Insect excluding mesh enhances Spotted-wing Drosophila (Drosophila suzukii) control in tunneled raspberry with limited effects on natural enemy abundance

Buck, N., Fountain, M. T., Potts, S. G. ORCID: https://orcid.org/0000-0002-2045-980X and Garratt, M. P. D. ORCID: https://orcid.org/0000-0002-0196-6013 (2024) Insect excluding mesh enhances Spotted-wing Drosophila (Drosophila suzukii) control in tunneled raspberry with limited effects on natural enemy abundance. Agriculture, Ecosystems and Environment, 359. 108756. ISSN 0167-8809 doi: https://doi.org/10.1016/j.agee.2023.108756 Available at https://centaur.reading.ac.uk/113392/

To link to this article DOI: http://dx.doi.org/10.1016/j.agee.2023.108756

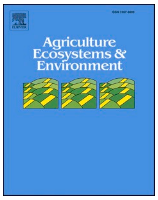
Publisher: Elsevier

Agriculture, Ecosystems and Environment 359 (2024) 108756

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee



Insect excluding mesh enhances Spotted-wing Drosophila (*Drosophila suzukii*) control in tunneled raspberry with limited effects on natural enemy abundance

Nicolas Buck [a,*], Michelle T. Fountain [b], Simon G. Potts [a], Michael P.D. Garratt [a]

[a] *School of Agriculture, Policy and Development, University of Reading, Whiteknights, Reading RG6 6AH, Berkshire, UK*
[b] *NIAB EMR, New Road, East Malling, Kent ME19 6BJ, UK*

ARTICLE INFO

Keywords:
Insect mesh
Integrated pest management
Natural enemies
Raspberries
Spotted wing Drosophila

ABSTRACT

Spotted-wing Drosophila (*Drosophila suzukii*) oviposits in a wide range of soft and stone fruit, which can result in a reduction of fruit quality and yield. An invasive, polyphagous species, *D. suzukii* targets ripe fruit, such as raspberries, which are commonly grown in polytunnels. With increasing restriction on the use of agrochemicals, effective alternative approaches to *D. suzukii* are needed. We assessed the impacts of insect mesh on *D. suzukii* abundance and oviposition in tunnel-grown raspberries, as well as how it impacts the abundance of other pests and natural enemies, fruit quality and tunnel microclimate. *Drosophila suzukii* abundance in traps was lower in mesh tunnels compared to adjacent non-crop areas although no significant difference between mesh and control tunnels was observed. Although *D. suzukii* emergence from harvested fruit was significantly lower on fruit collected in mesh tunnels compared to control tunnels. Mesh impacted sooty shoulder coverage of fruit and had only limited impacts on the abundance of natural enemies such as ants, spiders and parasitic wasps while increasing instances of peak temperature and humidity were found. We highlight the varying impacts mesh netting has on soft fruit production and discuss how these findings can be used to help incorporate insect mesh into IPM strategies to effectively control *D. suzukii*.

1. Introduction

Pests pose a serious threat to fruit and vegetable farmers globally. Insects are estimated to cause 18–26% of damage to crop production worldwide, valued at over $470 billion per annum, with most of this damage occurring prior to harvest (Culliney, 2014). A pest of particular concern is spotted-wing Drosophila, *Drosophila suzukii*, which causes significant economic damage to crops due to its ability to oviposit in a wide range of ripe and ripening fruit, with the oviposition site acting as a pathway for pathogens (Lee et al., 2011; Cini, Ioriatti and Anfora, 2012). The larval feeding further degrades the fruit flesh, reducing its quality (Grassi and Pallaoro, 2012). In California, revenues for raspberry and strawberry have been calculated to be reduced by 37% and 20%, respectively, due to *D. suzukii* damage (Goodhue et al., 2011). Minnesotan raspberry growers experienced a median yield loss of 20% due to damage by *D. suzukii* in 2017, highlighting the considerable threat this pest poses to fruit production (DiGiacomo et al., 2019).

Plant protection products (PPP), such as insecticides, limit damage by insect pests such as *D. suzukii,* and their use has increased four-fold over the last 50 years (Sarwar, 2015). However, PPPs can pose a risk to consumer health. Humans can be exposed to PPPs through a variety of pathways including direct consumption of crops (Boxall et al., 2009). In a study assessing raspberries in north-eastern Poland, 21% of fruit had detectable residues which exceeded the maximum residue limit (Łozowicka et al., 2012). Increased use of PPPs can also result in insect resistance to specific active ingredients which can increase the likelihood of more pest outbreaks (Zhang et al., 2007). *Drosophila suzukii* already has a reduced sensitivity to some PPPs (e.g. spinosad, zeta-cypermethrin and bifenthrin), indicating potential resistance (Gress and Zalom, 2019; Ganjisaffar et al., 2022). PPPs can also be harmful to non-target insects such as natural enemies which might otherwise predate pests (Wilson and Tisdell, 2001). Furthermore, the increased restriction of pesticides, especially in the UK and EU, is expected to reduce their availability as a control measure for *D. suzukii* (Hillocks, 2012). As

---

* Corresponding author.
E-mail addresses: nicolas.buck1@gmail.com (N. Buck), michelle.fountain@niab.com (M.T. Fountain), s.g.potts@reading.ac.uk (S.G. Potts), m.p.garratt@reading.ac.uk (M.P.D. Garratt).

https://doi.org/10.1016/j.agee.2023.108756
Received 23 February 2023; Received in revised form 19 September 2023; Accepted 20 September 2023

a result, more sustainable solutions are needed to reduce pest pressure on farms and increase crop yields, while limiting impacts on the environment and consumers.

Integrated Pest Management (IPM), which considers all plant protection methods and integration of appropriate measures to discourage the development of populations of harmful organisms on crops, while minimizing the risk to consumer health (Barzman et al., 2015) is a more sustainable solution to crop protection. IPM approaches vary depending on crop and pest type, commercial availability, and habitat context but biocontrol with natural enemies, cultural control such as crop rotation and hygiene, behavioural control using pheromone-based traps and insect-exclusion mesh can all be incorporated. Mesh provides a physical barrier which restricts entry of pests into the crop and can be placed over the crop or installed as doors on polytunnels. Polytunnels are commonly used to maximize the length of the growing season for certain crops such as raspberries (*Rubus idaeus*), as it can reduce the negative effects of heavy rain and strong winds, allowing growers to control conditions more easily than in open-field crops (Tuohimetsä et al., 2014). Raspberries are a popular crop to grow under polytunnels where harvest in both early and late crops can be accelerated due to the more favourable conditions they provide than in open-field settings (Żurawicz et al., 2018).

In a study to prevent *D. suzukii* damage in raspberries, using mesh significantly increased marketability of fruit compared with unmeshed plots (Stockton et al., 2020). However, a higher instance of crumbly berry virus was observed in the meshed plots, a possible indicator of pollination deficits (Stockton et al., 2020). In meshed polytunnel-grown raspberries, economic returns increased in line with increased *D. suzukii* infestation levels with an average net change in income of $11,105 per ha annually, indicating that installing mesh is a positive investment (Digiacomo et al., 2021). In meshed blueberry plots, no *D. suzukii* were found in traps or in fruit, with significant reductions in fruit damage and sugar content (hence ripening) compared with fruit from unmeshed plots (Cormier et al., 2015; Alnajjar et al., 2017). This evidence suggests that mesh can be an effective part of IPM, specifically for *D. suzukii* vulnerable fruit, potentially reducing the need for PPP applications (Chouinard et al., 2016) although many studies do not consider the full suite of potential negative effects installing mesh may have.

There are some potential negative drawbacks associated with deploying mesh to control pests. For example, if mesh installation is mistimed *D. suzukii* can become trapped within crops posing a risk to the fruit (Rogers et al., 2016). Mesh can also potentially impact the microclimate inside tunnels due to reduced ventilation. Crops like raspberries are not considered heat tolerant (Molina-Bravo et al., 2011) and produce lower yields, smaller fruits and lower fruit marketability when under heat stress at around 32 °C (Bradish et al., 2012). High relative humidity can also lead to increased mould on fruit (Bylemans et al., 2003). In one study, increased *Botrytis* damage was observed on raspberries grown under mesh, impacting some aspects of fruit quality (Stockton et al., 2020). Another study found no difference in temperature between meshed and unmeshed raspberry plots, with only slight increases in fruit weight and diameter in meshed treatments (Leach et al., 2016). Alterations in tunnel microclimate caused by mesh is still a concern for fruit growers. Mesh may also impede access to the crop by pollinators, limiting their ability to make contact with flowers and pollinate them, which may result in reduced fruit quality.

Another barrier to mesh implementation is cost. However, a structure already in place over the crop (e.g. a polytunnel) to attach the mesh can make the application less costly than other methods of pest control (Leach et al., 2016). Finally, the mesh may potentially interfere with natural pest control in protected cultivation by reducing access to the crop by natural enemies, thus exacerbating pest issues, as shown in apples, where exclusion mesh had a negative influence on natural enemies of the rosy apple aphid (*Dysaphis plantaginea*) (Dib et al., 2010).

To support wide-scale implementation of the mesh, a greater understanding of its place in IPM is needed, including the benefits it can deliver in controlling a key pest such as *D. suzukii*, as well as side-effects on beneficial insects and tunnel microclimate. The aim of this study was 1) to determine the effects of insect-exclusion mesh on *D. suzukii* abundance and fruit damage in polytunnel grown raspberry systems, 2) quantify the impact of mesh on the abundance of other pests and natural enemies in the crop, and 3) to make recommendations for the use of mesh to control pests throughout the growing season.

2. Materials and methods

2.1. Study sites

A replicated field trial was conducted from March to September in 2019 and 2021 on six sites in the south of England. Each 'site' was an individual soft fruit farm. Each crop (the blocks where the study tunnels were located were between 0.2 ha and 10.5 ha) consisted of rows of plastic-covered polytunnels, surrounded by vegetation-free tracks, and bordered by hedgerows or woodland. Across the sites, tunnel lengths ranged from 10 to 63 m and raspberries were grown in two or three trellis rows within the polytunnels. Honeybee hives were present on all sites, and in 2021 6 of the 18 tunnels used for study contained a commercial bumblebee hive. The presence or absence of commercial hives in tunnels was not noted in 2019.

2.2. Study design

The experiment compared meshed (treated) and unmeshed (control) polytunnels with respect to crop pests, beneficials and tunnel microclimate. Except for the mesh treatment, all other crop management practices were the growers' standard crop management (one conventional insecticide every 1–2 weeks from July) typical of the industry in the UK. Practices such as irrigation, ventilation and application of PPPs remained the same for both mesh and control tunnels.

Each replicate in this study was a 'tunnel pair' consisting of one meshed and one adjacent un-meshed tunnel. Each site had at least 3 replicates, except for one site in 2019 which had 2 replicates. Replicates used on each site were between 160 m and 996 m apart. Replicates with poor mesh management (tunnels where mesh was damaged, implemented too late or mesh doors not lowered after being raised) were removed from the analyses, leaving 6 replicates in 2019 and 7 in 2021, 13 in total. For the treated tunnels, mesh was installed at the tunnel entrances at either end of the polytunnels at the first sign of ripening fruit (late spring in the early crop and late mid-late summer in the late crop). In addition, the sides of tunnels were also meshed to a height of 1 m to cover side ventilation gaps. Growers were requested to lower mesh doors after spraying and picking operations, but other practices such as venting were carried out as normal, regardless of the mesh. The 'Gro-Net' mesh used for this study had a gauge size of 0.8 × 0.8 mm (supplied by Agrii, Cheltenham, UK). This study involved three varieties of raspberry and replicates were in production at different stages of the season, five replicates in early season (March to June) and fourteen replicates in late season (July to September, see Appendix 1 for full crop info for each tunnel).

2.3. Assessments

Evaluation of invertebrate pest and natural enemy abundance in the treated and control tunnels began at first flowering in each tunnel and finished after final harvest (see Appendix 1 flowering periods). Invertebrate surveys were carried out on three 10 m transects within each tunnel. Two transects were located at either end of the rows, ~5 m in from the tunnel edge, and one in the middle. For the tunnels with 2 crop rows, one row was randomly selected for the central transect and one edge transect. This row was then sampled twice, once on each of its two transects.

2.3.1. *Pests and natural enemies*

Each week, five randomly selected plants along each transect were sampled with three firm taps on a raspberry cane with a beating stick over a white plastic tray (46 ×36 cm, Kabi Plastics). The contents that fell onto the tray were identified to broad taxonomic groups (ant, anthocorid, aphid, beetle, capsid, hoverfly, lacewing, parasitic wasp, spider, spider mite, weevil and whitefly). These were then released back onto the same plant from which they were sampled. The AHDB Crop Walkers' Guide for Cane Fruit (Agriculture and Horticulture Development Board, 2013) was used to classify the pests and natural enemies found.

2.3.2. *Drosophila suzukii*

To assess *D. suzukii* numbers within tunnels, one Drosotrap (Biobest, Westerlo, Belgium) was placed in the middle of the center raspberry row in each tunnel, or the closest to the field edge for the tunnels with two rows. The trap was placed 1 m above the ground inside the foliage at the start of the season, prior to first flowering. An additional third trap for each replicate was placed on the crop edge nearest to each pair of study tunnels. Depending on tunnel location, this edge consisted either of fencing, hedgerows, or trees. Each trap contained 200 ml of DrosAttract (Biobest, Westerlo, Belgium) liquid bait. The trap contents were filtered using paper paint filters (OrangeHome, London, UK) each week and refilled with new DrosAttract. Trap contents were returned to the laboratory inside their filters and later identified under a microscope.

Drosophila suzukii emergence from fruit was assessed by sampling 45 ripe fruit per tunnel during the fruiting period. Fifteen fruits were collected randomly from each transect each week and placed in a clear Perspex box (23 ×8×12 cm) with a ventilated lid after fruit quality assessments were made. Every two days, all adult flies, both *D. suzukii* and others, were removed with a pooter and identified under a microscope. This was carried out for 20 days after fruit collection. Then recording was finished to avoid counting emerging flies from reinfested fruit.

2.3.3. *Fruit quality*

The 45 individual raspberry fruit per tunnel that were collected for *D. suzukii* emergence were first assessed for marketability, against a quality assessment manual provided by the industry partner. Bleed, colour, shape, mould, and sooty shoulder were all scored 1–4. Bleed (burst drupelets leaking raspberry juice) was scored: 1, no bleed and 4, showing large amounts of bleed on fruit. Colour was scored: 1, under ripe; 4, over ripe; and 3, being the desirable ripe red colour. Shape was scored: 1, no deformities and perfect shape, to 4, severe deformities. Mould (white or grey fungus, powdery in appearance) was scored: 1, no mould coverage of the fruit, and 4, large amounts of mould. Sooty shoulder (dark, dry 'sooty' deposits on top drupelets of the fruit) was scored: 1, showed no sooty shoulder coverage of the fruit, and 4, showed large amounts of sooty shoulder coverage. Fruit length was measured from the highest drupelet to the lowest drupelet of the fruit, and width at the widest point of the fruit, both with a digital calliper to the nearest millimetre. Mass was recorded to the nearest 0.001 mg on a weighing scale.

2.3.4. *Tunnel microclimate*

To measure microclimatic conditions in the tunnels, one EL-USB-2 (Lascar Electronics, Salisbury, UK) data logger was placed into a white triangular Delta trap (Koppert, Rodenrijs, Netherlands) with a cable tie and hung in the middle of the center row of each meshed and control tunnel as well as on the nearby site edge adjacent to the Biobest traps at each site. The data loggers took readings of temperature (°C) and relative humidity (%RH) every five minutes. Each week, the data were downloaded onto a laptop and the data loggers reset to begin the recording for the following week.

2.4. *Statistical analysis*

To assess the impacts of mesh on *D. suzukii* Drosotrap captures, emergence from fruit and pest and natural enemy abundance, 2019 ($n = 6$) and 2021 ($n = 7$) data were available (adult *D. suzukii* identified). Because tap sampling surveys began at an earlier date in 2021 than in 2019, comparisons of invertebrate groups between mesh and control tunnels before and after mesh installation was possible in 2021. For 2019, a post mesh installation analysis only was possible. To assess the effects of mesh on fruit marketability ($n = 7$, continuous measures and scoring system) and tunnel microclimates ($n = 7$, instances recording temperature and humidity ranges) data from 2021 were used. All statistical analysis was carried out in RStudio 4.2.2. The packages installed and used for all analysis included nlme, lme4, emmeans, ggplot2, readxl and dplyr.

2.4.1. *Mesh and Drosophila suzukii*

The Drosotrap data for the 2019 and 2021 seasons were averaged over the pre-mesh installation and post-mesh installation periods for each treatment (mesh vs control vs crop edge) for each replicate in each site per year, with separate models run for each period. To compare the catch rates in Drosotraps between the three trap locations, linear mixed-effects models were run with averaged count as the response variable, treatment as a fixed effect and site and replicate as nested random effects. A significant effect produced by the model ($p < 0.05$) was interpreted as a significant difference in the number of *D. suzukii* in traps between the three locations.

The 2019; and 2021, *D. suzukii* fruit emergence data ($n = 4$ in 2019, $n = 7$ in 2021) for each treatment (mesh and control) were compared using generalised linear-mixed effects model (glmer) with count as the response variable, treatment as the fixed effect, site and replicate as nested random effects and date as a crossed random effect. The 'family = poisson' function was specified for the models. A significant effect ($p < 0.05$) was interpreted as a significant difference in numbers of *D. suzukii* emerged from fruit between the two treatments.

2.4.2. *Mesh and pests and natural enemies*

To compare the abundance of pests and natural enemies between mesh and control tunnels, tap sample data were averaged across the weekly collections for each transect for the pre-mesh installation and post-mesh installation periods separately. Linear mixed-effects models were run with average abundance as the response variable, treatment as a fixed effect and site, replicate and transect as nested random effects. A significant effect produced by the model ($p < 0.05$) was interpreted as a significant difference in the abundance of each group between mesh and control tunnels.

2.4.3. *Mesh and fruit quality*

For this analysis, glmers were run with score for each quality metric as the response variable, treatment as the fixed effect and site, replicate and transect as the nested random effects. Linear mixed-effects models were run with mass, width or length measurement with the same fixed and random effects. For both the scored data and the continuous data (length, mass and width) a significant effect ($p < 0.05$) was interpreted as a significant difference in score or measurement between mesh and control tunnels.

2.4.4. *Mesh and tunnel microclimate*

To compare environmental conditions between mesh and control tunnels, temperature (30–35 °C) and humidity (80–90% RH and 91–100% RH) peaks inside the tunnels during the 2021 season were selected; raspberries are not considered heat tolerant and produce lower yield at high humidity (Molina-Bravo et al., 2011; Bradish et al., 2012). These conditions were analysed using a glmer with a count of recording instances of the respective conditions as the response, treatment (mesh and control tunnels) as the fixed effect and site and replicate as the nested random effects. As the data were a count, the ‘family = poisson’ was specified for the model. A significant effect ($p < 0.05$) was interpreted as a significant difference in the number of instances recorded at 30–35 °C, 80–90% RH or 91–100% RH in mesh or control tunnels for each treatment in each replicate.

3. Results

3.1. Effects of mesh on *Drosophila suzukii* abundance

3.1.1. Drosotrap catches

In 2019, prior to mesh installation, overall trap location had no significant effect on *D. suzukii* trap captures ($F=1.818$ $p = 0.212$). Pairwise comparisons showed no significant difference in trap catches of *D. suzukii* between control and edge traps ($t = -1.743$, $df=6$, $p = 0.226$), control and mesh traps ($t = 0$, $df=6$, $p = 0.999$), or edge and mesh traps ($t = 1.482$, $df=6$, $p = 0.269$). After mesh installation, overall trap location had a significant effect on *D. suzukii* trap captures ($F=4.281$, $p < 0.05$), with more captures in edge than mesh traps ($t = 2.774$, $df=6$, $p < 0.05$, Fig. 1A) in 2019.

In 2021, prior to mesh installation, overall trap location had no significant effect on *D. suzukii* trap captures ($F=0.067$, $p = 0.935$). After mesh installation, overall trap location had a significant effect on *D. suzukii* trap captures ($F=5.871$, $p < 0.05$), with more captures in edge than mesh traps ($t = 3.415$, $df=10$, $p < 0.05$, Fig. 1B).

3.1.2. Fruit emergence

In 2019 and 2021, fruit produced under control tunnels had roughly double the numbers of *D. suzukii* emerging per 15 fruit sample than those produced under mesh tunnels (2019: $z = -10.942$, $df=23$, $p < 0.005$, Fig. 2A, 2021: $z = 2.827$, $df=7$, $p < 0.005$, Fig. 2B).

3.2. Effect of mesh on pests and natural enemies

In 2019, after mesh installation, there was no significant difference in the mean number of the top six invertebrate groups sampled (ants, anthocorids, aphids, beetles, parasitic wasps and spiders). In 2021, there was no significant difference in the mean number of ants between mesh and control tunnels before mesh installation ($t = -0.854$, $df=23$, $p = 0.401$) but there was a significant difference after mesh installation with control tunnels having higher mean numbers than the mesh tunnels ($t = -2.496$, $df=26$, $p = 0.019$, Fig. 3B).

There was a significant difference in mean parasitic wasp numbers between mesh and control tunnels after mesh installation, with more in the control tunnels ($t = -2.596$, $df=26$, $p = 0.015$, Fig. 3E). However, there was also a significant difference prior to mesh installation for parasitic wasps ($t = -2.55$, $df=23$, $p = 0.017$). There was also no significant difference in the mean number of spiders between mesh and control tunnels before mesh installation ($t = 0.317$, $df=23$, $p = 0.754$), but there was a significant difference after mesh installation with more spiders in the mesh compared to the control tunnels ($t = 2.534$, $df=26$, $p = 0.017$, Fig. 3F).

3.3. Effect of mesh on fruit quality

There were no significant differences in raspberry quality measure, except for the presence of sooty shoulder on the fruit ($t = 2.737$, $df=23$, $p < 0.05$), with fruit produced under meshed treatments exhibiting significantly greater incidence of sooty shoulder (see Appendix 3 for non-significant effects). Around 2% of fruit in the meshed tunnels had a sooty shoulder score of 2–4 compared to 0% of fruit in the control tunnels.

3.4. Effects of mesh on tunnel microclimates

There were significantly more instances where 30–35 °C was recorded in the control compared to mesh tunnels before mesh installation ($z = -3.248$, $df=8$, $p < 0.005$) and more in the mesh compared to control tunnels after mesh installation ($z = 4.53$, $df=8$, $p < 0.0005$, Fig. 4A).

There was a significant difference in the instances 80–90%RH recorded between tunnels prior to mesh installation ($z = 8.83$, $df=8$, $p < 0.005$) but not after mesh installation ($z = -1.241$, $df=8$, $p = 0.215$). There was no difference in the number of instances where 91–100%RH was recorded between mesh and control tunnels before mesh installation ($z = -0.625$, $df=8$, $p = 0.532$), but there was a significant difference after mesh installation with more instances of 91–100%RH recorded in mesh tunnels ($z = 6.276$, $df=8$, $p < 0.005$, Fig. 4B). Three dataloggers (one for mesh, two for control tunnels) malfunctioned midway through the season, resulting in an absence of a

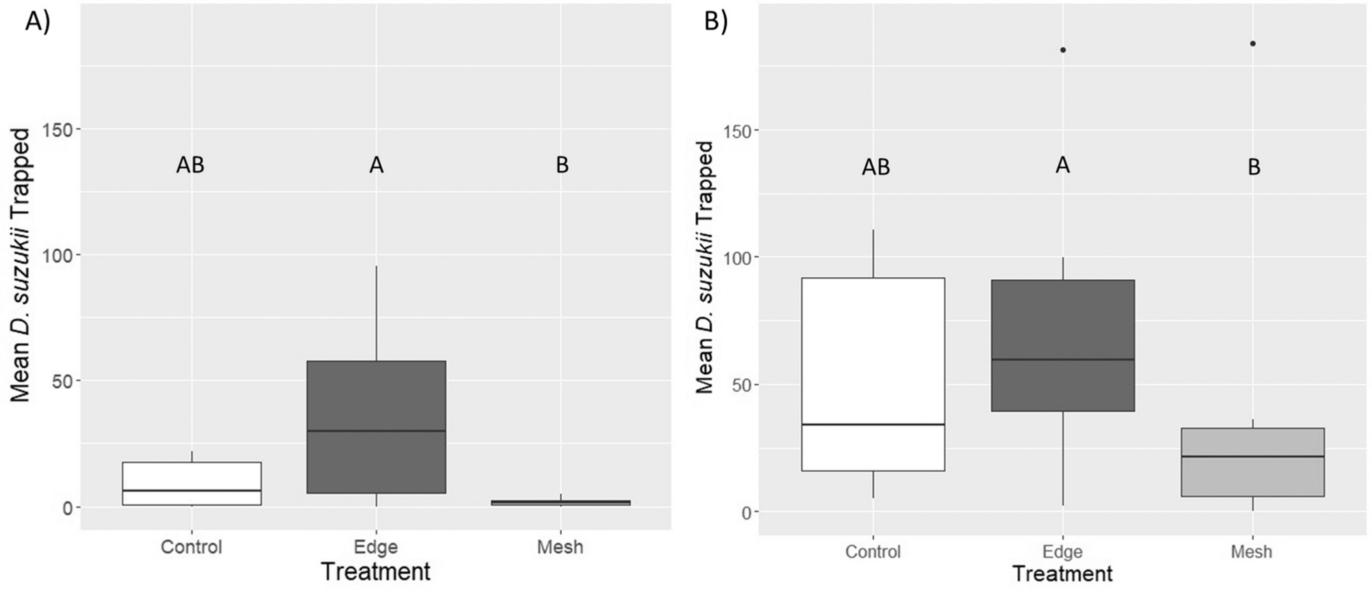


Fig. 1. Boxplot of *D. suzukii* Drosotrap catches in different trap locations during A) the 2019 season ($n = 6$) and B) the 2021 season once mesh was raised ($n = 7$). Letters indicate which treatments exhibit a significant difference between each other.

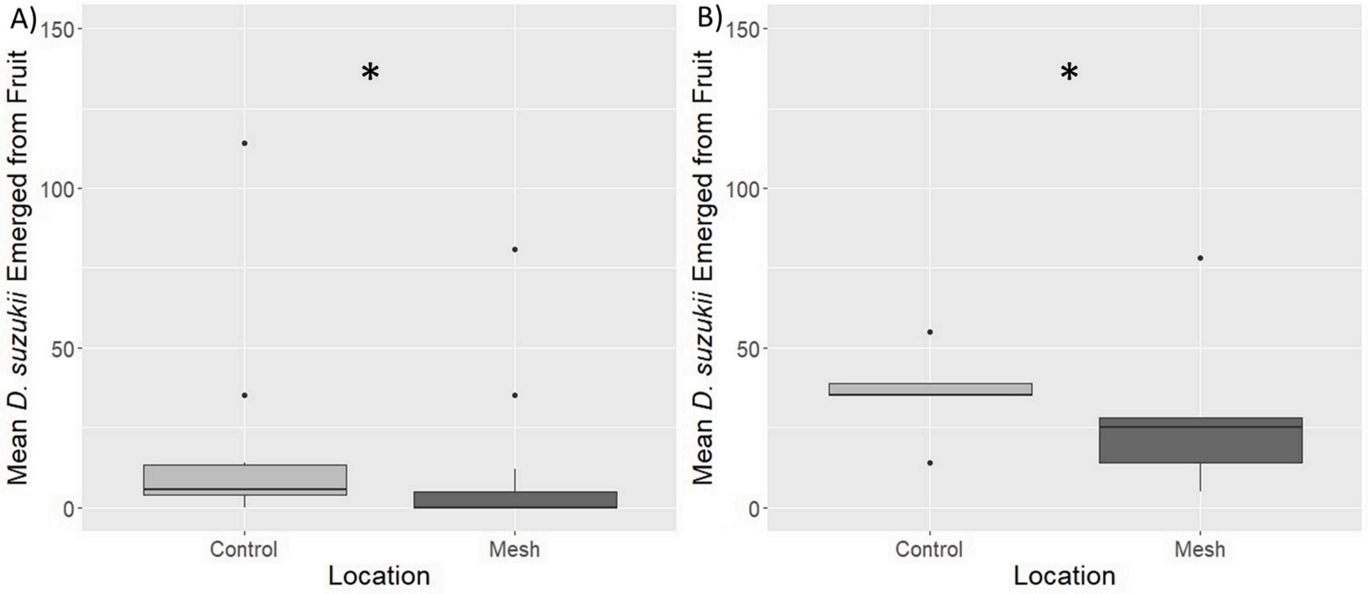


Fig. 2. Boxplot of mean adult *D. suzukii* emergence from fruit per 15 fruit sample under mesh and control tunnels during the A) the 2019 season (n = 6), and B) the 2021 season (n = 7). Asterisks indicate responses which were significantly affected by mesh treatments ($P < 0.05$).

week of temperature and humidity data for each logger. This may have reduced the total instances recording peak temperature and humidity for these replicates.

4. Discussion

4.1. Impacts of mesh

4.1.1. *Drosophila suzukii*

There were significantly fewer *D. suzukii* adults in traps inside meshed tunnels compared with the neighbouring edge traps in 2019 and 2021, but not between mesh and control tunnels. Positive impacts of mesh reducing *D. suzukii* abundance in the crop are widely documented. Mesh (gauge not specified) significantly reduced *D. suzukii* eggs (by 82%), larvae (by 74%) and adults (by 65%) in commercial raspberry polytunnels in one study (Leach et al., 2016), and reduced adult captures (75%), affected fruit weights (48%) and increased yield (63%) when compared with unmeshed tunnels in another study (Kuesel et al., 2023). Mesh (gauge not specified) also reduced the number of *D. suzukii* larvae per fruit by up to 95% in commercial wine grapes compared with open plots (Ebbenga et al., 2019). When mesh (gauge 0.85 ×1.4 mm) was used to cover blackberries on a t-trellis system and weighed down by paving stones, over 30 times more *D. suzukii* per fruit were observed in blackberries treated with organic insecticides than meshed blackberries (Kuesel et al., 2019). In commercial blueberry fields treated with a similar t-trellis mesh (gauge 1.0 ×0.6 mm) system, no *D. suzukii* adults emerged from fruit; whereas over 70 *D. suzukii* per 100 fruits emerged by the final harvest in unmeshed plots (Cormier et al., 2015). However, these open plots were not treated with insecticide, unlike in our study where mesh and control tunnel pairs were treated with the same PPP applications. With higher levels of pest pressure and damage, mesh is argued to be more cost efficient than applying PPPs, resulting in more positive net returns (Del Fava et al., 2017; Digiacomo et al., 2021). However, as there was a difference in emergence of adults from fruit between mesh and control tunnels in both years of our study, but less clear differences in trap catches, this indicates trap catches may not be a reliable proxy of damage to fruit from *D. suzukii* as they are not providing an estimate of adult females that are currently ovipositing in ripe fruit (Kirkpatrick et al., 2017; Kehrli et al., 2022).

4.1.2. Pests and natural enemies

After mesh installation, fewer ants and parasitic wasps and higher numbers of spiders were recorded in mesh tunnels compared to control tunnels. While all three groups are classified as natural enemies, ants are also known to protect aphids until the honeydew they produce is no longer a suitable food source (Goggin, 2007). Parasitic wasps and some spiders utilise raspberry pests, such as aphids, and so should be a focus for integration of natural enemies (Harwood et al., 2005; Hanni and Luik, 2006; Mitchell et al., 2010; Boivin et al., 2012). Encouragingly, mesh installation in our study resulted in higher numbers of spiders in the tunnels which could result in increased pest control. However, Leach et al. (2016) discovered a reduction in spiders when comparing mesh with unmeshed raspberry tunnels. The reduction in parasitoid numbers however is a concern and approaches should be sought to mitigate these effects. This could be achieved by introducing habitats inside tunnels (Mateos-Fierro et al., 2021) or through mass release of commercially produced parasitoids inside mesh tunnels (Dassonville et al., 2013). Certain parasitoid species including *Leptopilina japonica* and *Ganapsis brasiliensis* show potential for high parasitism of *D. suzukii* larvae (Giorgini et al., 2018), and may become a focus for future biocontrol should they become established in the UK. In addition, reduced use of insecticides may increase numbers of parasitoids in tunnels and therefore allow parasitoids to achieve higher parasitism of *D. suzukii*.

Effects on invertebrate abundance in polytunnels after mesh installation have been reported in other studies. In the US, mesh covering the ends of polytunnel-grown raspberries significantly reduced numbers of the Japanese beetle (*Popillia japonica*) observed in the crop (Burkness et al., 2022). Mesh also reduced numbers of the green June beetle (*Cotinus nitida*) and *P. japonica* in blackberry (Kuesel et al., 2019). In apples, mesh with larger holes (gauge 2.3 ×3.4 mm) allowed aphid parasitoids into the crop while excluding the apple maggot (*Rhagoletis pomonella*) (Chouinard et al., 2022). Mesh can also reduce numbers of syrphids and codling moth (*Cydia pomonella*) in apple trees, but increases numbers of the woolly aphid (*Eriosoma lanigerum*) and its parasitoid *Aphelinus mali* (Marshall and Beers, 2021). In nectarine orchards, mesh reduced damage from the oriental fruit moth (*Grapholita molesta*) and brown marmorated stink bug (*Halyomorpha halys*) by up to 90% and 78% respectively, when compared with plots treated with PPPs (Candian et al., 2021).

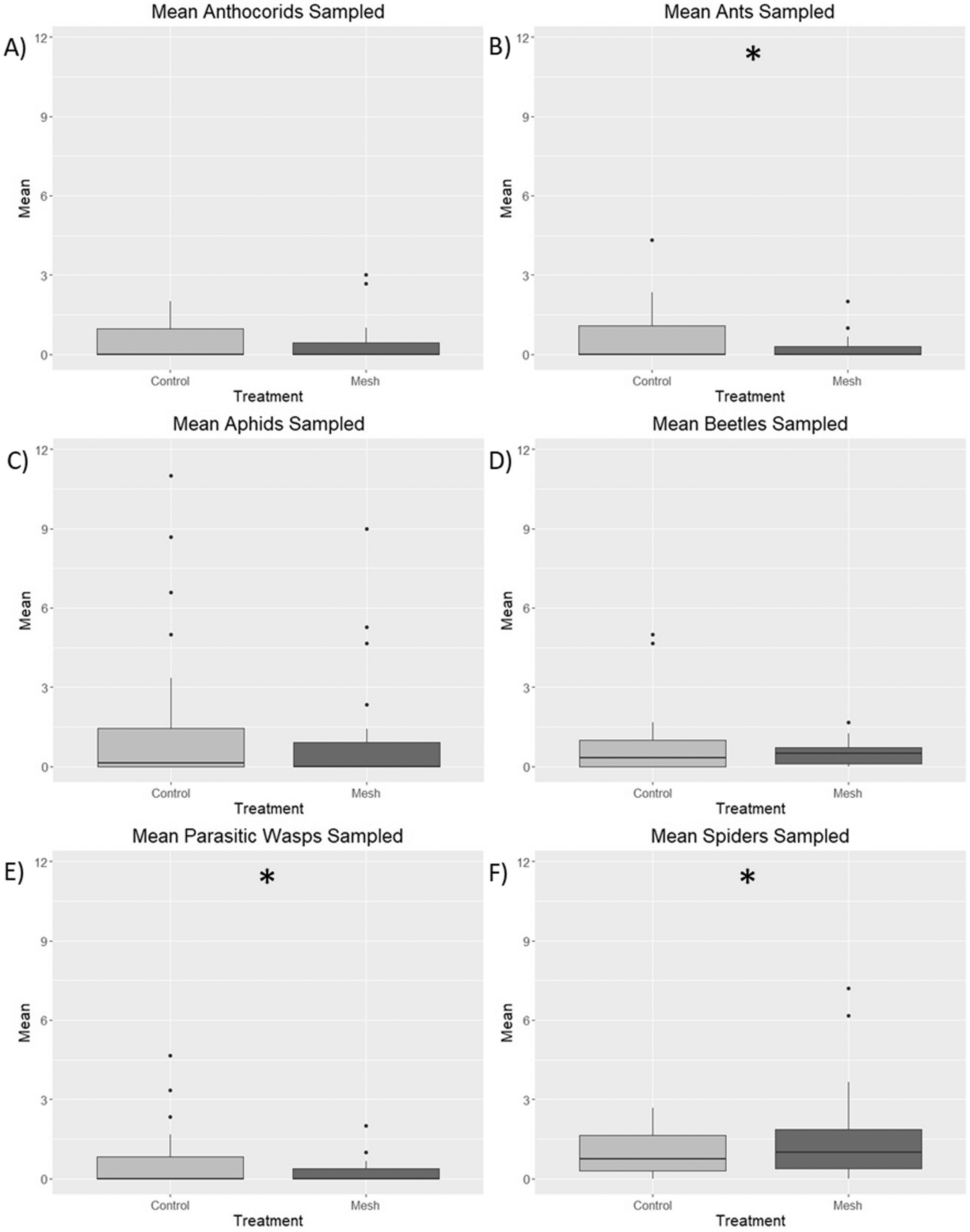


Fig. 3. Boxplot showing mean numbers of A) anthocorids, B) ants (significant), C) aphids, D) beetles, E) parasitic wasps (significant), and F) spiders (significant) tap sampled in mesh and control tunnels after mesh installation during the 2021 season (n = 7). Asterisks indicate responses which were significantly affected by mesh treatments (P < 0.05).

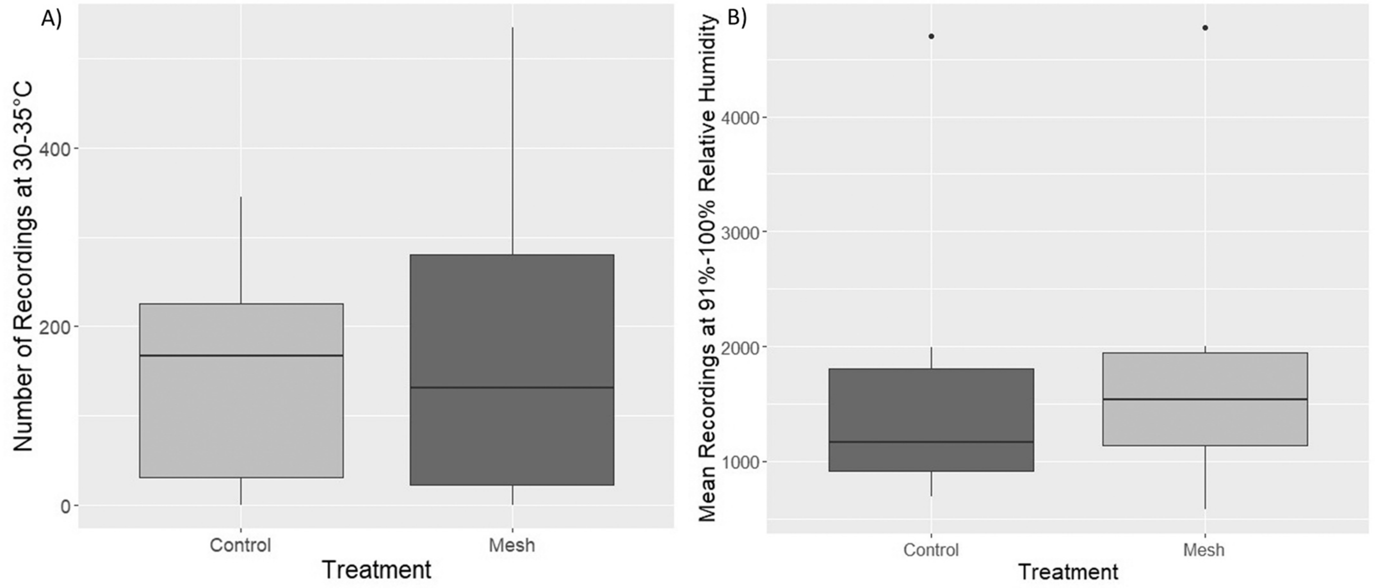


Fig. 4. Boxplot showing number of instances dataloggers recorded A) 30–35 °C (n = 6), and B) 91–100%RH (n = 6) in mesh and control tunnels on all sites after mesh installation during the 2021 season.

4.1.3. *Fruit quality*

Mesh increased the number of fruits that had a sooty shoulder score of 2–4 (4 being the highest category of sooty shoulder coverage). Although the incidence was only increased by 2% of the total fruits harvested compared to unmeshed tunnels, this could still be a commercial concern for growers. Increased temperatures and humidity may provide more favourable conditions for pathogens to establish in meshed crops (Stockton et al., 2020), particularly in regions or in seasons where fungal pathogens are particularly prevalent. This ultimately represents a potential trade-off of using mesh and so we recommend close monitoring of pathogens throughout the season if installing mesh on polytunnels. No other fruit quality metrics were affected in our study. Furthermore, other research has found only a limited impact of mesh on fruit quality. In netted raspberry polytunnels (gauge 0.95 ×0.95 mm), there was no difference in any fruit quality metric between meshed and open control plots (Leach et al., 2016; Digiacomo et al., 2021). Mesh also had no effect on the yield or sugar quality of blueberries (Cormier et al., 2015) and can even increase the fruit quality in some circumstances. Mesh significantly improved apple quality when compared with untreated controls (Chouinard et al., 2022). Stone fruit from netted trees had enhanced colour and sugar content compared to fruit from unmeshed trees (Lloyd et al., 2005), and meshed blackberries were two times more marketable than organic spinosad-sprayed blackberries (Kuesel et al., 2019). Another concern for growers is pollinator access to flowers; crumbly berry, an indicator of a lack of pollination, increased in meshed raspberry plots (Stockton et al., 2020), while a complete lack of pollinator access to raspberry flowers resulted in unmeshed flowers producing fruit 30% larger than those from meshed flowers (Cane, 2005).

4.1.4. *Tunnel microclimates*

Mesh tunnels experienced a higher number of instances of peak temperature (30–35 °C) and humidity (91–100% RH) when compared with open control tunnels after the mesh was implemented, which may have resulted in the increased occurrence of sooty shoulder on fruit in meshed tunnels in this study. Other research on mesh indicates only limited impact on the microclimate of crops. In a comparison between meshed and unmeshed primocane raspberries, there was no significant difference in temperature and only slight differences in humidity with meshed plots experiencing slightly lower humidity than unmeshed plots before dawn, in the afternoon and evening, which contrasts our findings (Stockton et al., 2020), although mesh structures were different in this study and did not cover doors on polytunnels. In a study on meshed polytunnel-grown raspberries, there was no significant difference in overall mean temperature between meshed and unmeshed tunnels (Leach et al., 2016), and temperature was similar in meshed and unmeshed blueberry plots (Cormier et al., 2015). Despite this, it should be noted that mesh has the potential to alter crop microclimate, especially in polytunnels. While it can provide shade to some parts of the crop, it may restrict airflow and lead to an increase in temperature within the tunnel, especially in the later parts of the growing season (Leach et al., 2016). Venting tunnels and installation of fan systems could limit the risk of increased ambient temperatures and humidity.

In contrast to our findings on humidity, other research indicates a limited impact on humidity within crops. When mesh (gauge 2.4 ×4.8 mm) was placed over nectarines in Italy, no significant difference in temperature and relative humidity between meshed and unmeshed nectarines was observed (Candian et al., 2021). Likewise, in apple plots in Washington, US where meshed cages (gauge 2.0 ×5.0 mm, and 2.2 ×3.4 mm) were placed over the apple trees (Marshall and Beers, 2021), no significant difference in relative humidity was recorded between the meshed and unmeshed trees or in Montreal, Canada (Chouinard et al., 2022). However, mesh gauges were larger in these studies compared to our study. A raspberry plot covered by a small mesh structure exhibited slightly lower relative humidity than the unmeshed control, but only one datalogger recorded humidity in this study (Stockton et al., 2020).

4.2. *Mesh management and recommendations*

Although sites where mesh was poorly installed (considerable mesh damage and mesh implementation several weeks after ripe fruiting) were excluded from our analysis, there was still variability in consistency with the way the mesh was implemented across tunnels in our study. Some tunnels exhibited slight mesh damage and others with implementation a week after first ripe fruiting. Furthermore, venting the tunnels by raising the side plastic coverings and the mesh doors to allow pickers and machinery access could have also exposed the crop to pests, but such challenges will be typical in any commercial operation. This may explain why there was no significant difference in Drosotrap catches between mesh and control tunnels, and even greater *D. suzukii* control could be achieved with efficient mesh management.

Given the challenges of installing mesh and maintaining a protective barrier throughout the season on commercial farms, we recommend placing mesh as a vertical barrier around the crop edge, which may reduce the risk of entry of low-flying *D. suzukii*, from hotspot areas although the height to which these mesh barriers are raised will be dependent on mesh availability and surrounding landscape context. As there was a significant difference in *D. suzukii* trap catches when compared with the crop edge, mesh may reduce population abundance within the crop while allowing machinery and pickers to enter the tunnels without having to raise and lower the mesh each time. Mesh can be expensive (Chouinard et al., 2016), so it could be targeted at higher risk sites. Despite the costs of mesh, it may help to reduce reliance on insecticide spraying programmes due to increased spider numbers maintaining pest suppression as well as reductions in *D. suzukii* damage. Due to potential reductions in use of sprays, costs of machinery and labour for crop maintenance may also be reduced if mesh is installed and maintained well. In addition, mesh can be kept on site and used for several growing seasons before needing to replace it, should considerable damage occur, highlighting its value as a long-term investment.

Future research should focus on finding consistently effective combinations of protective mesh barriers and other IPM approaches to mitigate the potential negative effects of mesh on pathogens, and some natural enemies (parasitoids) found in this study. We also recommend future research to focus on the impact of mesh as vertical barriers around the farm edge on *D. suzukii* abundance and damage on soft fruit farms. As *D. suzukii* populations can fluctuate, with a higher risk of damage in some years than others, it is important to develop management practices that remain effective, reliable and consistent. Mass release of natural enemies or habitat creation could be combined with mesh to promote effective IPM. Finally, a full cost-benefit analysis of all the associated costs and benefits of installing mesh would be helpful in informing when and where such practices would be commercially viable.

5. Conclusions

This study highlights the potential for mesh to limit numbers of *D. suzukii* entering raspberry polytunnels and how it impacts pest and natural enemy abundance in tunnels, fruit quality and tunnel microclimates. Because of the difficulty in maintaining the appropriate mesh management, we make recommendations on how to best use mesh on fruit farms, while emphasising its use in combination with a range of other IPM approaches. This could help inform farm management strategies to aid in controlling pest levels on fruit farms, specifically for raspberries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The research was funded as part of the BBSRC Waitrose Collaborative Training Partnership (BB/S507325/1) and supported by BerryWorld. We thank BerryWorld and their growers for their generosity in allowing us to carry out this study on their farms.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108756.

References

Agriculture and Horticulture Development Board. (2013) Cane fruit crop walker's guide. URL: https://horticulture.ahdb.org.uk/knowledge-library/cane-fruit-crop-walkers-guide (accessed 19 September 2019).

Alnajjar, G., Collins, J., Drummond, F.A., 2017. Behavioral and preventative management of Drosophila suzukii Matsumura (Diptera: Drosophilidae) in Maine wild blueberry (Vaccinium angustifolium Aiton) through attract and kill trapping and insect exclusion-netting'. Int. J. Entomol. Nematol. 3 (1), 51–61. Available at: 〈https://www.premierpublishers.org/ijen/090220177928.pdf〉.

Barzman, M. et al. (2015) 'Eight principles of integrated pest management', Agronomy for Sustainable Development. Springer-Verlag France, pp. 1199–1215. doi: 10.1007/s13593–015-0327–9.

Boivin, G., Hance, T., Brodeur, J., 2012. Aphid parasitoids in biological control. Can. J. Plant Sci. 92 (1), 1–12. https://doi.org/10.4141/CJPS2011-045.

Boxall, A.B.A., et al., 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. Environ. Health Perspect. 117 (4), 508–514. https://doi.org/10.1289/ehp.0800084.

Bradish, C.M., et al., 2012. Comparison of flavonoid composition of red raspberries (Rubus idaeus L.) grown in the Southern United States. J. Agric. Food Chem. 60 (23), 5779–5786. https://doi.org/10.1021/jf203474e.

Burkness, E.C., et al., 2022. Exclusion and repulsion of Popillia japonica (Coleoptera: Scarabaeidae) using selected coverings on high tunnel structures for primocane red raspberry. Insects 13 (9). https://doi.org/10.3390/insects13090771.

Bylemans, D., et al., 2003. Pest control by means of natural enemies in raspberry and red currants under plastic tunnel. IOBC/WPRS Bull. 26 (2), 37–44.

Candian, V., et al., 2021. First multi-target application of exclusion net in nectarine orchards: effectiveness against pests and impact on beneficial arthropods, postharvest rots and fruit quality. Insects 12 (3), 1–14. https://doi.org/10.3390/insects12030210.

Cane, J.H., 2005. Pollination potential of the bee Osmia aglaia for cultivated red raspberries and blackberries (Rubus: Rosaceae). HortScience 40 (6), 1705–1708. https://doi.org/10.21273/hortsci.40.6.1705.

Chouinard, G., Firlej, A., Cormier, D., 2016. Going beyond sprays and killing agents: Exclusion, sterilization and disruption for insect pest control in pome and stone fruit orchards. In: Scientia Horticulturae, 208. Elsevier B.V, pp. 13–27. https://doi.org/10.1016/j.scienta.2016.03.014.

Chouinard, G., Pelletier, F., Larose, M., 2022. 'Insect netting: effect of mesh size and shape on exclusion of some fruit pests and natural enemies under laboratory and orchard conditions'. J. Pest Sci. 96, 857–869.

Cini, A., Ioriatti, C., Anfora, G., 2012. A review of the invasion of Drosophila suzukii in Europe and a draft research agenda for integrated pest management. Bull. Insect 65 (1), 149–160.

Cormier, D., Veilleux, J., Firlej, A., 2015. Exclusion net to control spotted wing Drosophila in blueberry fields'. IOBC-WPRS Bull. 109 (2015), 181–184.

Culliney, T.W., 2014. Crop losses to arthropods. in Integrated Pest Management: Pesticide Problems, Vol.3. Springer Netherlands, pp. 201–225. https://doi.org/10.1007/978-94-007-7796-5_8.

Dassonville, N., Thiellemans, T., Gosset, V., 2013. FresaProtect and BerryProtect: mixes of parasitoids to control all common aphid species on protected soft fruit crops Product development and case studies from three years of experience'. Asp. Appl. Biol. 119, 79–87 (Available at: 〈https://www.viridaxis.com/wp-content/uploads/emr_case_studies.pdf〉).

Del Fava, E., Ioriatti, C., Melegaro, A., 2017. Cost–benefit analysis of controlling the spotted wing drosophila (Drosophila suzukii (Matsumura)) spread and infestation of soft fruits in Trentino, Northern Italy. Pest Manag. Sci. 73 (11), 2318–2327. https://doi.org/10.1002/ps.4618.

Dib, H., Sauphanor, B., Capowiez, Y., 2010. Effect of codling moth exclusion nets on the rosy apple aphid, Dysaphis plantaginea, and its control by natural enemies. In: Crop Protection, 29. Elsevier Ltd, pp. 1502–1513. https://doi.org/10.1016/j.cropro.2010.08.012.

DiGiacomo, G., et al., 2019. Economic impact of spotted wing drosophila (Diptera: Drosophilidae) yield loss on minnesota raspberry farms: a grower survey. J. Integr. Pest Manag. 10 (1) https://doi.org/10.1093/jipm/pmz006.

Digiacomo, G., et al., 2021. 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. J. Econ. Entomol. 114 (4), 1655–1665. https://doi.org/10.1093/jee/toab087.

Ebbenga, D.N., et al., 2019. Evaluation of exclusion netting for spotted-wing Drosophila (Diptera: Drosophilidae) management in minnesota wine grapes. J. Econ. Entomol. 112 (5), 2287–2294. https://doi.org/10.1093/jee/toz143.

Ganjisaffar, F., et al., 2022. Characterization of field-derived Drosophila suzukii (Diptera: Drosophilidae) resistance to pyrethroids in california berry production. In: Anderson, T. (Ed.), Journal of Economic Entomology. https://doi.org/10.1093/jee/toac118.

Giorgini, M., et al., 2018. Exploration for native parasitoids of Drosophila suzukii in China reveals a diversity of parasitoid species and narrow host range of the dominant parasitoid. Journal of Pest Science. Springer Berlin Heidelberg. https://doi.org/10.1007/s10340-018-01068-3.

Goggin, F.L., 2007. Plant-aphid interactions: molecular and ecological perspectives. Curr. Opin. Plant Biol. 399–408. https://doi.org/10.1016/j.pbi.2007.06.004.

Goodhue, R.E., et al., 2011. Spotted wing drosophila infestation of California strawberries and raspberries: Economic analysis of potential revenue losses and control costs. Pest Manag. Sci. 67 (11), 1396–1402. https://doi.org/10.1002/ps.2259.

Grassi, A., Pallaoro, M., 2012. Drosophila suzukii (Matsumura), a revolution for soft fruits in Trentino. Ecofruit. 15th Int. Conf. Org. Fruit. -Grow. 179–186.

Gress, B.E., Zalom, F.G., 2019. Identification and risk assessment of spinosad resistance in a California population of Drosophila suzukii. Pest Manag. Sci. 75 (5), 1270–1276. https://doi.org/10.1002/ps.5240.

Hanni, L., Luik, A., 2006. Parasitism of raspberry beetle (Byturus tomentosus F.) larvae in different cropping techniques of red raspberry'. Agron. Res. 4 (Special issue), 187–190.

Harwood, J.D., Sunderland, K.D., Symondson, W.O.C., 2005. Monoclonal antibodies reveal the potential of the tetragnathid spider Pachygnatha degeeri (Araneae: Tetragnathidae) as an aphid predator. Bull. Èntomol. Res. 95 (2), 161–167. https://doi.org/10.1079/ber2004346.

Hillocks, R.J., 2012. Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. Crop Prot. 85–93. https://doi.org/10.1016/j.cropro.2011.08.008.

Kehrli, P., et al., 2022. Optimization of the sampling method to monitor Drosophila suzukii infestation in vineyards. J. Appl. Entomol. 146 (4), 408–414. https://doi.org/10.1111/jen.12987.

Kirkpatrick, D.M., et al., 2017. Improving monitoring tools for spotted wing drosophila, Drosophila suzukii. Èntomol. Exp. Et. Appl. 164 (2), 87–93. https://doi.org/10.1111/eea.12602.

Kuesel, R., et al., 2019. Effects of fine-mesh exclusion netting on pests of blackberry. Insects 10 (8), 249. https://doi.org/10.20944/preprints201906.0006.v1.

Kuesel, R., et al., 2023. Fine-mesh exclusion netting reduces Drosophila suzukii (Diptera: Drosophilidae) infestation and improves organic fall-bearing raspberry yields. J. Econ. Entomol. 7, 1–10.

Leach, H., Van Timmeren, S., Isaacs, R., 2016. Exclusion netting delays and reduces Drosophila suzukii (Diptera: Drosophilidae) infestation in raspberries. J. Econ. Entomol. 109 (5), 2151–2158. https://doi.org/10.1093/jee/tow157.

Lee, J.C., et al., 2011. The susceptibility of small fruits and cherries to the spotted-wing drosophila, Drosophila suzukii. Pest Manag. Sci. 67 (11), 1358–1367. https://doi.org/10.1002/ps.2225.

Lloyd, A., et al., 2005. Evaluation of exclusion netting for insect pest control and fruit quality enhancement in tree crops. Acta Hortic. (694), 253–258. https://doi.org/10.17660/ActaHortic.2005.694.41.

Łozowicka, B., et al., 2012. Pesticide residues in raspberries (Rubus idaeus L.) and dietary risk assessment. Food Addit. Contam.: Part B Surveill. 5 (3), 165–171. https://doi.org/10.1080/19393210.2012.681398.

Marshall, A.T., Beers, E.H., 2021. Exclusion netting affects apple arthropod communities. Biological Control. Elsevier Inc. p,. https://doi.org/10.1016/j.biocontrol.2021.104805.

Mateos-Fierro, Z., et al., 2021. Active management of wildflower strips in commercial sweet cherry orchards enhances natural enemies and pest regulation services. In: Agriculture, Ecosystems and Environment, 317. Elsevier B.V. https://doi.org/10.1016/j.agee.2021.107485.

Mitchell, C., et al., 2010. Combining plant resistance and a natural enemy to control Amphorophora idaei. BioControl 55 (3), 321–327. https://doi.org/10.1007/s10526-009-9257-2.

Molina-Bravo, R., et al., 2011. A protocol to assess heat tolerance in a segregating population of raspberry using chlorophyll fluorescence. Sci. Hortic. 130 (3), 524–530. https://doi.org/10.1016/j.scienta.2011.07.022.

Rogers, M.A., Burkness, E.C., Hutchison, W.D., 2016. Evaluation of high tunnels for management of Drosophila suzukii in fall-bearing red raspberries: potential for reducing insecticide use'. In: Journal of Pest Science, 89. Springer Berlin Heidelberg, pp. 815–821. https://doi.org/10.1007/s10340-016-0731-1.

Sarwar, M., 2015. The killer chemicals as controller of agriculture insect pests: the conventional insecticides. Int. J. Chem. Biomol. Sci. 1 (3), 141–147.

Stockton, D.G., et al., 2020. Factors affecting the implementation of exclusion netting to control Drosophila suzukii on primocane raspberry. In: Crop Protection, 135. Elsevier Ltd,. https://doi.org/10.1016/j.cropro.2020.105191.

Tuohimetsä, S., et al., 2014. Fruit development in artificially self- and cross-pollinated strawberries (Fragaria × ananassa) and raspberries (Rubus idaeus). Acta Agric. Scand. Sect. B: Soil Plant Sci. 64 (5), 408–415. https://doi.org/10.1080/09064710.2014.919348.

Wilson, C., Tisdell, C., 2001. Why farmers continue to use pesticides despite environmental, health and sustainability costs. Ecol. Econ. 39 (3), 449–462. https://doi.org/10.1016/S0921-8009(01)00238-5.

Zhang, W., et al., 2007. Ecosystem services and dis-services to agriculture. Ecol. Econ. 64 (2), 253–260. https://doi.org/10.1016/j.ecolecon.2007.02.024.

Żurawicz, E., et al., 2018. A careful choice of compatible pollinizers significantly improves the size of fruits in red raspberry (Rubus idaeus L.). Sci. Hortic. 235 (February), 253–257. https://doi.org/10.1016/j.scienta.2018.02.064.