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Evaluation of Exclusion Netting for Spotted-Wing Drosophila (Diptera: Drosophilidae) Management in Minnesota Wine Grapes

Dominique N. Ebbenga,[1] Eric C. Burkness, and William D. Hutchison

Department of Entomology, University of Minnesota, 219 Hodson Hall, 1980 Folwell Avenue, St. Paul, MN 55108-6125 and [1]Corresponding author, e-mail: ebbe0031@umn.edu

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Abstract

Spotted-wing drosophila, *Drosophila suzukii* (Matsumura), an economically damaging invasive species of numerous fruit crops, was first detected in Minnesota in 2012. High fecundity, and short generation times facilitated a rapid rise in the global pest status of *D. suzukii,* particularly in North America and Europe. To date, the majority of crop injury research has focused on fruit crops such as blueberries, raspberries, and cherries. However, little is known regarding the impact of *D. suzukii* on the wine grape industry in the upper Midwest region of the United States. Field trials were conducted in Minnesota during the summers of 2017–2018 to examine season-long phenology of *D. suzukii* in wine grape vineyards and wineries, and to assess the efficacy of exclusion netting for control of *D. suzukii*. Four treatments were evaluated, 1) open plot check (control), 2) open plot treated with an insecticide, 3) exclusion netting, and 4) exclusion netting, with artificial infestations of *D. suzukii* adults. Exclusion netting was applied at véraison and removed at harvest. On each sample date, 20 berries (10 intact and 10 injured) were collected from each plot for dissection. The number of larvae and adults were recorded for each berry to determine infestation levels. As shown by mean larval infestations and injured berries across treatments, exclusion netting provided a significant reduction in the level of *D. suzukii* infested berries when compared with the untreated check. These results indicate that exclusion netting could provide an effective alternative management strategy for *D. suzukii* in wine grapes.

Key words: *Drosophila suzukii*, phenology, berry injury, integrated pest management, invasive insect pest

Drosophila suzukii (Matsumura), native to East Asia (Walsh et al. 2011, Daane et al. 2016), has become an invasive economic pest of berry crops in numerous countries, throughout the Americas and Europe, during the past decade (Asplen et al. 2015). *Drosophila suzukii*, also known as spotted-wing drosophila, was first recorded in North America in 2008 (Hauser 2011). *Drosophila suzukii* was subsequently found in Minnesota in 2012, and since its arrival has caused severe economic damage to the berry industry (Asplen et al. 2015, Digiacomo et al. 2019). The vast majority of drosophilid species attack overripe or fermenting fruit, as is common with *Drosophila melanogaster* (Meigen). Although *D. suzukii* will also colonize overripe fruit, the species prefers healthy ripening fruit, which creates the potential for excessive economic losses for most host crops (Asplen et al. 2015). The ability of *D. suzukii* to infest immature fruit is based on the female's serrated ovipositor that allows for penetration of the skin of healthy fruit and deposition of eggs (Lee et al. 2011a, Atallah et al. 2014). Once eggs hatch, the larvae begin to consume the flesh of the fruit as they undergo three larval instars, and eventually make the fruit soft and unmarketable (Asplen et al. 2015).

Drosophila suzukii has a wide host range, including raspberry, strawberry, blueberry and grape, as well as stone fruits such as cherry (Bellamy et al. 2013). Berry crops such as raspberries, blueberries, and strawberries have typically received the most attention from researchers because they are highly susceptible to *D. suzukii* infestations (Lee et al. 2011b; Burrack et al. 2013, 2015). However, for other hosts that are not as high risk for *D. suzukii* infestation, such as wine grapes (Holle et al. 2017, Pelton et al. 2017), little information has been established regarding the impact *D. suzukii* can have on the crop and resulting products such as wine (Ioriatti et al. 2015). Currently, it is believed that *D. suzukii* has difficulty infesting or laying eggs in wine grapes unless previous injury has occurred to the berry (Ioriatti et al. 2015, Holle et al. 2017). Wine grapes are susceptible to a physiological condition known as splitting where a sudden increase of water uptake or temperature causes the grape skin to split (Opara et al. 1997, Galvan et al. 2006a). Splitting, along with other forms of injury caused by birds, yellowjacket wasps, and disease-causing pathogens, expose the berry flesh and allow *D. suzukii* to oviposit in grape berries. Even when given the opportunity to infest wine grapes via previous injury, it has been shown that *D. suzukii* may still not have a high level of reproduction in wine grapes due to low survivorship of eggs (Lee et al. 2011b, Pelton et al. 2017). Thus, a more critical or growing concern for wine grape growers is the ability of *D. suzukii* to vector *Acetobactor* spp. from one grape to another by making contact with the either intact or injured berries (Ioriatti et al. 2018). While *Acetobactor* spp. can be present under normal field conditions (Zoecklein et al. 1995), *D. suzukii* presence can increase the rate in which *Acetobactor* spp. spreads and expedite the development of sour rot, creating a lower quality yield (Ioriatti et al. 2018). Acetobactor, also known as acetic acid bacteria (AAB) also impacts the amounts of AAB detected in the grape juice. When juice is contaminated with AAB, there is increased risk of alcohol being converted to acetic acid (vinegar) by AAB that may lead to unacceptable levels of volatile acidity in the wine (Zoecklein et al. 1995), potentially creating unmarketable wine. Based on these concerns, effective management options for *D. suzukii* are needed for wine grape production.

Current integrated pest management (IPM) strategies for *D. suzukii* include the use of a monitoring system for early-season detection (Cini et al. 2012, Pelton et al. 2016, Ebbenga 2018). Because an economic threshold for *D. suzukii* has not been established (Asplen et al. 2015), it is suggested that upon first trap catch of *D. suzukii*, growers begin a weekly program of insecticide applications. To minimize the risk of insecticide resistance, rotation among insecticide classes such as pyrethroids, organophosphates, and spinosyns is recommended (Haye et al. 2016, Hutchison & Wold-Burkness 2018). This situation has led to the use of insecticide applications as the primary form of control for *D. suzukii* in most crops (Bruck et al. 2011, Asplen et al. 2015). While insecticides have the ability to reduce *D. suzukii* populations, their effectiveness is primarily limited to the adult stage, and they have a relatively short period of residual control; thus, larvae may still be present in the fruit, and may emerge shortly after insecticide applications despite the impact on adult mortality (Van Timmeren and Isaacs 2013).

While chemical control continues to be the primary option for managing *D. suzukii* in most berry crops, it is important to evaluate alternative or complementary tactics when developing IPM programs (Cini et al. 2012, Asplen et al. 2015). For *D. suzukii*, which has been particularly challenging to control with insecticides, exclusion netting alone, or in combination with standard poly-based high tunnels, may be an additional approach to consider (Rogers et al. 2016). The use of exclusion netting creates a physical barrier that prevents pests like *D. suzukii*, from making contact with the crop. Rogers et al. (2016) determined that exclusion netting placed on high tunnel structures provided significant control of *D. suzukii* in fall raspberry, when compared to uncovered open plot treatments. In a similar study by Leach et al. (2016), use of exclusion netting on commercial high tunnels showed similar success in reducing *D. suzukii* infestation levels in raspberry. We are not currently aware of published research describing the use of exclusion netting in wine grape vineyards for the management of insect pests in general or *D. suzukii* specifically. Therefore, the objectives of this paper were to first document the phenology of *D. suzukii* in Minnesota vineyards and wineries in relation to crop development, and secondly to investigate the potential use of exclusion netting for management of *D. suzukii* in wine grapes.

Materials and Methods

Phenology Study

In 2017, trials were conducted at three locations to determine when *D. suzukii* was present in Minnesota vineyards and wineries. Locations included Hastings, Waconia, and Excelsior, MN. Scentry (Scentry Biologicals Inc., Billings, MT) traps and lures, accompanied with a drowning solution (water + one drop of soap to break surface tension), were used to track populations at each location. Hastings included four traps in the vineyard, and three traps inside the winery, whereas Waconia and Excelsior locations had two traps placed in both the vineyard and winery. At all three locations, traps were placed inside the winery where vats of wine were fermented, stored, and bottled. Traps in the vineyard were hung from the trellis system below the mid-canopy at approximately 1 m high, and traps in the winery were hung from hooks on walls at approximately 2 m high. Hastings vineyard traps were deployed 15 May, and winery traps were deployed 17 July For Waconia and Excelsior locations, traps were not deployed until 31 July and 15 August, respectively, due to limited access at each location. Traps in vineyards were removed 7 September and winery traps were removed 19 December.

In 2018, additional phenology trials were conducted in vineyards and wineries located near Hastings, Excelsior, and Stillwater, MN. Scentry traps and lures, accompanied with a drowning solution, were used to monitor relative *D. suzukii* populations. The Hastings location had four traps in the vineyard and three traps in the winery, all traps were deployed on 15 May. Traps at the Excelsior location consisted of three traps each in the vineyard and winery, also deployed 15 May. In Stillwater, traps were deployed 5 June, with three traps in both the vineyard and winery. Traps in vineyards were hung on the trellis system just below mid-canopy approximately 1 m high. Traps in the winery were hung in rooms with vats for fermenting grapes, and in bottling areas approximately 2 m high. Traps at the Stillwater location were removed 28 August, and Hastings and Excelsior traps were removed 24 September.

Scentry monitoring systems use a four-component lure and a drowning solution made of 89 ml of tap water and a drop of soap. For both years, trap contents were collected and the drowning solution was replaced weekly. Weekly samples were brought back to the lab and filtered through a medium nylon mesh (226 microns) paint strainer (AES Industries, Plant City, FL) to remove insects from the drowning solution. A dissecting microscope (Leica EZ4W, Leica Microsystems, Buffalo Grove, IL), was used to identify and count the total number of *D. suzukii*. Mean (±SEM) weekly trap catch was calculated for each location.

Exclusion Netting

Trials to assess the efficacy and use of exclusion netting as an alternative method for *D. suzukii* management were conducted at a commercial vineyard located in Hasting, MN in 2017 and 2018. Experimental plots were established on 10 August 2017 and 3 August 2018, respectively. Four treatments were evaluated and consisted of 1) open plot check (control), 2) open plot with insecticide applications, 3) netted plot, and 4) netted plot with artificial infestations of 25 male and 25 female adult *D. suzukii*. Each treatment was replicated four times within a single trellis (row) of 'Marechal Foch' wine grapes in a randomized complete block design. Scentry traps were placed in open plots (treatment 1) and netted plots (treatment 3) to monitor or verify the presence of *D. suzukii* in the experimental plots. Each plot consisted of a single panel within the trellis and was 7 m long with 1.5 m spacing between plots. Additionally, in 2018, three open (treatment 1), and three netted plots (treatment

3) had HOBO data loggers (Onset Computer Corporation, Bourne, MA) placed within the plot to determine whether netting had an impact on temperature. For both years, the trials were established when grapes reached 60–70% véraison, the growth stage when grapes begin exhibiting color change. Covered treatments consisted of one piece of 80-gram mesh netting (ExcludeNet, Tek-knit Industries, Quebec, CA) that was 6 m long × 4 m wide and was draped over both sides of the existing trellis system and enclosed at the base of the vines to prevent entry of *D. suzukii* (Fig. 1). To seal the netting, the sides and end pieces were rolled together and clipped with large and medium binder clips (Universal, Essendant Co. Deerfield, IL). To wrap around objects like vines and trellis posts, a short piece of 15-gauge wire was used to lace through the netting and wrap around the object for a tight seal (Fig. 1).

Weekly berry collections were made to determine whether the exclusion netting was effective at preventing *D. suzukii* infestation. Berry samples consisted of 10 injured and 10 uninjured berries and were collected by examining up to 20 clusters per plot. Availability of injured berries in netted plots was limited at times, which occasionally resulted in some netted plots having less than 10 injured berries being collected. Injured berries were characterized by physiological splitting, or any other injury caused by birds, yellowjackets, disease, and/or storms. Uninjured berries were characterized as fully intact berries with no apparent opening in the berry skin.

After initial setup, *D. suzukii* populations were assessed weekly, as described above, using the Scentry traps in open and netted plots. In each plot, the proportion of clusters with any form of berry injury was recorded based on a presence/ absence sample of 10 clusters. Each year, the grower gave a forecast for the harvest date and this was used to determine when insecticide applications in the open plots (treatment 2) and artificial infestations in the netted plots (treatment 4) would begin. Insecticide applications and artificial infestations were completed prior to weekly berry collections and continued until harvest. Insecticide applications consisted of zeta-cypermethrin (FMC Corp., Philadelphia, PA) at a rate of 118 ml/ha in 95 liters of water per hectare at 241 kPa. Insecticide applications were made using a CO_2 backpack sprayer with a 1.5-m boom (Bellspray, Inc, Opelousas, LA) fitted with 3 TeeJet XR8002 nozzle tips (TeeJet Technologies, Springfield, IL) and no screens, with a nozzle spacing of 50.8 cm. Applications were made to both sides of the trellis to ensure full coverage. Insecticide application dates were 6 and 13 September in 2017 and 16, 23, and 30 August in 2018. Artificial infestations were performed weekly by placing 25 male and 25 female *D. suzukii* flies in each replicate of treatment 4 on 1 and 8 September in 2017 and 16, 24, and 31 August in 2018. Berry collections to assess infestation levels were performed on 7 and 14 September in 2017 and 24 and 31 August and 7 September in 2018. For each berry collection, intact berries were removed from a cluster by cutting and leaving the pedicel intact to ensure no injury was present on the berry, while berries with injury were simply pulled from the cluster. Each berry was placed in an individual 30 ml cup and capped (Dart Container Corp., Mason, MI). Berry samples were brought back to the laboratory and placed in a Percival (Percival Scientific, Inc. Perry, IA) at 24°C 16:8 (L:D) h for 2 wk. After 2 wk, samples were dissected to determine *D. suzukii* infestation levels.

Data were analyzed using an analysis of variance (ANOVA) using R statistical software (R Core Team 2017). Berry infestation data were analyzed for each collection date separately with a square root transformation and a least significant difference (LSD) test for mean separation (R Core Team 2017). Arcsin transformation was performed on berry injury raw data prior to analysis where an ANOVA and LSD test for mean separation were conducted (R Core Team 2017). Means and standard errors are presented. Temperature data collected from HOBO loggers in 2018 trials were analyzed using a t.test (R Core Team 2017).

Results

Phenology Study

Results from the phenology study documented the presence of *D. suzukii* adults in both vineyards and wineries at all locations (Figs. 2 and 3). In 2017, at the Hastings vineyard (Fig. 2A), the *D. suzukii* adult

Fig. 1. Example of exclusion netting applied to a trellis system in the vineyard. Netting was thrown over the top wire, rolled up on all edges, and fastened with binder clips and wires to seal the netting.

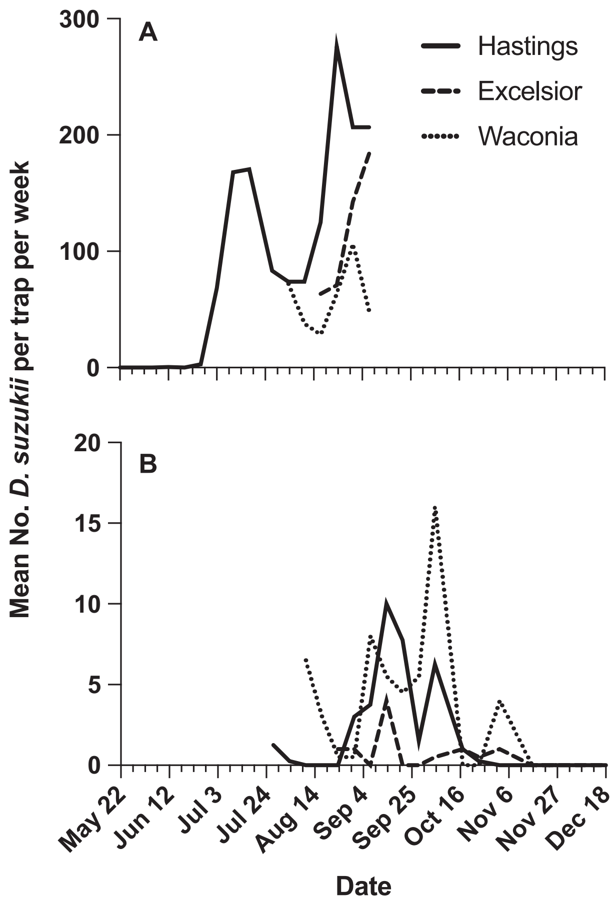

Fig. 2. Weekly mean adult *D. suzukii* trap catch across three locations for (A) vineyards and (B) wineries. Date ranges for trapping in 2017 Vineyards was Hastings: 30 May–17 September, Excelsior: 17 August–7 September, Waconia: 3 August–7 September; and in 2017 Wineries was Hastings 27 July–19 December, Excelsior: 24 August–19 December, Waconia: 10 August–28 November.

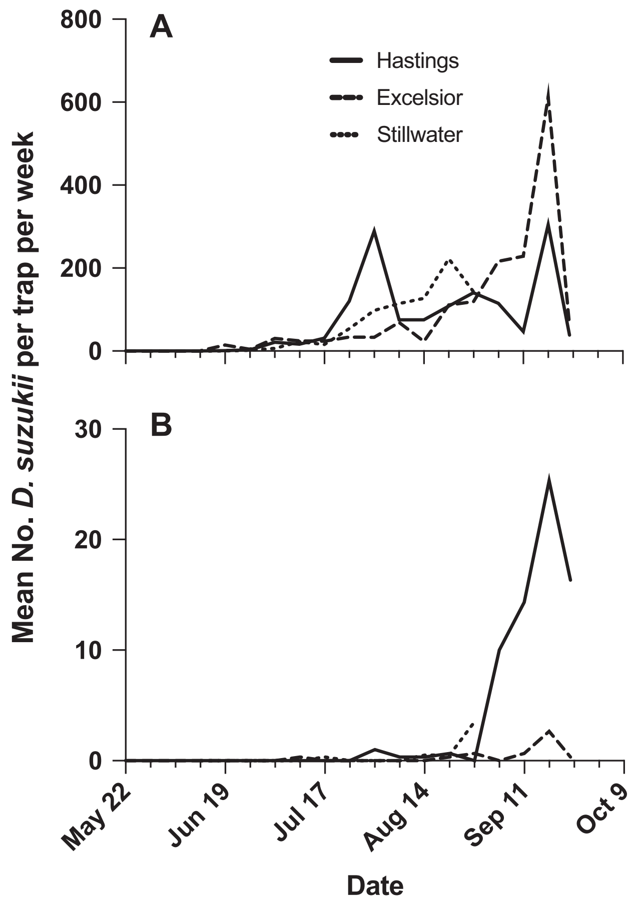

Fig. 3. Weekly mean adult *D. suzukii* trap catch across three locations for vineyards (A) and wineries (B). Date ranges for trapping in 2018 Vineyards was Hastings: 22 May–24 September, Excelsior: 22 May–24 September, Stillwater: 12 June–28 August; and in 2018 Wineries was Hastings 22 May–24 September, Excelsior: 22 May–24 September, Stillwater: 12 June–28 August.

population reached an initial peak on 17 July and proceeded to decrease rapidly just prior to véraison; on 17 August populations began to increase again after véraison. At the Excelsior and Waconia vineyard locations, populations appeared to follow a similar trend, increasing after véraison occurred (Fig. 2A). Once véraison occurred, *D. suzukii* trap catch in the wineries appeared to increase as well (Fig. 2B), although at population levels about one order of magnitude less than in the vineyards. After the first record of injury to grapes on 17 August, *D. suzukii* populations in the Hastings vineyard began to increase with a peak of ~276 flies per trap per week and slowly declined until the berries were harvested. Waconia and Excelsior had peak catches of ~106 and ~184 flies per trap per week, respectively (Fig. 2A).

In 2018, trap data for all vineyards and wineries were very similar to 2017 data (Fig. 3A and B). Trap catches increased after véraison. Vineyards had an order of magnitude higher trap catch than winery traps. In 2018, all traps were deployed 15 May to assess population trends as the crop becomes more susceptible. The first record of véraison occurring was 31 July. In 2018 trap data at Hastings (Fig. 3A), the population began to decrease after véraison occurred. However, a population increase started to develop for trap collections at all vineyards on 21 August, and the first record of injury was noted on 17 August.

Traps at each winery indicated the presence of *D. suzukii* with a mean number of 30 flies per trap per week. Despite the presence of *D. suzukii* in wineries, populations remained relatively low and never reached the levels typically found in Minnesota vineyards. All of the wineries in this study began processing juice and other wine production activities in late July. During the period of wine production, trap catch increased in the wineries (Figs. 2B and 3B).

Exclusion Netting

In 2017, there was a significant difference in mean number of larvae or adults per berry between both netted treatments, when compared to the open plot check (treatment 1) on each collection date, 7 September ($F = 6.66$; df = 3,9; $P = 0.012$), and 14 September ($F = 7.30$; df = 3,9; $P = 0.0001$) (Fig. 4). The open plot treatment with insecticide application (treatment 2) was not significantly different for mean number of larvae or adults per berry compared with the open plot check (treatment 1). On the first collection date, treatment 2 did not differ statistically from either the open check or the two netted plots, but for the second collection date, the insecticide-treated plots, while not significantly different from the open plot check treatment, did have significantly higher levels of adults/larvae per berry compared with both netted treatments (Fig. 4).

In 2018, comparisons of the netted plot (treatment 3) to the open plot check (treatment 1) revealed all three collection dates were significantly different for mean number of larvae/adults per berry. Data for the first collection date of 2018 (Fig. 5) shows a similar trend to the first collection date of 2017 with both netted

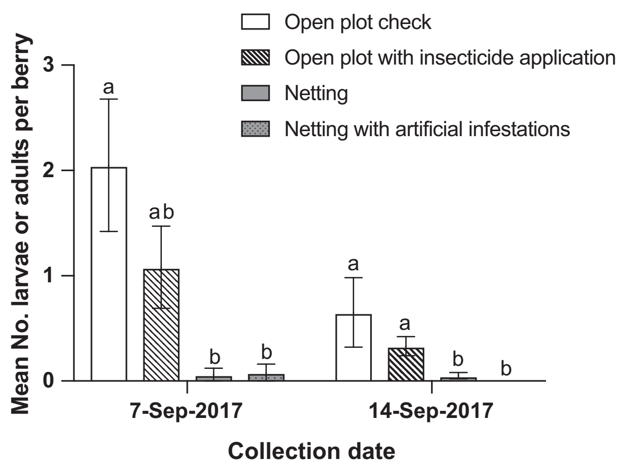

Fig. 4. Mean number of *D. suzukii* larvae or adults per injured berry (2017) for two collection dates. Intact berry collection data is not displayed due to zero-infestation exhibited in these collections.

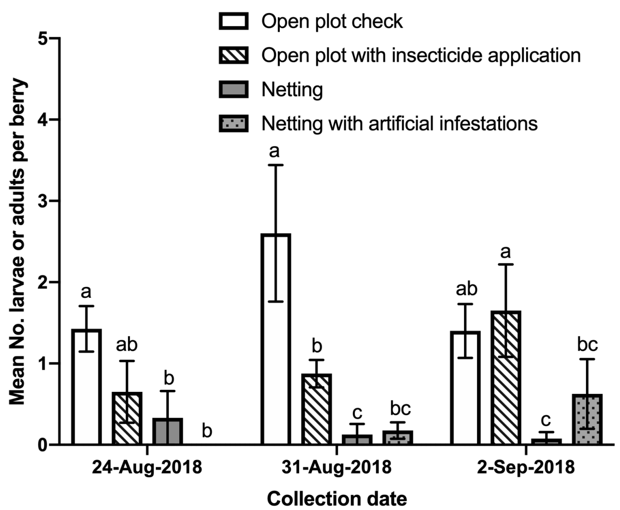

Fig. 5. Mean number of *D. suzukii* larvae or adults per injured berry (2018) for three collections dates. Intact berry collection data is not displayed due to zero-infestation exhibited in these collections.

plots being significantly different from the open plot check for mean number of larvae/adults per berry (24 August; F = 8.78; df = 3,9; P < 0.0001). Again, similar to 2017, the second collection date in 2018 shows both netted plots were significantly different from the open check for counts of larvae/adult per berry (31 August; F = 19.45; df = 3,9; P < 0.0001). However, the netted plot with artificial infestations was not significantly different when compared with the open plot treated with insecticide or the netted plot. On the third collection date, a significant difference between the netted plot (treatment 3) and both open plot treatments was found (7 September; F = 8.48; df = 3,9; P < 0.0001). In contrast, the open plot with insecticide treatment (treatment 2) and netted plot with infestations (treatment 4) were not different from each other or the open check (Fig. 5). Plots with HOBO loggers showed no significant difference in average temperature when comparing open (21.788 ± 0.081°C) and netted (21.74 ±0.050°C) plots (t = 0.71, df = 2, P = 0.55).

Another observation was noted in the weekly injury samples from each plot in the Hastings vineyard. Figure 6 illustrates

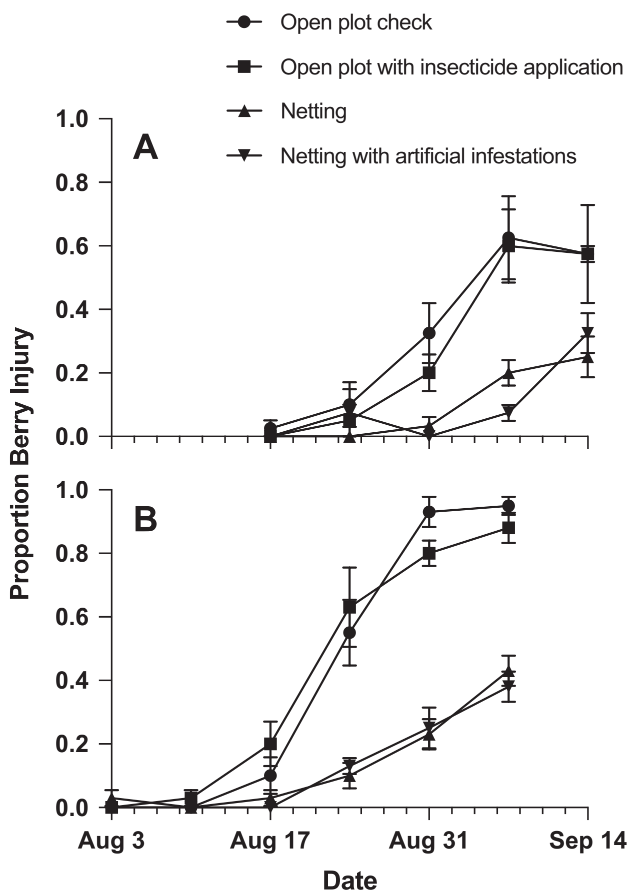

Fig. 6. Weekly mean proportion berry injury, including yellow jacket, bird, and weather damage and berry splitting, Hastings, MN, (A) 2017 (B) 2018.

Table 1. Analysis of variance results for the proportion of grape clusters with berry injury for treatment, date, and treatment by date interactions

	Date	P value	F statistic	df
Treatment	2017	<0.0001	16.22	3
Treatment	2018	<0.0001	40.50	3
Date	2017	<0.0001	37.87	4
Date	2018	<0.0001	108.64	5
Treatment × Date	2017	0.0254	2.16	12
Treatment × Date	2018	<0.0001	6.03	15

significant differences in the proportion of clusters with injury from the 10-cluster sample in each plot. Netted plot treatments had a significantly lower overall proportion injury when compared to open plots (Table 1). A significant interaction between treatment and date was also observed for both years (Table 1)

Discussion

The phenology studies for 2017–2018 indicate that *D. suzukii* was present at each of the three vineyards and wineries in the east-central Minnesota production area. These results confirm that *D. suzukii* populations begin to increase in vineyards at the onset of véraison and as berries begin to mature and soften. There is a relatively short lag time between véraison and peak *D. suzukii* populations. This delay may be explained by *D. suzukii* biology, where under ambient field temperatures, 8–10 d are necessary to complete a generation (Lee et al. 2011a), indicating that populations of *D. suzukii* will begin to increase significantly about 8–10 d after berry injury occurs and they become susceptible to *D. suzukii* egg laying. This generation time coincides with the peak in *D. suzukii* populations in the vineyard, indicating that once véraison begins, and injury has occurred to the berries, *D. suzukii* oviposition likely begins in grapes. Another possibility, as described by Ioriatti et al. (2015), is *D. suzukii* attraction to berries increases as sugars begin to accumulate, following véraison, and adults from nearby hosts may migrate to the vineyard and use the grapes as an adult food source rather than an oviposition site. However, trap data shows that *D. suzukii* populations are present in low numbers in the vineyard well before véraison takes place. Understanding *D. suzukii* phenology in relation to crop development, can assist growers in improving the timing of pest management strategies. For example, in the exclusion netting trial we waited to deploy the netting until 60–70% véraison as prior to this the grapes are hard and not susceptible to *D. suzukii* oviposition or feeding. To help guide growers on the best management strategies, further studies may be needed to determine reasons why *D. suzukii* are present in vineyards when host availability appears to be low or nonexistent. Some studies have documented *D. suzukii* movement in other crops such as raspberries, and blueberries (Rice et al. 2017, Evans et al. 2017, Jaffe et al. 2019), but few studies on *D. suzukii* population dynamics in wine grapes in the Midwest United States have been published (Asplen et al. 2015; Pelton et al. 2017). However, Pelton et al. (2016), examined surrounding woodland areas where non-crop hosts are present, and revealed that *D. suzukii* is captured in traps located in vineyards as they move from woodland areas to grapes throughout the season.

Growers also have a significant concern for the presence of *D. suzukii* inside their wineries. Traps deployed in this study confirmed that *D. suzukii* is present in the wineries but not until production processes begin. The traps also reflect a relatively low population of <30 *D. suzukii* per trap per week (Figs. 2 and 3B) compared to vineyard trap data. Populations may remain low in wineries because of management efforts that vintners undertake such as traps, chemical control inside the winery, or exclusion efforts to stop *D. suzukii* and other undesirable fruit flies from entering the winery. Similar to Cha et al. (2015) trap samples did include other drosophilid species besides *D. suzukii* but data were not recorded for these species. A follow-up study to assess the species composition and relative abundance of different fly species present in the wineries may help guide growers in management efforts in their wineries (Holle et al. 2019).

The trials we conducted testing exclusion netting as a possible alternative for control of *D. suzukii* in wine grapes, show promising results. When comparing the open plot check to the netted plot, there was ~95% reduction in mean number of larvae/adults per berry. In 2017, in the artificially infested netted plot, the infestations did not cause a significant increase in infested berries. The lack of infestation could be a result of the decrease in injured berries documented in the netted plots (Fig. 6A and B). *Drosophila suzukii* females have difficulty penetrating the skin of an intact berry, and because the netted plots had a lower level of overall injury, oviposition may have been reduced (Pelton et al. 2017, Holle et al. 2017). In addition, the lack of berry injury may have created limited food sources for adult flies. In 2018, while mean number of larvae/adults per berry was still low in comparison to the untreated check, there was an increase in infested berries over time as the berry collections were completed. During 2018, the vineyards experienced highly variable weather with periods of drought followed by heavy rainfall, potentially leading to high levels of physiological splitting injury. While injury in the netted plots in 2018 remained significantly lower than the open plots, there was still more injury within the netting than the 2017 field season (Fig. 6A and B). This increase in damage could be one of the reasons more berries were infested over time.

Another important relationship between the treatments was evident for both of the open plots. As noted in Figs. 4 and 5, the plot treated with insecticide provided no significant reduction in *D. suzukii* larvae/adult presence per berry for the majority of sample dates when compared to the open plot check. Data from the two open plots further demonstrate the relative ineffectiveness of chemical control, using current spray recommendations, for *D. suzukii* under field conditions (total of 2 or 3 spray applications per year) when compared to the use of exclusion netting. Similar results were observed for exclusion netting studies for *D. suzukii* management in raspberry (Rogers et al. 2016).

The differences in berry injury among all treatments is another unforeseen benefit from the use of exclusion netting (Fig. 6). This decrease in injury is partly due to the fact the netting not only excludes *D. suzukii*, but it also prevents other vertebrate and invertebrate pests from feeding on the berries and provides physical protection from wind, hail, and heavy rains. Physiological splitting occurs when the grape berries absorb water too fast; this can occur via rapid uptake through the roots, but also can occur directly via berry skin (Opara et al. 1997, Galvan et al. 2006b). While netted plots do not prevent the uptake of water through the root system, the netting does create additional shelter for the berries from direct rainfall, which could slow or alter the absorption process via less direct precipitation exposure to the grape clusters (Opara et al. 1997). As grapes mature beyond véraison, there are numerous pathways for injury to occur (Coombe 1995, Opara et al. 1997, Galvan et al. 2006b); while we did not specifically examine all sources of berry injury to wine grapes, weekly injury assessments were valuable to demonstrate differences in the proportion of berry injury across treatments. A significant interaction for the proportion of clusters with berry injury was found between date and treatment (Table 1) for both years of the study. These data further demonstrate the tendency for wine grape berry injury to increase as they mature over the season. However, with the application of exclusion netting, injury is significantly reduced compared to plots where exclusion netting was not applied. This added protection reduces injury and hence *D. suzukii* infestation, but also by reducing over-all injury, grapes are less prone to infection from airborne pathogens.

Although our results show excellent efficacy using exclusion netting for managing *D. suzukii* in wine grapes, exclusion netting will have a high initial capital investment. The exclusion netting used in these studies was an 80-gram mesh (ExcludeNet, Tek-Knit Industries) purchased from Berry Protection Solutions (Stephentown, New York) with a cost of approximately $550 per 100 × 4 m roll. Depending on the spacing between vine trellises, the initial investment could exceed $7,000/ac; however, it is important to note that the netting can be used for several years in temperate climates, which reduces the annual production costs, and improves net returns over time. By substantially reducing *D. suzukii* infestations, exclusion netting provides a higher quality yield for growers, and protects fruit from birds, wasps, hail, and heavy rain. In addition, because the netting can replace late-season insecticide use near harvest, it reduces the risk of potential environmental impacts on nontarget insects, such as pollinators, and the potential risk of unacceptable pesticide residues. As with other fruit crops, exclusion netting is, therefore, an additional management strategy for organic wine grape producers.

This study documents *D. suzukii* population levels in both wine grape vineyards and wineries during 2017–2018 in Minnesota. Information collected in the vineyards will be useful in developing IPM programs to better inform growers about alternative tactics, and alternatives to insecticides, as they manage *D. suzukii* in the Midwestern United States. Creating an awareness of alternative management options such as exclusion netting and demonstrating the efficacy of these options is critical to expand pest management efforts for *D. suzukii* in wine grapes. Continued research into biology of and management of *D. suzukii* and other fruit fly species in wine grapes is necessary to refine management strategies. Specifically, research is urgently needed to better understand the potential risk of *D. suzukii* and other fruit fly species as vectors of AAB, and the risks to wine grape production in the Midwest U.S. region.

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