# PLASTIC MULCHES DECREASE ADULT AND LARVAL POPULATIONS OF *DROSOPHILA SUZUKII* IN WISCONSIN RASPBERRY

by

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**Abstract**

The invasive spotted-wing drosophila, *Drosophila suzukii,* is a major pest of fruit crops world-wide. Management of *D. suzukii* relies heavily on chemical control in both organic and conventional systems, and there is a need to develop more sustainable management practices. We evaluated the viability of plastic mulches as a cultural practice for *D. suzukii* in fall-bearing raspberry and assessed the mulches' impacts aspects of canopy microclimate relevant to *D. suzukii*. Black, white, and metallic plastic mulches reduced adult *D. suzukii* populations by 41-51% and larval populations by 52-72% compared to the grower standard. None of the mulches influenced canopy temperature or relative humidity, but metallic mulches increased canopy light intensity compared to the black mulch. Radiance in the spectrum visible to *D. suzukii* was altered by the mulch treatments, with overall higher radiance above white and metallic mulches compared to the black mulch and control. Future studies will determine whether changes in radiance are associated with the reported reduction in *D. suzukii* populations. Plastic mulches are a promising cultural practice for managing *D. suzukii* since they can reduce adult and larval populations.

**Introduction**

Small fruit production is greatly impacted by the invasive pest spotted-wing drosophila, *Drosophila suzukii* (Diptera: Drosophilidae). First detected in the continental US in 2008 (Hauser, 2011), the fly has quickly spread from its native range in Eastern Asia throughout the United States and to most major fruit-producing regions of the world (CABI, 2016). Females use their serrated ovipositor to saw through the skin of undamaged, ripening fruit to lay their eggs (Kanzawa, 1939; Walsh et al., 2011). Once the eggs hatch, larvae feed inside the fruit, making fruit unmarketable. For smaller scale growers, *D. suzukii* damage reduces yield of marketable fruit substantially, making susceptible crops difficult to grow economically and sustainably (Farnsworth et al., 2017; DiGiacomo et al., 2019). For larger scale growers selling to processors, *D. suzukii* infestation can lead to complete loss because of zero-tolerance policies set by processors (Bruck et al., 2011). Susceptible crops include raspberry, blackberry, blueberry, strawberry, sweet and tart cherry, and some cultivars of wine grapes (Lee et al., 2011; Bellamy et al., 2013; Ioriatti et al., 2015; Pelton et al., 2017; Kamiyama and Guédot, 2019).

Currently, management of *D. suzukii* relies heavily on chemical control in organic and conventional systems (Haye et al., 2016). Large-scale growers apply broad-spectrum insecticides every 4-7 days from detection until harvest (Van Timmeren and Isaacs, 2013). In California, the cost of chemical controls was estimated at $1,161 per hectare for conventional and $2,933 for organic growers (Farnsworth et al., 2017). Few effective insecticides are approved for organic production (Sial et al., 2019), giving organic growers limited options for control. Recently, *D. suzukii* has been reported to show reduced sensitivity to some active ingredients, including spinosad, which is the main insecticide for *D. suzukii* in organic systems (Van Timmeren et al., 2018; Gress and Zalom, 2019). Other concerns include detrimental impacts on beneficial insects and potential secondary pest outbreaks (Sarkar et al., 2020). In tandem with chemical control, cultural practices have been shown to help manage *D. suzukii*, including harvesting fruit promptly, field sanitation, burial or composting of infested fruit, and exclusion netting (Leach et al., 2016, 2018; Hooper and Grieshop, 2020). However, these methods are labor intensive, requiring harvest every 2-3 days and frequent removal and destruction of damaged fruit, and often must be complemented with chemical control (Leach et al., 2016, 2018).

Cultural practices that modify the crop canopy microclimate have the potential to reduce *D. suzukii* infestation due to the fly's sensitivity to temperature and humidity (Tochen et al. 2016; Guédot et al. 2018). Adult summer morph *D. suzukii* thrive in warm but not hot temperatures, with the highest rate of population increase between 20-28 °C (Hamby et al., 2016), and an upper developmental threshold of 30.9 °C (Ryan et al., 2016). In the field, low populations of *D. suzukii* are observed in California in the summer, suggesting development or activity are slowed by hotter temperatures (Wang et al., 2016). *Drosophila suzukii* also thrives in high relative humidity, with the longest survival and most eggs laid at 94% relative humidity in the lab (Tochen et al. 2016). In the field, females laid more eggs in the inner canopy of blackberry and blueberry, likely due to the darker, cooler, more humid environment (Diepenbrock and Burrack, 2017; Evans et al., 2017). Thus, increasing the temperature and reducing humidity in the canopy could deter *D. suzukii* from laying eggs or disrupt immature development inside fruit.

Polyethylene mulches have been used since the 1960s to modify the microclimate in fruit and vegetable agroecosystems to achieve weed control, earlier ripening, improved fruit quality, and increased yield (reviewed in Tarara 2000; Lamont 2005; Kasirajan and Ngouajio 2012). However, polyethylene mulch is difficult to dispose of or recycle and contributes to persistent plastic pollution (Kasirajan and Ngouajio, 2012). Mulches made from biodegradable materials have been developed as an alternative, and have been shown to have the same benefits as polyethylene mulches (Anzalone et al., 2010; Girgenti et al., 2012; Miles et al., 2012; Costa et al., 2014; Devetter et al., 2017; Bandopadhyay et al., 2018; Ghimire et al., 2018). In raspberry biodegradable plastic mulches improved plant growth, yield, and weed management (Zhang et al., 2019).

Polyethylene and biodegradable plastic mulches are made in different colors, and some colors have been successful at controlling insect pests. Black plastic mulch is the standard among growers worldwide due to its ability to raise soil temperatures and kill weeds (Tarara 2000; Kasirajan and Ngouajio 2012), but its impacts on insects are inconsistent. Black mulch deterred aphids from watermelon and yellow squash (Farias-Larios and Orozco-Santos, 1997; reviewed in Greer and Dole, 2003; Ban et al., 2009), but attracted aphids, whiteflies, and thrips to tomatoes (Greer and Dole, 2003). White and metallic (also referred to as reflective or aluminum) plastic mulches may be more effective at repelling insects since they reflect more solar radiation, increasing air temperatures and light intensity while decreasing humidity (Decoteau et al., 1989; Gordon et al., 2008; Andreotti et al., 2010; Nottingham and Kuhar, 2016; Smrke et al., 2019). The effect of white mulch was also inconsistent, since it reduced Mexican bean beetles in snap beans (Nottingham and Kuhar, 2016) and deterred aphids from yellow squash and watermelon (Farias-Larios and Orozco-Santos, 1997; Greer and Dole, 2003), but attracted aphids, thrips, and whiteflies to tomatoes (Greer and Dole, 2003). Metallic mulch more consistently reduced insects pest populations, including Asian citrus psylla on citrus trees (Croxton and Stansly, 2014), tarnished plant bugs in strawberry (Rhainds et al., 2001), and pear psylla in pear (Nottingham and Beers, 2020). In vegetable crops, metallic mulches reduced aphids, thrips, whiteflies, cucumber beetles, and leafhoppers, and also reduced insect-vectored viruses (Summers and Stapleton, 2002; Greer and Dole, 2003; Nyoike and Liburd, 2010; Simmons et al., 2010). However, metallic mulch increased tomato pinworm and fruitworm in tomato (Schalk and Robbins, 1987). It remains largely unknown whether plastic mulches can control pests in the family Drosophilidae, including *D. suzukii*.

Recently, woven fabric weedmat was tested for *D. suzukii* management in blueberry with inconclusive results. In Florida, weedmat (color unspecified) numerically reduced adult *D. suzukii* captured in lured traps, but differences were not significant (Parkins, 2018). In a multi-state study also in blueberry, black weedmat caused no significant reduction in *D. suzukii* populations, but reductions in fruit infestation were reported at one site with newly established plants (Rendon et al., 2019). These studies suggest that mulches might be viable for managing *D. suzukii* under some conditions. However, it remains unknown if the small reductions in *D. suzukii* were caused by unfavorable abiotic conditions in the canopy or another attribute of the black weedmat, such as color.

The goal of this study was to evaluate the impact of black, white, and metallic plastic mulches on *D. suzukii* in fall-bearing raspberry. In the first objective, we assessed the impact of plastic mulches on adult and larval populations of *D. suzukii*. We hypothesized that plastic mulches would cause a decrease in *D. suzukii* adult populations and larval infestation of fruit. In the second objective we evaluated the impact of plastic mulches on the raspberry canopy microclimate. We hypothesized that white and metallic plastic mulches would increase canopy temperatures, time above *D. suzukii*'s upper thermal development threshold, and light intensity, and reduce canopy relative humidity. We hypothesized that the black mulch would not change the canopy microclimate, since it is likely to reflect less light due to its darker color, therefore leading to a smaller decrease in *D. suzukii* adult populations than the white and metallic mulches.

## Methods

### *Grower advisory panel*

We established a grower advisory panel of five Wisconsin berry growers to help guide research questions, plan experiments, problem-solve, provide feedback, and ensure the research is practical and relevant to regional farmers. The advisory panel met at the Wisconsin Fresh Fruit and Vegetable Conference in January 2019 for project planning, and again in 2020 to provide feedback and suggestions after sharing results.

### *Plot set up, maintenance, and experimental design*

This study was conducted on a small commercial fruit and vegetable farm in Iowa County, WI, USA in 2019 and 2020. The raspberry plants were established in 2012 in Plano silt loam in rows 30 m long and 0.5 m wide with 3.05 m between rows for a total area of 0.08 hectares. Alley ways were planted with orchard grass and straw was applied in the rows in the winter before canes emerged. The study was established in two rows each of fall-bearing cultivars ‘Caroline’ and ‘Polana’. Each plot was irrigated with 1.3 cm drip tape with emitters every 5.1 cm, which was placed down the middle of each row. Plots were irrigated identically when needed. Weeds were removed by hand from the gap between mulches and in the control plots as necessary. No insecticides were applied in 2019 or 2020.

Mulches were applied by hand in late April 2019 and 2020 when raspberry canes were just emerging from below straw mulch. Two mulch strips 7.6 m long and 70 cm wide were laid on each side of the row with a ~10 cm gap down the center of the row for canes to grow (Figure S1). All edges were secured with 15.25 cm biodegradable stakes (Eco Turf Midwest, Bensenville, IL) spaced about every 30 cm. Since the plastic mulches restricted the area where raspberry canes could emerge, canes in the control plots that grew outside the 10 cm center strip were pruned both years in June.

The mulch treatments included black biodegradable mulch (Organix AG Film in 0.9 mil, Organix Solutions, Bloomington, MN), white-on-black biodegradable (Organix AG Film in 0.9 mil), and metallic-on-white polyethylene mulch (SHINE N'RIPE in 1.25 mil, Imaflex, Montreal, Quebec), and a grower standard control, where grass filled in the space between the raspberry canes and the alleyway. The treatments were set up in a randomized complete block design with plots of all four treatments in each row, totaling 16 treatment plots.

*Objective 1: Impact of plastic mulches on D. suzukii*

The raspberry field was monitored weekly for the presence of *D. suzukii* using three Scentry SWD traps (Scentry Biologicals, Billings, MT) with a drowning solution of 100 mL apple cider vinegar and one drop of unscented dish soap (Seventh Generation, Burlington, VT). Once *D. suzukii* was detected, the adult population was monitored in the experimental plots using one 15.25 $cm^2$ clear sticky card (Alpha Scents, West Linn, OR) placed in center of each plot in the fruiting zone. As the plants grew, the sticky cards were adjusted vertically to account for changes in canopy height. The sticky cards were replaced every 7 d, and the number of male and female *D. suzukii* caught on each card was recorded.

To assess larval infestation of fruit, 36 ripe fruits (~100 g) were randomly collected from each plot every two weeks from August 19 to October 8, 2019. The salt flotation method was used to determine the number of larvae in half of the fruit sample (Dreves et al., 2014). The other half was placed in plastic rearing cups with mesh lids and flies were reared to the adult stage to determine the proportion of *D. suzukii* to other Drosopholids. Rearing cups were kept at ambient lab conditions for 3 weeks, and then all flies were identified. In 2020, methods were modified slightly to allow for weekly sampling. Each week from August 25 to September 29, 2020, samples of 23 fruits were randomly collected from each plot and 18 fruits were used in the salt flotation tests and 5 fruits were placed in rearing cups. All flies that emerged in both years were identified as *D. suzukii*, so no adjustments were made to the data.

*Objective 2: Impact of plastic mulches on raspberry microclimate*

Canopy temperature, relative humidity (RH), and light intensity were monitored continuously from July 9 to October 18, 2019 and July 3 to October 6, 2020. HOBO data loggers were hung in the fruiting zone, and height was adjusted vertically as described for the sticky cards. Temperature and RH were recorded every minute using HOBO U23 Pro v2 Data Loggers (OnSet, Bourne, MA) attached underneath a 25.4 cm diameter white plastic plate radiation shield. Light intensity was recorded every minute using HOBO Pendant MX Temperature/Light data loggers measuring in lux, a measure of the intensity of light between 400-700 nm, as perceived by the human eye.

To characterize the radiance in the canopy, a spectrometer (HR 1024i, Spectra Vista Corporation, Poughkeepsie, NY) was used to collect light data in the ranges of 350-2500nm across 1024 spectral channels (bands) with a resolution of 1 nm. The spectrometer was carried into the treatments plots to measure the canopy conditions using a 25° field of view fiber optic cable with a pistol-grip for accurate targeting. Data in the treatment plots was collected in a single row of cultivar ‘Caroline’. On September 2-5, 2020, readings were taken in all four treatments on each day between 8 AM and 11 AM, when flies are active (Jaffe and Guédot, 2019). On both sides of the row, readings were taken from nadir (pointing straight downward) at 40 cm and 80 cm above the ground at five evenly spaced horizontal positions along the plot. Three readings, each with a scan time of 2 seconds, were taken at every position for a total of 60 readings per treatment. As a reference for the baseline radiance of the mulches, reference readings were recorded above mulches stretched across a 43.1 x 43.1 cm embroidery clip frame after every 15 readings taken in the treatment plots. The reference measurements for the control treatments were taken with the empty frame placed on grass.

*Data analysis*

<u>Adult and larval populations</u>

The adult and larval populations were compared between treatments using a two-step approach analyzing zero and non-zero data separately to meet model assumptions. Logistic regressions were used to analyze the presence of adults or larvae with a binary indicator of *D. suzukii* presence / absence as the response variable. Linear mixed-effects models with log-transformed response variables were used to compare differences in the number of *D. suzukii* when present. For all models, the fixed effects were mulch treatment, row, and year, and the random effect was week crossed with year. For the linear mixed effects model of the number of larvae in fruit samples, the female population trapped on sticky cards in the week before fruit sampling was an additional fixed effect. Tukey post-hoc tests were conducted following significance of fixed effects. To determine the overall change in adult and larval populations over the two years, percent change from controls was calculated. The two-year infestation rate was calculated for each mulch treatment [(total number of adults or larvae)/total number of days or fruits sampled], divided by the two-year infestation rate for the controls, and multiplied by 100. This number was subtracted from 100 for the percent reduction compared to the control.

Canopy temperature and humidity

Data for 2019 and 2020 were analyzed separately due to missing data from July to August 2019 caused by a data logger malfunction. Differences in mean, maximum, and minimum daily temperature and mean and minimum RH were analyzed using generalized least squares regression with a moving average of order 3 (Box and Jenkins, 1970; Koreisha and Pukkila, 1990). The fixed effects were mulch treatment and row. Mean RH was a fixed effect for the temperature models and mean temperature was a fixed effect for the RH models. Since most maximum RH values were 100%, the data was analyzed using a two-step approach. Logistic regressions were used to analyze presence of RH readings equal to 100% with a binary indicator of 100% RH / <100% RH as the response variable. Ordinary least squares linear models were used to compare differences in maximum RH values <100%. The fixed effects were mulch treatment, row, and date.

Differences in daily time above *D. suzukii*'s thermal developmental threshold (Ryan et al., 2016) and below 70% RH (as in Schöneberg et al., 2020) were analyzed separately for zero and non-zero data. Logistic regressions were used to analyze presence of temperature or RH readings beyond each threshold with a binary indicator of above / below threshold as the response variable. Negative binomial regressions were used to compare differences in the number of minutes per day beyond each threshold. For all models, the fixed effects were mulch treatment, row, and date.

Canopy light conditions

Differences in mean and maximum daily light intensity were analyzed using ordinary least squares linear regression with log-transformed response variables. The fixed effects were mulch treatment, row, year, and a log-transformed one-day lag to account for autocorrelation of the data (Box and Jenkins, 1970). Data from one experimental plot was removed from the 2020 data because logger placement was inconsistent with other plots due to small plant size.

The radiance data was processed using customized Python scripts based on SpecDAL (http://github.com/EnSpec/SpecDAL), which extracted and reformatted the raw signal data to produce data frames for analyses. Data was manually inspected to remove outliers. Radiance analyses were run on spectra thought to be visible to *D. suzukii;* color vision has been studied extensively in *Drosophila melanogaster*, and is thought to be highly conserved in *Drosophila* species (Kelber and Henze, 2013; Little et al., 2019), which are most sensitive to ultraviolet (UV), blue, and green light with less sensitivity of wavelengths above 600nm (Hardie, 1979; Yamaguchi et al., 2010; Kelber and Henze, 2013; Schnaitmann et al., 2013). The shortest wavelength measured by our spectrometer is 338nm, so our analyses included wavelengths from 330-680 nm.  To identify spectra where treatment significantly effects radiance, separate ordinary least squares linear regressions were run with each wavelength log transformed as the response variable. Treatment, position in the plot, and date were fixed effects.

All analyses were performed in RStudio (RStudio Team 2020). Data were organized using ‘dplyr’ and ‘lubridate’. Regressions were performed using ‘lme4’, ‘car’, ‘nlme’, and ‘MASS’. Post-hoc tests used ‘emmeans’. All data was plotted in ‘ggplot2’ and the PCA plot was made using ‘ggbiplot’.

## Results

**Table 1:** Statistical parameters using mulch treatment, row, and year as predictors of adult *D. suzukii* adult population, overall and separated by sex, measured using clear sticky cards and larval population measured using salt floats.

| | | | Adult fly population | | Female fly population | | Male fly population | | Larvae in fruit | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Effect | df | χ2 | p>χ2 | χ2 | p>χ2 | χ2 | p>χ2 | χ2 | p>χ2 |
| Presence of flies | Mulch | 3 | 15.99 | 0.001 | 10.27 | 0.016 | 20.64 | <0.001 | 8.02 | 0.046 |
| | Row | 3 | 13.80 | 0.003 | 13.30 | 0.004 | 12.22 | 0.007 | 3.05 | 0.38 |
| | Year | 1 | 7.20 | 0.007 | 8.06 | 0.005 | 7.48 | 0.006 | 6.18 | 0.013 |
| | Female pop. | - | - | - | - | - | - | - | 0.01 | 0.92 |
| Number of flies | Mulch | 3 | 28.80 | <0.001 | 19.82 | <0.001 | 6.49 | 0.09 | 24.42 | <0.001 |
| | Row | 3 | 39.18 | <0.001 | 34.87 | <0.001 | 21.95 | <0.001 | 2.62 | 0.45 |
| | Year | 1 | 11.36 | <0.001 | 10.53 | 0.001 | 4.37 | 0.037 | 2.09 | 0.15 |
| | Female pop. | - | - | - | - | - | - | - | 0.54 | 0.46 |

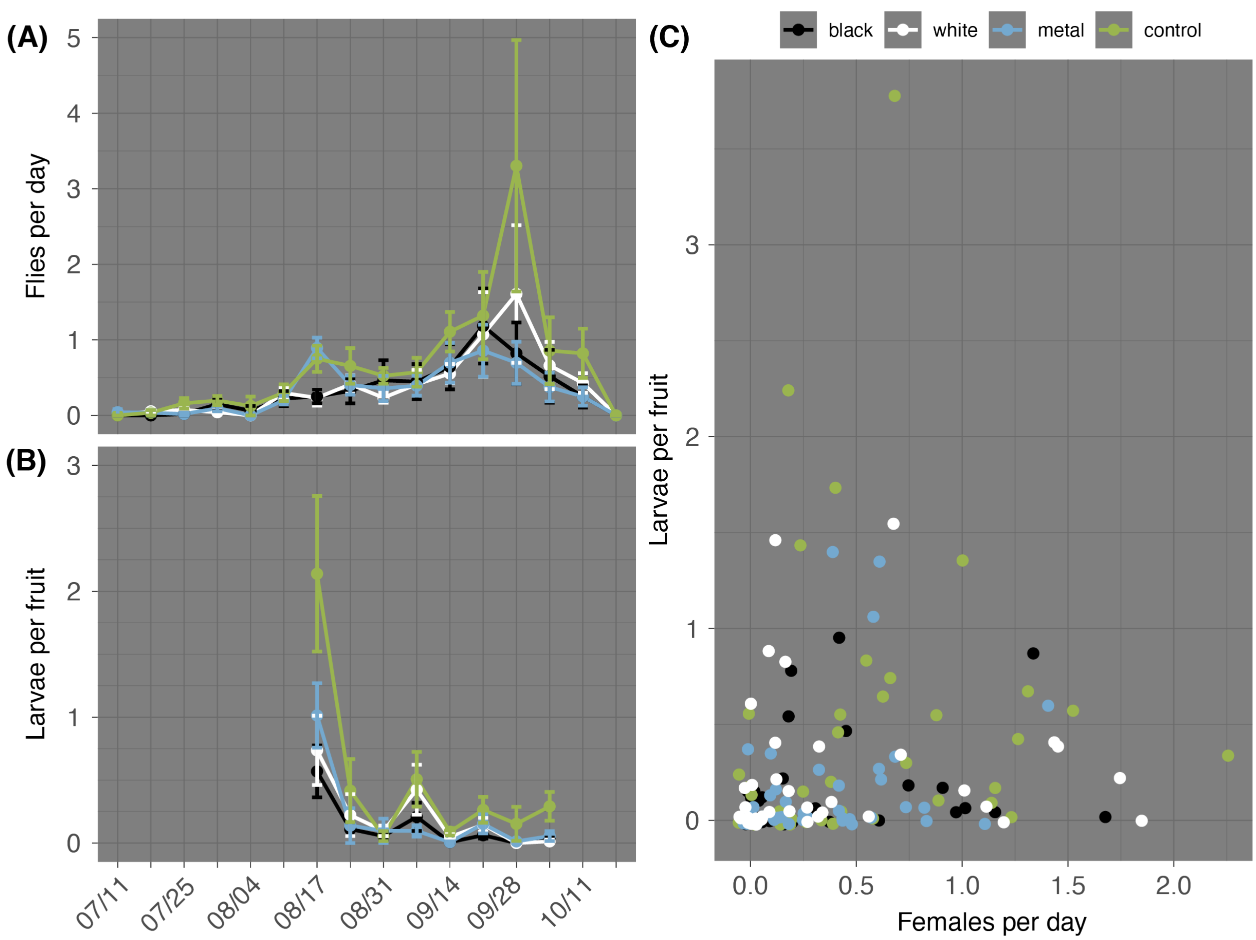


**Figure 1:** Effect of plastic mulches on adult and larval D. suzukii populations. (A) Mean (± SE) adult D. suzukii captured per day on clear sticky cards placed in the fruiting zone and (B) Mean (± SE) larvae per fruit assessed using the salt float method assessed in 2019 and 2020. (C) Relationship between larval infestation of fruit and female population the previous week assessed in 2019 and 2020.

*Objective 1: Impact of plastic mulches on D. suzukii*

The mulch treatments had a significant effect on the presence and number of adult flies captured on clear sticky cards (Table 1). Flies were present on traps above the black mulch less than in the control plots (p<0.001, Figure 1). When separated by sex, the results were the same as above for females (p=0.0089), but males were present on sticky cards above both the black (p<0.001) and white (p=0.017) mulches less than in control plots. When flies were present, lower numbers were found on traps above all the mulch treatments compared to controls (Figure 1). The results were the same for females, but there was no difference in the number of male flies captured above all the mulch treatments (Table 1). Over two years, the total number of flies trapped was reduced by 51% above the black and metallic mulches and by 42% above the white mulch. Fly populations

**Table 2:** Statistical parameters using mulch treatment, rows, and RH or temperature as predictors of canopy temperature or relative humidity measured every minute using HOBO data loggers. Model type is indicated in parentheses with GLS for generalized least squares, LR for logistic regression, OLS for ordinary least squares.

| | | | Mean temperature (GLS) | | Minimum temperature (GLS) | | Maximum temperature (GLS) | | | | Mean RH (GLS) | | Minimum RH (GLS) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Effect | df | LRT | p>χ2 | LRT | p>χ2 | LRT | p>χ2 | Effect | df | LRT | p>χ2 | LRT | p>χ2 |
| 2019 | Mulch | 3 | 0.009 | 1.00 | 0.00 | 1.00 | 0.23 | 0.97 | Mulch | 3 | 0.38 | 0.94 | 0.64 | 0.89 |
| | Row | 3 | 0.033 | 1.00 | 0.19 | 0.98 | 0.14 | 0.99 | Row | 3 | 0.85 | 0.84 | 0.28 | 0.96 |
| | RH | 1 | 2.61 | 0.11 | 317.43 | <0.001 | 261.76 | <0.001 | Temp. | 1 | 30.99 | <0.001 | 30.47 | <0.001 |
| 2020 | Mulch | 3 | 0.040 | 1.00 | 0.11 | 0.99 | 0.78 | 0.85 | Mulch | 3 | 0.40 | 0.94 | 0.70 | 0.87 |
| | Row | 3 | 0.14 | 0.99 | 0.054 | 1.00 | 1.20 | 0.75 | Row | 3 | 2.14 | 0.54 | 1.68 | 0.64 |
| | RH | 1 | 26.49 | <0.001 | 56.81 | <0.001 | 167.37 | <0.001 | Temp. | 1 | 88.65 | <0.001 | 4.96 | 0.026 |

| | | | Maximum RH 100 vs <100 (LR) | | Maximum RH <100 (OLS) | | Above / below 30.9 °C threshold (LR) | | Hours above 30.9 °C threshold (OLS) | | Above / below 70% RH threshold (LR) | | Hours above 70% RH threshold (OLS) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Effect | df | χ2 | p>χ2 | F | p>F | χ2 | p>χ2 | F | p>F | χ2 | p>χ2 | χ2 | p>χ2 |
| 2019 | Mulch | 3 | 0.703 | 0.87 | 0.44 | 0.72 | 1.34 | 0.72 | 1.11 | 0.77 | 0.49 | 0.92 | 0.30 | 0.96 |
| | Row | 3 | 1.60 | 0.66 | 1.32 | 0.29 | 1.78 | 0.62 | 0.31 | 0.96 | 0.16 | 0.98 | 1.79 | 0.62 |
| | Date | 1 | 80.16 | <0.001 | 9.05 | 0.006 | 527.12 | <0.001 | 3.73 | 0.053 | 85.93 | <0.001 | 40.68 | <0.001 |
| 2020 | Mulch | 3 | 0.35 | 0.95 | 0.45 | 0.72 | 7.27 | 0.064 | 0.78 | 0.85 | 0.37 | 0.95 | 0.14 | 0.99 |
| | Row | 3 | 1.47 | 0.69 | 0.53 | 0.67 | 6.50 | 0.090 | 0.28 | 0.96 | 1.47 | 0.69 | 2.92 | 0.40 |
| | Date | 1 | 45.83 | <0.001 | 11.06 | 0.002 | 281.90 | <0.001 | 4.65 | 0.031 | 93.12 | <0.001 | 25.89 | <0.001 |

Data for 2019 and 2020 were analyzed separately due to missing data in 2019 caused by a data logger malfunction.

differed for both years of the study, with higher populations observed in 2019 than 2020 (Table 1).

The presence and number of larvae in fruit samples was also affected by the mulch treatments (Table 1). While treatment was a significant effect in the model, Tukey post-hoc tests identified no significant treatment differences for the presence of larvae in fruit. The number of larvae per fruit was lower in all the mulch treatments compared to the control (Figure 1). Over two years, the total number of larvae in sampled fruit was reduced 72% by the black mulch, 61% by the metallic mulch, and 52% by the white mulch. Larvae were present in fruit samples more often in 2019 than 2020, but the number of larvae in fruit was not different between years. The female fly population in the week prior to fruit sampling was not a significant predictor of presence or number of larvae in fruit (Table 1).

*Objective 2: Impact of plastic mulches on raspberry microclimate*

There were no differences among treatments for the temperature or RH in the raspberry canopy (Table 2). There were also no differences among treatments in the presence of temperatures above the 30.9 C developmental threshold, presence of RH less than 70%, or the amount of time beyond either threshold.

**Table 3:** Statistical parameters using mulch treatment, row, year, and a 1-day lag as predictors of canopy light intensity measured every minute using HOBO data loggers placed in the raspberry fruiting zone during the 2019 and 2020 growing seasons.

| | | Mean light intensity | | Maximum light intensity | |
|---|---|---|---|---|---|
| Effect | df | F | p>F | F | p>F |
| Mulch | 3 | 0.31 | 0.82 | 3.10 | 0.026 |
| Row | 3 | 10.03 | <0.001 | 6.83 | <0.001 |
| Year | 1 | 31.63 | <0.001 | 24.15 | <0.001 |
| 1-day lag | 1 | 1535.62 | <0.001 | 1101.24 | <0.001 |

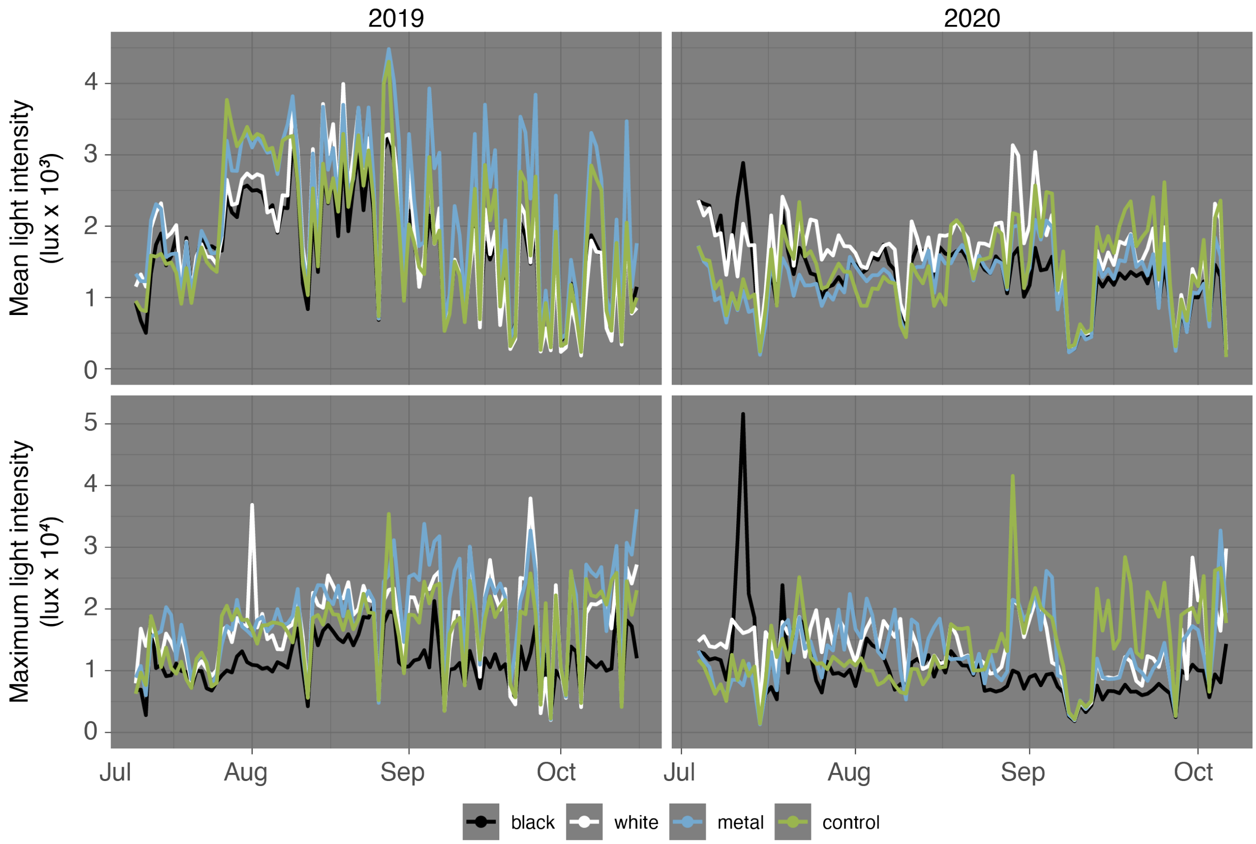


**Figure 2:** Effect of plastic mulches on daily mean and maximum light intensity (lux) in the canopy of raspberry plants in the 2019 and 2020 growing seasons. Data was recorded using HOBO sensors placed in the fruiting zone.

Mean light intensity was not impacted by the mulch treatments (Table 3), but maximum light intensity was higher in the canopy above the metallic mulch compared to the black mulch ($p=0.019$, Figure 2). Year was a significant factor in both the mean and maximum light intensity models, with higher light intensity in 2019 than 2020 (Table 3).

There were differences in radiance among treatments at all wavelengths tested (all $p<0.001$, Figure 3). Radiance was numerically highest for the metallic and white mulches, and lower for the black mulch and control plots (Figure 3). Position that the reading was taken in the plot was a significant effect for all wavelengths (all $p<0.001$), with consistent differences in radiance on the north versus south side of each row.

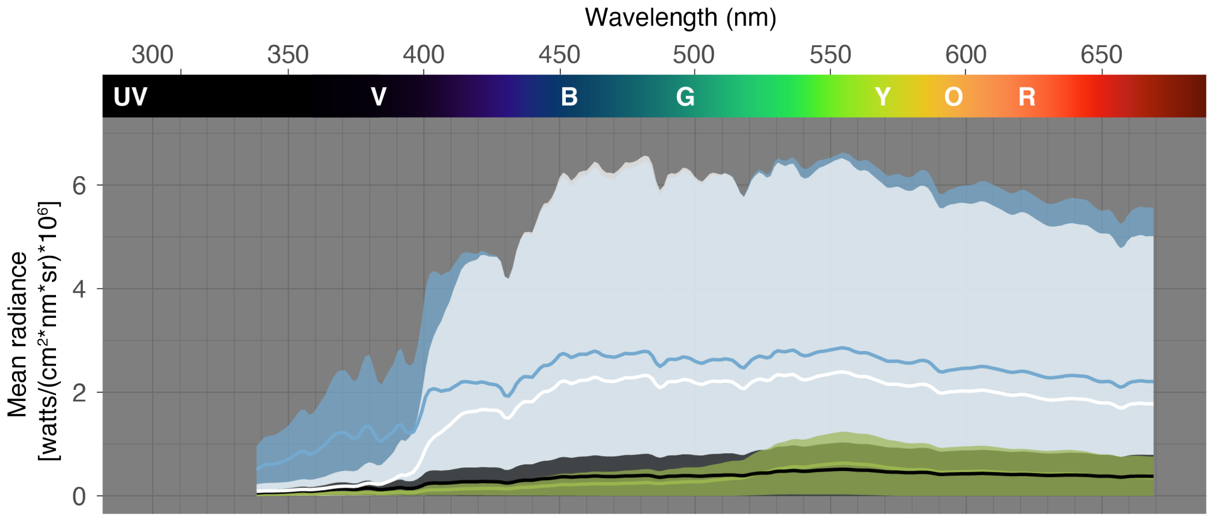


**Figure 3.** Characterization of radiance above mulch treatments in raspberry plot measured in spectra visible to *Drosophila* (330-680nm). Mean (± SD) radiance of the mulch treatments measured in the experimental plots.

## Discussion

Black, white, and metallic plastic mulches reduced the number of adult *D. suzukii* in the canopy and decreased larval infestation of raspberry fruits. The female fly population the week prior to sampling was not a predictor of larval infestation of fruit. Counter to our expectations, there were no clear differences in canopy temperature and humidity among treatments. Maximum light intensity was higher for the metallic mulch than the black mulch, and our radiance data revealed higher radiance above both the white and metallic mulches compared to the black mulch and the control.

Plastic mulches may be more effective than other types of mulches previously tested for managing *D. suzukii.* Indeed, our results show that plastic mulches reduced adult populations in the canopy by nearly 50% and larval infestation of fruit by up to 72%. We recorded the lowest adult populations above the black and metallic mulches, and the lowest level of larval infestation in fruit above the black mulch. In contrast, Rendon et al. (2019) found no effect of black weed mat on *D. suzukii* emergence from blueberries. It remains unknown why black plastic mulch reduces *D. suzukii* populations while black weed mat does not. The effect could be due to some quality of the plastic mulch material (such as reflectivity or permeability) or variable efficacy of mulches by crop and region.

While our study showed plastic mulches reducing both adult and larval populations, understanding the correlation between these populations may be important for determining how plastic mulches reduce *D. suzukii.* It remains unknown whether the mulches are deterring adult flies and thereby reducing larval infestation, altering oviposition behavior, or increasing mortality of immatures stages inside the fruit. The female fly population in the week prior to fruit sampling was not a predictor of larval infestation of fruit in our study. In California raspberries, adult trapping of *D. suzukii* and larval infestation were generally correlated, but the strength and significance of the correlation varied by the type of lure in the traps and organic versus conventional management (Hamby et al., 2014). The authors did report frequent instances of low trap captures with high larval counts. In another study, the number of adults caught in baited traps was not a significant predictor of larval infestation in cold climate wine grapes (Pelton et al., 2017).

We hypothesized that canopy microclimate could impact *D. suzukii* populations as shown by other studies (Hamby et al., 2016; Guédot et al., 2018), but we found no effect of the plastic mulches on canopy temperature or relative humidity. Our results are consistent with a study in snap beans finding no difference in canopy temperature and humidity among black, white, and metallic mulches (Nottingham and Kuhar, 2016). In contrast, metallic mulch increased canopy temperature in summer squash (Gordon et al., 2008) and nectarine (Andreotti et al., 2010). In blueberry, black weed mat increased canopy temperature (Strik et al., 2020). We cannot draw any conclusions about the effect of canopy microclimate on *D. suzukii* populations in this study. Canopy conditions in all treatment plots were frequently in the optimal range for *D. suzukii* (Hamby et al., 2016; Tochen et al., 2016), with temperatures between 20-28 °C and RH above 94% occurring almost daily. Temperatures infrequently exceeded 30.9 °C, *D. suzukii*'s upper developmental threshold (Ryan et al., 2016), which is consistent with a previous study in Wisconsin raspberries (Guédot et al., 2018). It is possible that differences in canopy temperature and humidity could be detected closer to the ground, where *D. suzukii* can also be found in raspberry (Jaffe and Guédot, 2019), so future studies will compare conditions in the lower canopy versus the fruiting zone.

The metallic mulch increased maximum light intensity in the canopy compared to the control, but measurements of light intensity in lux were not different among the black mulch, white mulch, and control plots. Our radiance data gave us a more in-depth view of light conditions in the canopy, identifying differences in radiance across the entire 338-680 nm spectrum. The white and metallic mulches had higher radiance than the black mulch and control, especially at wavelengths above 400 nm. It is clear that the plastic mulches change the radiance in the raspberry canopy compared to the control plots and additional analyses will determine whether changes in radiance are associated with the reduction in *D. suzukii* populations. Similar to our results, Nottingham and Kuhar (2016) measured higher reflected light intensity (400-700nm) above white and metallic mulch in snap beans, attributing the subsequent reduction of Mexican bean beetle to the change in light conditions.  Similarly, Croxton and Stansly (2014) observed more Asian citrus psylla in trees above the metallic mulch on cloudy days than sunny days, concluding that metallic mulch repelled psylla. Overall, the ability of plastic mulches to change canopy temperature, humidity, and light intensity seems to be highly variable by agroecosystem, crop, and climate. Plastic mulches should be tested for *D. suzukii* management in other susceptible crops and climates to confirm efficacy in different regions.

This study demonstrates that plastic mulches are an effective cultural practice for managing *D. suzukii* in fall-bearing raspberry in Wisconsin. Plastic mulches could be used alongside other cultural practices such as frequent harvesting and field sanitation for a more robust integrated pest management program. Overall, plastic mulches are a promising new tool for more sustainable management of *D. suzukii.*

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This research was conducted on the forcibly ceded land of the Ho-Chunk people. Agroecology sees the land on which we grow food in a broader, socio-ecological lens. Land stewardship is a critical component of the agroecological lens, and native people have stewarded this land throughout many generations. Understanding the history of this land is an important first step in achieving equity and justice in our food systems.

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