. (Growers in the Midwest have an incentive to remove netting at the end of each season to preserve their investment during winter months.) We used the most conservative estimate, 24 h, for netting installation and removal.

Material expenses for the insecticide trials were estimated using application rates recorded by researchers and advertised

Table 1. Partial budget parameters necessary for analysis of *D. suzukii* control and net revenue

Added Outflows	Added Inflows
Additional costs (C_t)	Additional returns (R_t)
Reduced returns (R_0)	Reduced costs (C_0)
Total additional costs and returns ($C_t + R_0$)	Total additional returns and reduced costs ($R_t + C_0$)
Net change in income $NCI_{0t} = (R_t + C_0) - (C_t + R_0)$	

Table 2. Annual material and labor input costs for organic *D. suzukii* treatments

	Material and labor costs (\$)
Exclude netting ^a (\$ per m ²)	0.01
Fabric clips ^b (\$ per clip)	0.18
Organic insecticides ^c	
Entrust (\$ per oz)	14.28
Erythritol (\$ per oz)	0.01
Grandevo (\$ per oz)	1.77
Water (\$ per gallon)	0.02
6 oz. vented clamshell berry containers ^d (\$ per container)	0.08
Packing tray ^e (\$ per tray)	1.32
Labor for treatment, harvest and packing ^f (\$ per hour)	13.54

^aExclude netting was applied to high tunnel end panels, 80 g, assumed 7-year useful life. 31.21 m² (336 ft²) per end wall (each end wall measures 12' × 28'). Source: Berry Protection Solutions. <https://www.berryprotectionsolutions.com>.

^bUsed to attach netting to end walls, assumed 10-year useful life. 36 clips per tunnel. \$1.75/clip. Source: Growers Solution. <https://www.growersolution.com/product-search.html>.

^cSee Supp. Table S3 (online only) for insecticide application rates.

^dSource: Item #434H160. Webstaurant Supply Store. <https://www.webstaurantstore.com/6-oz-vented-clamshell-produce-container-case/434H160.html>

^eSource: Item #1350. Glacier Valley Enterprises, Inc. <https://www.glacierv.com/SPD/item-no-1350--tray-produce--corrugated--250-pack--800005C1-1471886894.jsp>.

^fSource: USDA—NASS, Farm Labor. Field worker wage rates, Lakes Region. 'Wage Rates by Type of Worker—Region and United States: July 9–15, 2017'; 'Wage Rates by Type of Worker—Region and United States: July 8–14, 2018'; 'Wage Rates by Type of Worker—Region and United States: July 7–13, 2019'.

retail prices (Table 2). Water, used to dilute insecticide concentrates, was valued by the UMN's West Central Research and Outreach Center (\$0.02/gallon). Labor for insecticide treatments included the time needed by researchers to prepare and apply chemicals and to clean sprayer equipment following treatments (1.75 h per application for 0.20 ha).

Harvest and packing labor were not recorded for the University of Minnesota field trials and instead were quantified using estimates from Michigan State University, College of Agriculture & Natural Resources field trials (Eric Hanson, Department of Horticulture, personal communication) where researchers were able to harvest and pack 3.40 kg (7.5 lbs) of raspberries per hour. The Michigan State University harvest and packing labor estimates were recorded for primocane (fall-bearing) raspberries in high tunnel conditions with a planting density similar to the University of Minnesota field trial experiments. Packing container needs (170.10 g or 6 oz. vented plastic clamshell) and produce trays (self-locking, vented, corrugated 49.53 cm × 39.70 cm × 10.74 cm [19.50 in. × 15.63 in. × 4.23 in.]) were estimated using prices from Internet wholesale suppliers WebstaurantStore and Glacier Valley Enterprise, LLC, respectively. Labor for all activities (treatment, harvest, packing) was valued at \$13.54/hour—the 2017–2019 average for seasonal field labor in the Lakes region (USDA-NASS 2017, 2018, 2019).

Raspberries were valued using weighted average retail prices for certified organic berries compiled by the USDA Agricultural Marketing Service in 2017–2019 and converted to a median 3-year price (\$18.21/kg or \$8.26/lb). Retail prices were chosen because the

majority of raspberry growers in Midwestern states market direct-to-consumers rather than through wholesale channels (Bruce et al. 2019, Supp Table 2 [online only]).

Quantifying the economic benefits for the PB required isolating the effects of *D. suzukii* at harvest from abiotic effects such as weather and temperature as well as disease and other pests. The task of physically separating fruit that was unmarketable due solely to *D. suzukii* was impractical as berries that are infested with *D. suzukii* often present additional problems (e.g., molding, sunscald and crumbling). Therefore, we applied the 2-year weighted average *D. suzukii* infestation rates of lab incubated fruit (LAB_{0t}) to berries that were identified visually as unmarketable for any reason and thus culled at harvest (HC_{0t}). By applying the *D. suzukii* lab infestation rates to visually unmarketable berries at harvest, we generated theoretical culls attributable only to *D. suzukii*. We represent these 'detectable' *D. suzukii* culls as SC_{0t} = LAB_{0t} * HC_{0t}, and suggest that they are similar to 'low' pest pressure calculations assumed in other studies. The estimated marketable yield after detectable *D. suzukii* culls are removed, DMY_{0t}, can be represented as DMY_{0t} = TY_{0t} - SC_{0t}, where TY_{0t} is total yield at harvest. The percent of detectable infestation is represented as DMY_{0t}/TY_{0t}. Using DMY_{0t}, we were able to determine whether the benefits of treatment (change in baseline DMY₀ vs. DMY_t) outweighed the costs of each *D. suzukii* treatment.

PB results were tested for robustness by applying a sensitivity analysis to address grower risk factors such as postharvest shipment rejections, yield fluctuations and market price variability. We accounted for postharvest shipment rejection by applying the same lab infestation rates (LAB_{0t}), to berries that were otherwise considered visibly marketable at harvest and ready for retail distribution. Potential yield loss due to 'undetectable' infestation is represented as UC_{0t} = LAB_{0t} * DMY_{0t} and the estimated marketable yield with undetectable yield losses removed as UMY_{0t} = (DMY_{0t} - UC_{0t}). Fruit with visibly undetectable *D. suzukii* appear marketable at harvest but may show signs of *D. suzukii* infestation by the time they reach the shipping destination. By accounting for both detectable and undetectable *D. suzukii* infestation we capture the full effect of treatment gains and losses. Detectable and undetectable *D. suzukii* infestation can be compared to 'low' and 'high' pest pressure assumed in economic threshold and economic injury literature.

We applied yield data from the top performing year, 2019, to explore how a 'best case' production scenario would affect the net returns of different treatments in the detectable and undetectable *D. suzukii* infestation scenarios. We chose to explore the impact of improved yield variation on the economic analysis as 2019 yields were found to be comparable with the results from previous Minnesota field research.

To explore the impact of price risk on the PB results, we applied negative or downward pressure on market prices to explore how costs and benefits would change with seasonal fluctuations and grower decisions to sell into wholesale, rather than retail, markets. We calculated net returns using prices that were reduced by 25%, 50% and 75%.

Results

Among the three years of this study and the two-year average (2018–2019) data, significant differences in yield were observed (ANOVA, $F_{3,32} = 4.170$, $P = 0.0134$), where 2018 and the two-year average had significantly lower yields compared to 2019 (Table 3). There were no effects of treatment (ANOVA, $F_{2,32} = 0.484$, $P = 0.6209$),

Table 3. Yield and *D. suzukii* Fruit Infestation, MN red raspberries, 0.20 hectares (0.50 acres)

	2017 no treat.	2018 treat.	2019 treat.	2018–2019 avg
<i>High Tunnels</i>				
Total yield (TY) ^a , kg	582.40	569.51	756.66	663.08
Fruit infested with visibly detectable <i>D. suzukii</i> , kg (% TY)	124.73 (21.4)	67.81 (11.9)	8.07 (1.1)	37.94 (5.7)
Fruit infested with visibly undetectable <i>D. suzukii</i> , kg (% TY)	406.48 (69.8)	204.42 (35.9)	19.02 (2.5)	111.72 (16.8)
Total fruit infested with <i>D. suzukii</i> , kg (% TY)	531.21 (91.2)	272.23 (47.8)	27.09 (3.6)	149.66 (22.6)
Marketable yield after detectable <i>D. suzukii</i> removed, kg	457.67 (78.6)	501.70 (88.1)	748.59 (98.9)	625.14 (94.3)
Marketable yield after undetectable <i>D. suzukii</i> removed, kg	175.92 (30.2)	365.09 (64.1)	737.64 (97.5)	551.36 (83.2)
Marketable yield after detectable and undetectable <i>D. suzukii</i> removed, kg	51.19 (8.8)	297.28 (52.2)	729.57 (96.4)	513.42 (77.4)
<i>Open Plots</i>				
Total yield ^a (kg)	665.78	253.34	928.22	590.78
Fruit infested with visibly detectable <i>D. suzukii</i> fruit, kg (% TY)	145.26 (21.8)	5.90 (2.3)	68.11 (7.3)	37.01 (6.3)
Fruit infested with visibly undetectable <i>D. suzukii</i> , kg (% TY)	444.42 (66.8)	16.67 (6.6)	250.55 (27.0)	133.61 (22.6)
Total fruit infested with <i>D. suzukii</i> , kg (% TY)	589.68 (88.6)	22.57 (8.9)	318.66 (34.3)	170.61 (28.9)
Marketable yield after detectable <i>D. suzukii</i> removed, kg (% TY)	520.52 (78.2)	247.44 (97.7)	860.11 (92.7)	553.77 (93.7)
Marketable yield after undetectable <i>D. suzukii</i> removed, kg (% TY)	221.36 (33.2)	236.67 (93.4)	677.67 (73.0)	457.17 (77.4)
Marketable yield after detectable and undetectable <i>D. suzukii</i> removed, kg (% TY)	76.10 (11.4)	230.77 (91.1)	609.56 (65.7)	420.16 (71.1)

^aRepresents cumulative organic red raspberry harvest from .20 ha.

nor an interaction of treatment and year (ANOVA, $F_{2,32} = 1.995$, $P = 0.1525$), on total yield. Similar results were observed when analyzing marketable yield (ANOVA, $F_{3,32} = 3.273$, $P = 0.034$), where 2018 had significantly lower marketable yields compared to 2019 (Table 3). There were no significant effects of treatments (ANOVA, $F_{2,32} = 0.068$, $P = 0.9347$) or interactions between treatments and years (ANOVA, $F_{2,32} = 2.503$, $P = 0.0978$). There was a statistically significant interaction between the effects of treatment and year on the number of trapped *D. suzukii* ($F_{1,320} = 49.20$, $P < 0.0001$). Tukey's post hoc test revealed that only the 2019 open field plot had significantly more trapped *D. suzukii* than the other treatments or years at the $\alpha = 0.05$ level (Table 4).

The proportion of *D. suzukii* infested fruit, measured in the lab as undetectable infestation (Table 3) was significantly different among treatments (ANOVA, $F_{2,32} = 22.87$, $P < 0.0001$), years (ANOVA, $F_{3,32} = 25.51$, $P < 0.0001$), and there was an interaction between treatments and years (ANOVA, $F_{2,32} = 10.52$, $P = 0.0003$). Tukey's post hoc test revealed that all treatments were different from each other, with untreated open plots (average proportion infestation = 0.773) having significantly more infestation than high tunnels with exclusion netting (average proportion infestation = 0.404) and open plots with insecticide application (average proportion infestation = 0.216), respectively. Additionally, among the years of this study, 2017 had significantly more infestation across all treatments compared to the other years (Table 3).

Yield and infestation results were similar for the organic pesticide trials (Table 3). Cumulative total yield (kg/0.2 hectare) and marketable yield (kg/0.2 hectare) were numerically higher for the open plots sprayed with organic pesticides in 2018 and 2019 compared to the open plots without treatment in 2017. Again, however, cumulative total yield (ANOVA, $F_{2,32} = 0.484$, $P = 0.6209$) and marketable yield (ANOVA, $F_{2,32} = 0.068$, $P = 0.9347$) were not significantly different between treatments. The proportion of infested marketable fruit was significantly different between the open plot organic pesticide treatment (0.216 ± 0.04) and open plot without organic pesticide treatment (0.886 ± 0.04 ; ANOVA, $F_{2,32} = 22.87$, $P < 0.0001$).

Although the field trials found no statistically significant effects of treatment on cumulative yield, differences in infestation suggest that organic growers would benefit economically from the application of *D. suzukii* controls. When accounting for visually-infested

Table 4. Mean ($\pm$ SEM) of *D. suzukii* adults caught in baited traps, weekly, for selected field treatments, Morris, MN, 2017–2019

Year	Treatment	<i>D. suzukii</i> trap-1 wk-1 (mean $\pm$ SEM) ^a
2017	High tunnel, no exclusion netting	39.8 $\pm$ 9.7 a
2018	High tunnel, exclusion netting	33.7 $\pm$ 10.2 a
2019	High tunnel, exclusion netting	0.6 $\pm$ 0.2 a
2017	Open plot, no chemical treatment	16.2 $\pm$ 4.3 a
2018	Open plot, organic pesticides	23.7 $\pm$ 6.7 a
2019	Open plot, organic pesticides	198.6 $\pm$ 34.3 b

^aMeans followed by different letters indicate significance, using Tukey's hsd ($P < 0.05$).

or detectable *D. suzukii* berries, the total benefits for high tunnel growers, measured as the value of gross returns with exclusion netting plus the reduced harvest costs when no treatment is in place (high tunnels without netting), exceeded total costs (materials and labor) in the detectable *D. suzukii* infestation scenario (Table 5). The average annual net change in income (2018–2019) with exclusion netting in place was positive totaling \$2,203.56 for .20 hectares (0.50 acres). Over a five-year period, cumulative gains totaled \$11,017.80 for 0.20 hectares (0.50 acres). It follows that the benefit-cost ratio (BCR) for the high tunnel exclusion netting treatment is >1 . The BCR for this scenario measures 1.22 suggesting that for every \$1.00 invested annually, the exclusion netting returns \$0.22 change in income (Table 5).

Conversely, we found that organic insecticides did not quite pay for themselves using .20 ha plots; the cost of insecticide treatments out-weighed any numerical yield gains (Table 6). The net change in income (NCI_{0t}) totaled $-\$117.53$ annually for 0.20 hectares (0.50 acres) and $-\$587.67$ after five years of cumulative loss for 0.20 hectares (0.50 acres; Table 6). The BCR for organic insecticides was 0.99, however, suggesting that while the strategy does not break even, economic losses are relatively negligible for growers managing small-scale plots (Table 6).

When undetectable *D. suzukii* infestation losses were accounted for, both strategies became more attractive economically. Undetectable *D. suzukii* infestation measured 16.8% for the high

Table 5. Partial budget analysis: detectable *D. suzukii* infestation in high tunnel with netting (2018–2019 avg) vs. high tunnel without netting (2017), MN organic red raspberries, 0.20 hectares (0.50 acres)

Added outflows		Added inflows	
Additional costs (C_t) (\$/0.20 ha)		Additional returns (R_t) (\$/0.20 ha)	
80g Exclude Net ^a	103.68	w/netting	11,385.35
Fabric clips ^b	50.40		
Net install/removal labor ^c	324.96		
Clamshell containers ^d	125.03		
Cardboard flats ^e	122.25		
Harvest + pack labor ^f	1,128.58		
Reduced returns (R_0) (\$/0.20 ha)	8,334.17	Reduced costs (C_0) (\$/0.20 ha)	
w/o netting		Clamshell containers	91.53
		Cardboard flats	89.50
		Harvest + pack labor	826.25
Total costs ($C_t + R_0$) (\$/0.20 ha)	10,189.07	Total benefits ($R_t + C_0$) (\$/0.20 ha)	12,392.63
Net change in income (NCI_{0t}) ^g (\$/0.20 ha): 2,203.56			
Cum. change in income, 5 yr (\$/0.20 ha): 11,017.80			
Benefit-cost ratio (BCR_{0t}) ^h : 1.22			

^a168 SF per tunnel or 672 square feet for four tunnels (each measuring 28' × 92') on 0.20 ha (0.50 acres), assumed 7-year useful life.

^b72 clips per tunnel or 288 clips for four tunnels (each measuring 28' × 92') on 0.20 ha (0.50 acres), assumed 10-year useful life.

^cFor the high tunnel exclusion netting treatment, labor included adding and removing netting each season. Time estimated was 6 h per tunnel per year.

^dEach vented clamshell berry container holds 6 ounces of berries. Retail price is \$0.08 per container.

^eEach flat holds 18–6 oz plastic clamshell containers. Retail price is \$1.32/flat.

^fLabor includes time to harvest, sort and pack berries. Harvest and pack rates were assumed to equal 3.40 kg (7.5 lbs) of raspberries per hour.

^g $NCI_{0t} = (R_t + C_0) - (C_t + R_0)$.

^h $BCR_{0t} = (R_t + C_0)/(C_t + R_0)$.

Table 6. Partial budget analysis: detectable *D. suzukii* infestation, open plots with organic insecticide treatment (2018–2019 avg) vs. open plots without insecticide treatment (2017), MN red raspberries, .20 hectares (.50 acres)

Added outflows		Added inflows	
Additional costs (C_t) (\$/0.20 ha)		Additional returns (R_t) (\$/0.20 ha)	
Organic insecticide #1 ^a	186.03	w/organic insecticide	10,084.24
Organic insecticide #2 ^b	273.06		
Water for insecticide concentrate	1.25		
Labor for insecticide apps ^c	189.56		
Clamshell containers ^d	110.76		
Cardboard flats ^e	108.29		
Harvest + pack labor ^f	999.75		
Reduced returns (R_0) (\$/0.20 ha)	9,478.67	Reduced costs (C_0) (\$/0.20 ha)	
no insecticide		Clamshell containers ^d	104.10
		Cardboard flats ^e	101.79
		Harvest + pack labor ^f	939.71
Total costs ($C_t + R_0$) (\$/0.20 ha)	11,347.37	Total benefits ($R_t + C_0$) (\$/0.20 ha)	11,229.84
Net change in income (NCI_{0t}) ^g (\$/0.20 ha): –117.53			
Cum. change in income, 5 yr (\$/0.20 ha): –587.67			
Benefit-cost ratio (BCR_{0t}) ^h : 0.99			

^aTwo applications of spinosad (Entrust SC Naturalyte) in 2018 and 6 applications in 2019.

^bTwo applications of erythritol (Now Foods, Bloomington, IL) in 2018 and 6 applications of spinosad-chromobacterium (Grandevo WDG, Marrone Bio Innovations, Davis, CA) in 2019.

^cLabor included time spent to prepare and apply insecticides and to clean the sprayer after each use. Time recorded by field researchers was 105 min per application for 0.20 ha (0.50 acres).

^dEach vented clamshell berry container holds 6 ounces of berries. Retail price is \$0.08 per container.

^eEach flat holds 18–6 oz plastic clamshell containers. Retail price is \$1.32/flat.

^fLabor includes time to harvest, sort and pack berries. Harvest and pack rates were assumed to equal 3.40 kgs (7.5 lbs) of raspberries per hour.

^g $NCI_{0t} = (R_t + C_0) - (C_t + R_0)$.

^h $BCR_{0t} = (R_t + C_0)/(C_t + R_0)$.

tunnels fitted with exclusion netting (2018–2019 avg.) compared to 69.8% for high tunnels with open sides and no netting (2017) bringing total *D. suzukii* infestation to 22.6% and 91.2%, respectively (Table 3). The CBA suggested that the installation of exclusion

netting on high tunnels would return an additional \$6,675.64 in income annually for 0.20 hectares (.50 acres) or \$33,378.20 cumulatively over five years for 0.20 hectares (0.50 acres) when undetectable infestation is counted as a total loss (Table 7). The BCR

for exclusion netting using postharvest infestation losses measured 3.40 suggesting that for every \$1.00 invested in this strategy, a high tunnel grower would net a \$2.40 change in income (Table 7).

Similarly, undetectable infestation observed in otherwise marketable fruit postharvest was 22.6% (2018–2019 avg.) for open field plots sprayed with insecticides and 66.7% for open plots without chemical treatment (2017) bringing total *D. suzukii* infestation to 28.9% and 88.6%, respectively (Table 3). The open plot organic pesticide treatment yielded a \$4,853.67 change in income annually for 0.20 hectares (0.50 acres) or \$24,268.33 for 0.20 hectares (0.50 acres) over a five-year period compared to the open plot without chemical treatment (Table 8). The BCA for the organic pesticide treatment when visibly undetectable postharvest losses were included is 2.64 suggesting that for every \$1.00 invested in this strategy, an additional \$1.64 is generated in income (Table 8).

For the sensitivity analysis on yield we substituted 2019 ‘best year’ yields in place of the 2018–2019 yield averages to explore the impact of more representative yields. The efficacy trials revealed that the 2019 yields were statistically different from the cumulative 2018–2019 yields and were more comparable with yields from previous Minnesota field research. Cumulative 2019 yields for high tunnels with exclusion netting averaged 756.66 kg (1,668.15 lbs) compared to 663.08 kg (1,461.84 lbs) for 2018–2019 when accounting for detectable *D. suzukii* (Table 3). The difference in infestation and yield led to a 2-fold increase in net income for the exclusion netting treatment—from \$2,203.56 per 0.20 ha annually (2018–2019 avg.) to \$4,178.17 per 0.20 ha annually (2019 ‘best year’) based on the increased spread in detectable yield losses. The 2019 exclusion netting treatment returned a BCA of 1.40 (Table 9). Similar results were observed when undetectable infestation losses were applied. The net change in income jumped from \$6,675.64 per 0.20 ha annually (2018–2019 avg.) to \$10,339.68 per 0.20 ha annually (2019 ‘best year’) with a BCA of 4.38 (Table 9).

Significant yield gains, 73% and 57%, also were observed in 2019 for open plots treated with organic insecticides compared to

2018 and 2018–2019 average yields, respectively. Unsurprisingly, the CBA produced a positive net change in income when 2019 yields alone were considered for both detectable and undetectable *D. suzukii* infestation scenarios. The net change in income increased from –\$117.53 per 0.20 ha annually (2018–2019 avg.) to \$4,786.62 per 0.20 ha annually (2019 ‘best year’) when applying detectable infestation losses (Table 9). The BCA rose from 0.99 (just below break-even) to 1.40. Similarly, when additional undetectable *D. suzukii* infestation losses were considered, the net change in profit improved from \$4,853.67 (2018–2019 avg.) to \$7,883.20 (2019 ‘best year’). The resulting BCA increased from 2.64 to 3.33 (Table 9).

For the sensitivity analysis on price, organic raspberry prices received by growers were reduced by 25%, 50% and 75% to explore conservative organic premium losses (nonorganic raspberry prices for 2017–2019 averaged 25% less than organic prices) and wholesale alternatives (wholesale prices paid to growers typically average 50% of the retail price; Table 10). The exclusion netting strategy could withstand a price drop almost equal to 75% in the detectable *D. suzukii* infestation scenario and a price drop >75% when undetectable infestation was accounted for without losing money on treatment (Table 10). Profitability losses, however, escalated as the price paid to growers decreased in the detectable *D. suzukii* infestation scenario for organic insecticides with the CBA decreasing from 0.99 to 0.87 (Table 10). When undetectable *D. suzukii* were counted, the organic insecticide treatment broke-even on costs when prices paid to growers fell by 75% (Table 10).

Discussion

Our research sheds new light on the economic profitability of organic-based control strategies for small-scale fruit growers facing the challenge of *D. suzukii* infestations in berry crops. The partial budget (PB) analysis suggests that small-scale high tunnel growers

Table 7. Partial budget analysis: undetectable *D. suzukii* infestation, high tunnel with exclusion netting (2018–2019 avg) vs. high tunnel without netting (2017), MN organic red raspberries, 0.20 hectares (0.50 acres)

Added outflows		Added inflows	
Additional costs (C_i) (\$/0.20 ha)	103.68	Additional returns (R_i) (\$/0.20 ha)	9,349.56
80 g Exclude Net ^a	50.40	w/netting	
Fabric clips ^b	324.96		
Net install/removal labor ^c	125.05		
Clamshell containers ^d	122.27		
Cardboard flats ^e	1,128.74		
Harvest + pack labor ^f			
Reduced returns (R_0) (\$/0.20 ha)	932.17	Reduced costs (C_0) (\$/0.20 ha)	
w/o netting		Clamshell containers ^d	10.92
		Cardboard flats ^e	10.01
		Harvest + pack labor ^f	92.42
Total costs ($C_i + R_0$) (\$/0.20 ha)	2,787.27	Total benefits ($R_i + C_0$) (\$/0.20 ha)	9,462.91
Net change in income (NCI_{0i}) ^g (\$/0.20 ha): 6,675.64			
Cum. change in income, 5 yr (\$/0.20 ha): 33,378.20			
Benefit-cost ratio (BCR_{0i}) ^h : 3.40			

^a168 SF of netting assumed per tunnel or 672 square feet for four tunnels (each measuring 28' × 92') on 0.20 ha (0.50 acres), assumed 7-year useful life.

^b72 clips per tunnel or 288 clips for four tunnels (each measuring 28' × 92') on 0.20 ha (0.50 acres), assumed 10-year useful life.

^cFor the high tunnel exclusion netting treatment, labor included adding and removing netting each season. Time estimated was 6 h per tunnel per year.

^dEach vented clamshell berry container holds 6 ounces of berries. Retail price is \$0.08 per container.

^eEach flat will hold 18–6 oz plastic clamshell containers. Retail price is \$1.32/flat.

^fLabor includes time to harvest, sort and pack berries. Harvest and pack rates were assumed to equal 3.40 kg (7.5 lbs) of raspberries per hour.

^g $NCI_{0i} = (R_i + C_0) - (C_i + R_0)$.

^h $BCR_{0i} = (R_i + C_0)/(C_i + R_0)$.

Table 8. Partial budget analysis: undetectable *D. suzukii* infestation, open plots treated with organic insecticides (2018–2019 avg) vs. open plots without insecticides (2017), MN organic red raspberries, 0.20 hectares (0.50 acres)

Added outflows		Added inflows	
Additional costs (C_t) (\$/0.20 ha)		Additional returns (R_t) (\$/0.20 ha)	7,651.20
Organic insecticide #1 ^a	186.03	w/organic insecticide	
Organic insecticide #2 ^b	273.06		
Water for insecticide concentrate	1.25		
Labor for insecticide apps ^c	189.56		
Clamshell containers ^d	89.64		
Cardboard flats ^e	82.17		
Harvest + pack labor ^f	758.54		
Reduced returns (R_0) (\$/0.20 ha) w/o insecticide	1,385.78	Reduced costs (C_0) (\$/0.20 ha)	
		Clamshell containers ^d	16.23
		Cardboard flats ^e	14.88
		Harvest, pack labor ^c	137.39
Total costs ($C_t + R_0$)	2,966.03	Total benefits ($R_t + C_0$)	7,819.70
Net change in income (NCI_{0t}) ^g (\$/0.20 ha): 4,853.67			
Cum. change in income, 5 yr (\$/0.20 ha): 24,268.33			
Benefit-cost ratio (BCR_{0t}) ^h : 2.64			

^aTwo applications of spinosad (Entrust SC Naturalyte) in 2018 and 6 applications in 2019.

^bTwo applications of erythritol (Now Foods, Bloomington, IL) in 2018 and six applications of spinosad-chromobacterium (Grandevo WDG, Marrone Bio Innovations, Davis, CA) in 2019.

^cLabor included time spent to prepare and apply insecticides and to clean the sprayer after each use. Time recorded by field researchers was 105 min per application for 0.20 ha (0.50 acres).

^dEach vented clamshell berry container holds 6 ounces of berries. Retail price is \$0.08 per container.

^eEach flat holds 18–6 oz plastic clamshell containers. Retail price is \$1.32/flat.

^fLabor includes time to harvest, sort and pack berries. Harvest and pack rates were assumed to equal 3.40 kg (7.5 lbs) of raspberries per hour.

^g $NCI_{0t} = (R_t + C_0) - (C_t + R_0)$.

^h $BCR_{0t} = (R_t + C_0)/(C_t + R_0)$.

Table 9. Partial budget analysis: ‘best year’ yield performance, organic *D. suzukii* control treatments versus no treatments, MN organic red raspberries, 0.20 hectares (0.50 acres)

	High tunnel w/netting; Best year yield: 2019		Open plot w/insecticides; Best year yield: 2019	
	Detectable <i>D. suzukii</i>	Undetectable <i>D. suzukii</i>	Detectable <i>D. suzukii</i>	Undetectable <i>D. suzukii</i>
Added outflows (\$/0.20 ha)				
Additional costs	2,126.58	2,126.97	2,542.91	1,999.60
Reduced returns	8,334.17	932.17	9,478.67	1,385.78
Total costs	10,460.75	3,059.14	12,021.58	3,385.39
Added inflows (\$/0.20 ha)				
Additional returns	13,631.64	13,285.47	15,662.60	11,100.09
Reduced costs	1,007.28	113.35	1,145.60	168.50
Total benefits	14,638.92	13,398.82	16,808.20	11,268.59
Net change in income (\$/0.20 ha)	4,178.17	10,339.68	4,786.62	7,883.20
Cum. change in income, 5 yr (\$/0.20 ha)	20,890.85	51,698.40	23,933.11	39,416.01
Benefit-cost ratio	1.40	4.38	1.40	3.33

benefit from the use of exclusion netting in a variety of risk scenarios explored (infestation, yield and price). Similarly, small-scale organic open field growers would benefit from the application of insecticides when pest pressure reaches a minimum threshold of >6% infestation or undetectable *D. suzukii* are accounted for post harvest.

Findings from our study are similar to previous research for conventional controls which concluded that the cost of insecticide treatments outweighed the benefits of *D. suzukii* control for soft fruit crops when low or, in this study, detectable pest pressure exists (Lee et al. 2011, Yeh et al. 2020). However, the PB results for the organic insecticide treatment came close to breaking-even suggesting that organic price premiums almost compensate for the higher value of the organic insecticides. Furthermore, our findings concur with Del Fava et al. (2017) who concluded that exclusion netting (in comparison

to a bundled IPM treatment of conventional insecticides) became increasingly more profitable as pest damage intensified, namely under high pest pressure or, in our study, when undetectable *D. suzukii* infestation losses were taken into consideration.

The method used to isolate *D. suzukii* damage is an important step towards quantifying grower returns on treatment. We used available organic field trial yields and lab-incubated fruit to quantify detectable and undetectable *D. suzukii* infestation. The infestation rates were found to be statistically different using a two-way ANOVA comparing the total yields amongst treatment and year on the number of *D. suzukii* caught in traps. Detectable infestation (visibly detectable *D. suzukii* at time of harvest) was $\approx 6\%$ for both organic treatments compared to 21.8% and 21.4% for the untreated high tunnel and open plots, respectively. The undetectable

Table 10. Sensitivity analysis: benefit–cost ratio (BCR) with 25–75% reduction in organic retail price paid to growers

	High tunnel w/netting, 2018–2019 avg.		Open plot w/insecticides, 2018–2019 avg.	
	Detectable <i>D. suzukii</i>	Undetectable <i>D. suzukii</i>	Detectable <i>D. suzukii</i>	Undetectable <i>D. suzukii</i>
Baseline CBA (\$18.21/kg or \$8.26/lb)	1.22	3.40	0.99	2.64
CBA w/25% price reduction (\$13.66/kg or \$6.20/lb)	1.18	2.46	0.97	2.26
CBA w/50% price reduction (\$9.11/kg or \$4.13/lb)	1.11	1.88	0.94	1.76
CBA w/75% price reduction (\$13.66/kg or \$6.20/lb)	0.98	1.11	0.87	1.08

infestation (*D. suzukii* eggs and early-instar larvae present in lab tests postharvest) was considerably higher than detectable infestation at harvest indicating significant economic risks for growers. Undetectable infestation measured 33.7% for the high tunnels with netting compared to 91.2% for the tunnels without netting and 22.6% for the plots treated with insecticides compared to 88.6% for untreated plots. The detectable and undetectable *D. suzukii* infestation losses estimated in our study can serve as a proxy for ‘low’ and ‘high’ pest pressure assumed in economic threshold and economic injury literature. We suggest that as *D. suzukii* pressure increases, so too do the economic benefits associated with organic controls for small-scale growers in the Upper Midwest.

These results have important implications for the soft fruit industry. Our research indicates that a zero-tolerance threshold for *D. suzukii* may not be realistic for several reasons. First, the Minnesota research team was experienced at recognizing *D. suzukii*, yet was unable to visually detect all berries that were infested at the time of harvest. It was not until after harvest, in the lab, that *D. suzukii* infestations were fully identified and confirmed. This is consistent with observations made by Leach et al. (2016) and Del Fava et al. (2017). Second, our research accounted for fruit that was infested with *D. suzukii* eggs and first instar larvae postharvest, counting 100% of this fruit a total loss as would be done at the retail level. For this reason, our research also highlights the importance of postharvest small fruit handling techniques, particularly for growers who market into wholesale sales channels. Good handling practices, such as maintaining cold storage (Jakobs et al. 2017) or implementing other tactics such as deterrent essential oils (Bedini et al. 2020) will be necessary to reduce postharvest losses. Fruit for the UMN laboratory trials was incubated at approximately 22°C for 7 d before we assessed infestation, which gave eggs and early-instar larvae time to develop. However, growers can manage this risk by ensuring adequate cold storage for 72 h, eggs and early-instar *D. suzukii* can be prevented from developing further (Aly et al. 2017), suggesting that, even in retail stores and farmers markets, fruit should be kept at low temperatures to prevent further development of larvae.

Our economic results are reasonable as suggested by conservative input assumptions (maximum spray rates, inclusion of postharvest handling expenses and no assumed increase in harvest labor as pest pressure increased). Likewise, the results are stable as confirmed by the sensitivity analysis for yield and price.

Although our study identified several positive outcomes for organic management of *D. suzukii*, there are some limitations with our study. First, the field trial controls (no treatment) took place during the year prior to the treatment applications. Differences in pest pressure in Minnesota can vary by year and can therefore

lead to differences in marketable harvests (e.g., Ebbenga et al. 2019). However, our 2017 baseline infestation compared similarly to infestation rates observed two years earlier at the Rosemount Research and Outreach Center, Rosemount, MN (44.728104°N, 93.096785°W) (Rogers et al. 2016).

Secondly, the field trials found no significant marketable yield differences between the high tunnel exclusion and open plot yields (Table 3, $P = 0.9347$). Previous research suggests that high tunnels provide a more productive environment for raspberries and other crops – bearing higher quality fruit and greater cumulative yields in Minnesota (Rogers et al. 2016). High tunnel raspberry yields for the 2018–2019 average were significantly lower than conventional yields observed in other MN high tunnel and open field trials initiated prior to arrival of *D. suzukii* in MN (Yao and Rosen 2011) but slightly better than high tunnel trials conducted several years after the arrival of *D. suzukii* (Rogers et al. 2016).

We suggest that the 2019 ‘best year’ yields are more consistent with yields observed in previous Minnesota field research (Rogers et al. 2016) and may represent a more realistic yield for experienced growers. Yields in 2019 were 49% and 247% higher compared to 2018 yields for the exclusion netting and organic insecticide treatments, respectively.

In perennial horticultural crops such as raspberries, there are many factors that can influence yield variability. Yield differences in 2018 v. 2019 were attributed by field researchers to the ‘learning curve’ experienced when using newer practices, such as exclusion netting, which may reflect similar learning curves for growers during the first year of implementation for these practices. Phytotoxicity, for example, was experienced with the spinosad (Entrust SC Naturalyte)-erythritol (Now Foods, Bloomington, IL, U.S.A.) chemical rotation in 2018. Likewise, the late application of exclusion netting in 2018 allowed late-season *D. suzukii* to enter the tunnels and shelter from external environmental conditions (rain, low temperatures, wind) as evidenced by the higher infestation rates in 2018. This sheltering effect was observed recently in fall-bearing raspberry field trials (Stockton et al. 2020). Moreover, an unusually early frost in 2018 abbreviated the already limited MN harvest period. Although the 2018 harvest season was shorter than 2017 and 2019, it is representative of the variability in weather conditions in the Upper Midwest, and challenges associated with a fall bearing fruit crop. Harvests were halted after the first frost in both the field plots and high tunnels. Continued harvests in the high tunnels would have increased yield outcomes and improved economic results in both detectable and undetectable *D. suzukii* infestation scenarios.

Finally, our study assumes the maximum level of chemical treatments and therefore may overestimate the costs of pesticide treatment during low pest pressure periods. Although this assumption is

valid based on previous management challenges in MN raspberry (Rogers et al. 2016), it is also likely that growers would adjust treatment frequency to coincide with the intensity of pest pressure. Thus, costs in our analysis represent upper bounds for organic chemical treatment costs. Future research is warranted to explore the effectiveness of organic insecticides at varied application rates and to explore the yield benefits associated with season extension and prolonged harvests in high tunnels. Furthermore, we suggest that future research explore the scientific and economic advantages of postharvest handling needed to arrest the development of *D. suzukii* eggs and early-instar larvae.

Supplementary Data

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

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