

The Distance Between Forests and Crops Affects the Abundance of *Drosophila suzukii* During Fruit Ripening, But Not During Harvest

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Abstract

Drosophila suzukii (Matsumura; Diptera: Drosophilidae) is an invasive pest with the ability to reproduce not only in various soft fruit crops, but also in numerous wild hosts. Forests and forest edges harbor many wild hosts, provide suitable microclimatic conditions and are therefore thought to enhance the abundance of *D. suzukii*. Although the comprehension of pest activity based on specific landscape elements is important to implement efficient management strategies, knowledge of how forests affect the abundance of *D. suzukii* in nearby crops is very limited. We conducted a monitoring study with liquid baited traps across different crops at different distance from the forests. During fruit ripening, more flies were captured in crops closer to forests (22.21 % decrease per 500 m distance), whereas there was no significant relationship during harvest. Since color can affect the efficiency of *D. suzukii* traps, we have used traps either with a red or black lid. Acquired data suggest that traps with black lids capture significantly more flies than traps with red lids. We provide a quantitative estimation of how and when distance from adjacent forests affects the abundance of *D. suzukii* in crop fields. Our results can help consultants and farmers to estimate the pest pressure of *D. suzukii* in crop fields near forested, noncrop areas and to implement appropriate control strategies when *D. suzukii* populations increase and fruit becomes susceptible to infestation.

Key words: liquid bait; pest monitoring; soft fruit; spotted wing drosophila, trap color

The spotted wing drosophila, *Drosophila suzukii* Matsumura (Diptera: Drosophilidae), is an invasive, devastating pest that threatens soft fruit production in Europe and America (Beers et al. 2011, Walsh et al. 2011, Calabria et al. 2012, Cini et al. 2012). In contrast to other *Drosophila* species, *D. suzukii* is attracted to and can lay eggs in undamaged, ripening and ripe fruits. Wounds in the fruit skin after oviposition of *D. suzukii* make fruit more susceptible to subsequent infestation with other insects and pathogenic microorganisms (Hamby et al. 2012, Swett et al. 2016, Rombaut et al. 2017). In addition, the developing *D. suzukii* larva damages the fruit. Consequently, the small-fruit industry and the market have a zero tolerance to *D. suzukii* infestation (Bruck et al. 2011, Haye et al. 2016), which requires efficient control strategies against this pest to minimize financial losses (Walsh et al. 2011, Cini et al. 2012). *D. suzukii* has a broad host range for reproduction, including various soft-skinned fruit crops like cherries, plums, grapes, and various berries (Beers et al. 2011, Lee et al. 2011a, Walsh et al. 2011). In addition, numerous noncrop plants, including wild blackberries, wild strawberries, wild cherries, elder, rosehip, and many more, serve

as hosts (Lee et al. 2015, Kenis et al. 2016). Many wild hosts grow in forests and forest edges near crops, indicating that this natural habitat could be a significant source of *D. suzukii* (Poyet et al. 2014, Kenis et al. 2016, Pelton et al. 2016).

Besides the availability of host plants, *D. suzukii* is sensitive to microclimatic conditions. Adults avoid hot and dry habitats and prefer a microclimate with mild temperatures and high humidity, since unfavorable climatic conditions affect their fecundity (Kinjo et al. 2014, Tochen et al. 2016, Diepenbrock and Burrack 2017, Evans et al. 2017). Microclimatic conditions also influence overwintering success (Zerulla et al. 2015). During winter, *D. suzukii* is less often captured in crop habitats than in noncrop habitats (Harris et al. 2014, Wang et al. 2016), but mainly in woody areas (Rossi Stacconi et al. 2016). It is therefore assumed that *D. suzukii* uses protective woody sites for overwintering (Fountain et al. 2018), although that has not yet been fully clarified by scientific studies. Unlike more or less open crop fields, nearby forests could provide a refuge with suitable microclimatic conditions during the hot and dry periods in summer and for overwintering.

In landscapes consisting of a mosaic of various host crops, wild host plants and different abiotic microhabitats, the spatial and temporal pest pressure of *D. suzukii* can be very variable. One component of an efficient insect pest management strategy is the comprehension of pest activity based on landscape elements (Schneider 1989, Holland and Fahrig 2000), which also applies to *D. suzukii* (Santoemma et al. 2018). However, knowledge on how forests and forest edges affect the temporal and spatial abundance and therefore pest pressure of *D. suzukii* is limited. This makes it a challenge for farmers to estimate the local and temporal risk of *D. suzukii* infestations for specific crop fields and to conduct effective, economic and ecologically reasonable control strategies at the right timing (Dorsaz et al. 2017). Pelton et al. (2016) showed that the activity of *D. suzukii* in raspberry fields at the beginning of the season is earlier in landscapes with a high proportion of woodland, whereas Thistlewood et al. (2018) found no effect of any landscape parameter on the first catch date of *D. suzukii* in different crops. Santoemma et al. (2018) showed a positive correlation between forest cover and female density as well as crop damage in cherry orchards. Due to *D. suzukii*'s high dispersal ability (Tait et al. 2017), it is not possible to relocate crop fields to greater distances from natural habitats than the pest's dispersal area (Santoemma et al. 2018). It is therefore important to better understand to what extent adjacent forests increase the frequency of *D. suzukii* in the crop fields. However, Pelton et al. (2016) and Klick et al. (2016) pointed out that there is only limited information on how the distance of natural landscape elements to crop fields affect *D. suzukii* population dynamics and pest pressure. Since trapping numbers from monitoring can be linked to the absolute pest density of *D. suzukii* and could be used for management decisions (Kirkpatrick et al. 2018), quantitative estimations of the extent to which adjacent forests increase the abundance of *D. suzukii* in crop fields are essential.

In this study, we evaluated how distance from the adjacent forest (at least 1 ha area including undergrowth) affects the local abundance of *D. suzukii*. We used commercially available traps filled with a liquid *D. suzukii* bait based on wine-vinegar, one of the standard approaches to monitoring *D. suzukii* (Rossi Stacconi et al. 2016). We also compared the effectiveness of traps with red or black lids. Black and red correspond well to the color spectrum of the host fruits of *D. suzukii* and are described as the most preferred colors (Basoalto et al. 2013, Renkema et al. 2014, Kirkpatrick et al. 2016, Rice et al. 2016). Since *D. suzukii*, in contrast to native *Drosophila* species in Europe and America, specifically attacks ripening fruits, we conducted the monitoring from the period of fruit ripening until fruit was ripe during harvest. Our goal was to assess how distance from the adjacent forest, presenting a potential source of *D. suzukii*, affects local pest abundance in crop fields during fruit ripening and during harvest.

Material and Methods

Monitoring

The monitoring was conducted in the region between Hünenberg and Zug at the lake of Zug in Switzerland (Table 1). Clear plastic traps (Profatec AG, Malans, Switzerland) with colored lids and entry holes on the side of the lid were used. At every trap location, one trap with a red and one with a black lid was installed 1–1.5 m from each other. The traps were positioned at least 5 m into the crop field and hung within the host fruit zone. Positions of black and red traps at a specific trap location were switched weekly in order to minimize position effects. Traps were filled with 60 ml of commercial liquid

Table 1. Crop field coordinates and distances from the adjacent forest

Coordinates	Crop	Distance from the adjacent forest (m)
47.18466 N, 8.49936 E	Plum	1,000
47.18970 N, 8.52234 E	Plum	1,400
47.19038 N, 8.46474 E	Plum	10
47.20472 N, 8.54186 E	Plum	200
47.17708 N, 8.41296 E	Strawberry	350
47.18530 N, 8.50167 E	Raspberry	1,000
47.17764 N, 8.41069 E	Blackberry	200
47.17747 N, 8.41351 E	Blueberry	350

wine-vinegar *D. suzukii* bait (Riga AG, Ellikon, Switzerland). The entire content in each trap was collected and replaced weekly by fresh bait. The collected bait liquid with all captured insects was assessed weekly in the laboratory under a binocular microscope and the number of *D. suzukii* males and females counted. In calendar week 40, the bait could not be renewed because of an unforeseen incident. The counted flies therefore were equally assigned to calendar week 40 and 41. Since excluding these data did not change the results, the data were retained in the model. According to the phenological development stage of specific crops in specific crop fields, the monitoring was conducted during fruit ripening (calendar week 31–37) until harvest (calendar week 33–42), because the arrival of *D. suzukii* in the crops usually corresponds to fruit susceptibility during ripening and harvest times (Hampton et al. 2014, Thistlewood et al. 2018). Eight trap pairs were installed in four different plum orchards, two in blueberry, raspberry, and blackberry fields, and one in a strawberry field. Forests measured at least 1 ha and included underwood. The distance of the forest edge to the trap sites (10, 200, 350, 1,000, and 1,400 m) was measured by using the mapping platform of the Swiss Confederation (www.map.geo.admin.ch).

Statistical Data Analysis

We used R 3.3.1 (R Development Core Team 2016) and the R-package nlme (Lindstrom and Bates 1990) to perform linear mixed effects models to analyze the log-transformed number of captured flies for ripening and ripe fruits during harvest separately. *Distance from the adjacent forest* was scaled by dividing the variable by its standard deviation. Both full models used the fixed variables *lid color* (black or red), *distance from the adjacent forest* and the interaction between those two variables. The nonsignificant interactions were removed during model simplification. Decisions to remove interactions were based on likelihood ratio tests and the Akaike information criterion (AIC). Due to the limited number of replicates per crop, *crop type* was treated as a random factor. Therefore, the models evaluate broadly how *crop type* affects the abundance of *D. suzukii* among a range of crop fields. Since not all calendar weeks were represented equally across all crops, *calendar week* was treated as a random effect, taking into account different climatic conditions and corresponding fluctuations in the *D. suzukii* population during the observation period. The decision to additionally include the random effects *site* and *trap pair* within crop fields was based on the AIC. *Site* was included in both models, whereas *trap pair* was only included in the model during harvest. Intraclass correlations between observations within specific random effect levels was calculated as $d^2/(d^2 + \sigma^2)$, where d^2 is the variance of the intercept of

the random factor and σ^2 the variance of the residuals (Zuur et al. 2009). Due to the temporal autocorrelation, including an autoregressive–moving-average (ARMA: $p = 0$, $q = 1$) error structure in the model for ripening fruits and a residual autocorrelation structure in the model for ripe fruits during harvest clearly improved model fits (based on AIC). Visual inspection of residual plots was used to test for deviations from homoscedasticity or normality and temporal autocorrelation.

Results

During fruit ripening, more flies were captured in crops closer to the adjacent forest ($t_{1,52} = -7.72$, $P = 0.005$, Fig. 1). The abundance of *D. suzukii* in the monitored crops decreased by 22.21% per 500 m increasing distance from the adjacent forest.

Lid color had a significant overall effect on fly capture ($t_{1,52} = 3.75$, $P = 0.001$). For instance, red traps placed 10 m next to the forest captured on average 108 flies, in a range of 50 (mean – SE) to 230 flies (mean + SE), whereas black traps captured on average 129 flies, in a range of 64 (mean – SE) to 290 flies (mean + SE). Asymmetric intervals are due to back transformation of logarithmic values. The random effects revealed that the intraclass correlation of fly captures within crop types was 0.81, but only 0.08 within sites. There was no obvious correlation in fly captures within the same calendar week (0.00).

When fruits were ripe during harvest, there was no significant relationship between the number of captured flies and distance from the adjacent forest ($t_{1,92} = -0.70$, $P = 0.501$). The abundance of *D. suzukii* in the monitored crops decreased only by 7.09% per 500 m increasing distance from the adjacent forest.

Lid color had a significant overall effect on fly capture ($t_{1,92} = 4.95$, $P < 0.001$). For instance, red traps placed 10 m next to the forest captured on average 149 flies, in a range of 65 (mean – SE) to 343 flies (mean + SE), whereas black traps captured on average 199 flies, in a range of 92 (mean – SE) to 487 flies (mean + SE). The random effects revealed that the intraclass correlation of fly captures within sites was 0.81, but only 0.02 within crop types, 0.02 within trap pairs, and 0.08 within calendar weeks.

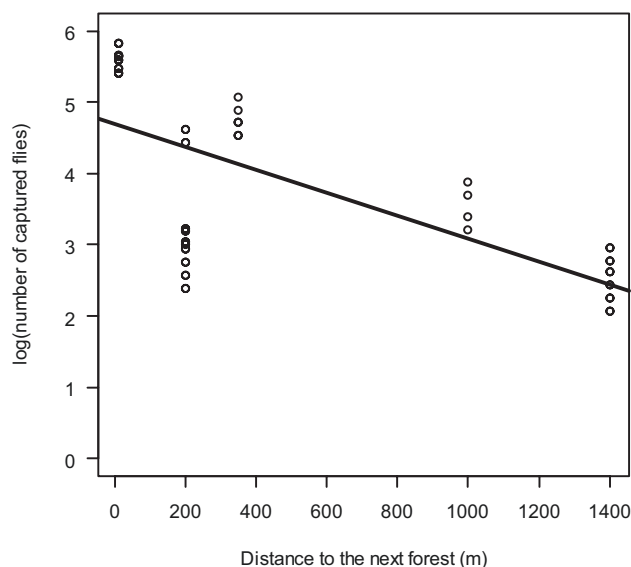


Figure 1. Fitted values of the number of *Drosophila suzukii* (logarithmic scale) captured with liquid baited traps, installed in various crops, differing in distance from the adjacent forest.

Discussion

Effect of Trap Distance From the Adjacent Forest on *D. suzukii* Captures in Crop Fields

During fruit ripening, the abundance of *D. suzukii* in crops closer to the adjacent forest was higher than in crops at further distances (Fig. 1). This implies that forests are a source of *D. suzukii* early in the crop season. Various wild hosts growing in forests support *D. suzukii* (Kenis et al. 2016). Pelton et al. (2016) found a high abundance of *D. suzukii* in resource-rich woodlands surrounding raspberry fields. For instance, black cherry *Prunus serotina*, one of the main woody forest invaders in Europe, is a reservoir for the development and persistence of *D. suzukii* populations (Poyet et al. 2014). Wild host plants can enable the presence and spread of *D. suzukii* in landscapes, where no host crop plant exist (Garantonakis et al. 2016). Flies, which developed as larvae in wild host fruits grown in forests, could migrate to crops (Diepenbrock et al. 2016). Wang et al. (2016) suggested that fly populations move among sites separated by less than 2 km and Sautoemma et al. (2018) found that the relation between forest cover and female adult density in cherry orchards was best explained in a spatial scale radius of 500 m. Our monitoring revealed that the abundance of *D. suzukii* in the monitored crops decreased by 22.21% per 500 m increasing distance from the adjacent forest (Fig. 1). This suggests a significant migration of *D. suzukii* from forests to crop fields during the availability of ripening fruits. Although most studies, including our study, at the landscape level on *D. suzukii* were conducted with a biased distribution of traps (Thistlewood et al. 2018), future studies with traps on a finer scale and further distances from the adjacent forest could provide a better picture of how flies migrate into the host crop.

D. suzukii could use olfactory cues to migrate from the adjacent forest to crop fields during fruit ripening. *D. suzukii* is more sensitive to volatiles associated with fruit ripening (Keeseey et al. 2015) and is less strongly attracted by fermented fruits than *Drosophila melanogaster* MEIGEN (Karageorgi et al. 2017). In addition, *D. suzukii* females with greater egg loads chose raspberry odors over fermentation odors in a choice arena (Wong et al. 2018). Attraction to rotten fruits is also driven by adult food preferences and not only by requirements for oviposition (Karageorgi et al. 2017). Once fruit started to color, host fruits are generally susceptible to oviposition by *D. suzukii* (Lee et al. 2011b). Bernardi et al. (2017) found no difference in susceptibility between different ripening stages of strawberries in a no-choice bioassay. However, when ripe fruits are available, *D. suzukii* prefers ripe over unripe or ripening fruits, since skin firmness in riper fruits generally decreases, facilitating oviposition (Lee et al. 2016, Bernardi et al. 2017). In contrast, Poyet et al. (2014) found that *D. suzukii* preferred ripening over ripe black cherry *P. serotina* and suggested an increasing chance of the larvae to fully develop and reach maturity before the mesocarp of the fruit totally decays.

When mainly ripe fruits were available during harvest, there was no significant relationship between distance from the adjacent forest and the abundance of *D. suzukii* in the monitored crops, although the number of captured flies had more than doubled compared to fruit ripening. This indicates either that immigration into crops occurs mainly during the ripening period before harvest or that immigration during harvest is negligible compared to flies hatching directly in the crops. The intraclass correlation of fly captures within specific sites was low during fruit ripening, but rather high during harvest. This implies that the number of flies was location-specific during harvest, suggesting locally establishing subpopulations. In addition, fruit type (Lee et al. 2011b, Cini et al. 2012), different crop

field structures and plant-specific canopy characteristics (Toda 1992, Keeseey et al. 2015) can influence the attractiveness of different crops for *D. suzukii*. In our study, fly captures within the same crop type were clearly correlated during fruit ripening and slightly during harvest, indicating crop-specific abundance of *D. suzukii*. More detailed data are required to assess the specific attractiveness of certain crops at different stages of ripening.

While monitoring the frequency of adult *D. suzukii* can be a weak predictor for later larval infestation (Hamby et al. 2014, Burrack et al. 2015, Cha et al. 2018), it can nevertheless be positively correlated with current fruit infestation (Hamby et al. 2014, Pelton et al. 2016). In addition, Kirkpatrick et al. (2018) recently proposed how to link trap capture numbers from monitoring to the absolute pest density of *D. suzukii* and how to use them for management decisions. In host crops close to forests (Santoemma et al. 2018), timely preventive measures during fruit ripening—such as nets (Leach et al. 2016, Mazzi et al. 2017), mass trapping (Dorsaz et al. 2017), or application of mineral particle films on fruit surfaces (Cahenzli et al. 2018)—are important to reduce the development of local subpopulations.

Although our study shows in accordance with Klick et al. (2016), Pelton et al. (2016) and Santoemma et al. (2018) that natural habitats promote the presence of *D. suzukii*, natural habitats could also have positive control effects on already established populations in crops. Natural habitats of *D. suzukii* could pull flies from crop fields during periods with unsuitable climatic conditions, play a role for insecticide resistance management and enhance natural *D. suzukii* antagonists (Haye et al. 2016, Klick et al. 2016). Further studies are necessary to assess the ambivalent effect of natural habitats on *D. suzukii*.

Effects of Trap Lid Color on *D. suzukii* Capture

Several studies with sticky traps (Kirkpatrick et al. 2016, Rice et al. 2016, Kirkpatrick et al. 2017) and baited traps (Basoalto et al. 2013, Renkema et al. 2014) revealed that red and black are the most attractive colors to *D. suzukii*. Most day-active insects possess photoreceptors that cover the whole visible light spectrum, including red (Wakakuwa et al. 2004). Although the visual system of *D. melanogaster* is insensitive to red light, circadian entrainment to red light was observed (Hanai et al. 2008). Furthermore, Kirkpatrick et al. (2016) points out that the sensitivity of receptors to red can differ on species level in insects and showed, aside from the preference for red, that *D. suzukii* perceives colors, not just the level of target brightness. In our study, traps with black lids generally captured more *D. suzukii* than traps with red lids, during fruit ripening and during harvest. In contrast, most other studies examining effects of different colors on capture efficiency found no significant differences between red and black (Renkema et al. 2014, Kirkpatrick et al. 2016, Rice et al. 2016, Kirkpatrick et al. 2017). Furthermore, color preferences may vary depending on crop and season (Basoalto et al. 2013, Lee et al. 2013). Nevertheless, the findings of our study conducted across different crops suggest that black traps capture more *D. suzukii* than red traps. This must be taken into account, as a change in the sensitivity of the monitoring systems can influence the estimation of pest pressure. Future studies, with a higher number of replicates in different crops, could assess whether our findings are valid in a large number of crops.

Conclusions

As expected, the monitored abundance of *D. suzukii* depended on various parameters, such as crop type, trap color and fruit ripening

stage. In addition, we show that distance from the adjacent forest significantly affects the abundance of *D. suzukii* during fruit ripening, but not during harvest. Our results contribute to a better understanding of how and when the surrounding landscape influences the abundance of *D. suzukii* in crop fields. Our findings can help consultants and farmers to estimate the pest pressure of *D. suzukii* in crop fields near forested, noncrop areas and to implement appropriate control strategies when *D. suzukii* populations increase and fruit becomes susceptible to infestation.

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Author Contributions

I.B. and J.F. conceived the monitoring and I.B. performed the assessments. C.D. and F.C. analyzed the data and F.C. conducted the statistical analyses. F.C. wrote the manuscript, complemented by contributions from I.B., C.D., and J.F. F.C. and I.B. contributed equally to the study. All authors read and approved the manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

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