



Seasonal monitoring of *Drosophila suzukii* (Diptera: Drosophilidae) in a mixed fruit production system



D.W. Harris, K.A. Hamby*, H.E. Wilson, F.G. Zalom

Department of Entomology and Nematology, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA

ARTICLE INFO

Article history:

Received 13 May 2014

Revised 18 August 2014

Accepted 27 August 2014

Available online 2 September 2014

Keywords:

Spotted wing drosophila

Seasonal phenology

Overwintering

Host reservoirs

Small farms

Gardens

ABSTRACT

Drosophila suzukii Matsumura (Diptera: Drosophilidae), an invasive pest native to Southeast Asia, is now reported throughout North America and Europe. We used traps baited with apple cider vinegar to monitor *D. suzukii* adult presence in multiple crops and associated fruiting plants at the Wolfskill USDA Germplasm Repository in Winters, CA, USA from 2011 to 2013. Traps were placed in small (~160 m × 40 m on average) almond, apricot, cherry, fig, grape, mulberry, peach, persimmon, plum, and pomegranate deciduous fruit orchard blocks as well as a citrus block and evergreen trees located near a house at the repository. *D. suzukii* was present in all blocks with the greatest monthly deciduous fruit captures in the cherry and fig blocks. Few *D. suzukii* were captured in almond, apricot, pomegranate and grape blocks. Deciduous fruit blocks had two distinct periods of trap capture: spring through midsummer and again in fall. Most deciduous fruit blocks had low trap captures during the hottest summer months (August to September) and the coldest winter months (December to April). However, from late December through mid-January, high trap captures were associated with the citrus and house sites. This study provides seasonal trapping data of *D. suzukii* adults in an unsprayed multi-crop mosaic, and may serve as a model of adult capture patterns across smaller mixed-crop commercial orchards and associated urban landscapes.

© 2014 Korean Society of Applied Entomology, Taiwan Entomological Society and Malaysian Plant Protection Society. Published by Elsevier B.V. All rights reserved.

Introduction

Drosophila suzukii (Matsumura) (Diptera: Drosophilidae) is native to Southeast Asia and was originally described as a pest of cherries (*Prunus* spp.) in Japan in 1916 (Kanzawa, 1936). It was first detected outside of its native range in Hawaii in 1980, and then in California in 2008 (Walsh et al., 2011). It has since been found in 33 states in the continental United States, Canada, Mexico, and Europe (Hauser, 2011; Cini et al., 2012; Lee et al., 2012; National Agriculture Pest Information System [NAPIS], 2013). Female *D. suzukii* have a highly sclerotized and serrated ovipositor, which allows oviposition in ripening pre-harvest fruits as well as ripe, overripe, and fallen or damaged fruit (Lee et al., 2011; Walsh et al., 2011). *D. suzukii* infest a wide range of host fruit and have been recorded from many stone and small fruits (Lee et al., 2011; Walsh et al., 2011; Wilson et al., 2013; Yu et al., 2013). Larval feeding activity in the fruit makes the fruit flesh soft and brown at the site of oviposition, which often allows secondary damage from other insect pests, fungi, or bacteria resulting in unmarketable fruits and potentially high economic damage (Goodhue et al., 2011; Walsh et al., 2011). In California, USA, raspberries alone, an estimated 300 million dollars could be lost annually if 20% damage is observed (Bolda et al., 2010; Walsh et al., 2011), and

revenues could be decreased by 37% if *D. suzukii* is not managed (Goodhue et al., 2011). Considering the potential for economic damage in this single crop and in this limited range, it is likely that *D. suzukii* will be a source of economic damage in many crops around the world.

Mixed-crop production systems and urban landscapes could be especially susceptible to *D. suzukii* because of *D. suzukii*'s potential to use a wide range of hosts as resources (Cini et al., 2012; Yu et al., 2013). In mixed fruit production settings, resources are available for a longer duration due to the staggered fruiting periods of the various crops that are grown in close proximity to one another. Although *D. suzukii* does not infest intact, ripe, thicker-skinned fruit (Bellamy et al., 2013; Atallah et al., 2014), and therefore is not considered a commercial pest in these crops, *D. suzukii* may use overripe or damaged fruits. These alternate resources could create a reservoir of flies that will then infest hosts where *D. suzukii* is economically damaging. Additionally, recent work has found *D. suzukii* populations in wild hosts (Poyet et al., 2014), which could be the result of source populations in crop hosts or serve as an additional reservoir for crop hosts. This creates a challenge for *D. suzukii* monitoring and management strategies. Finally, because *D. suzukii* populations can build rapidly [at temperatures between 79 °F and 82 °F (26 °C–28 °C), SWD can complete a generation (from egg to adult) in about 10 days] and generations begin to overlap early in the season, degree-day models are difficult to apply for its management (Tochen et al., 2014).

* Corresponding author. Tel.: +1 530 752 0275.

E-mail address: kahamby@ucdavis.edu (K.A. Hamby).

Adult trap captures have been reported in a number of recent studies that focus on a single crop host (e.g. Dalton et al., 2011; Lee et al., 2012, 2013; Burrack et al., 2013; Wilson et al., 2013), but little information is available for monitoring adult *D. suzukii* in a mosaic of small fruit orchards. This study used traps baited with apple cider vinegar to record seasonal variations in *D. suzukii* adult densities in different crops within a mixed fruit production system during a two-year period. Our aim was to measure *D. suzukii* adult abundance and associate it with fruit presence, temperature, and precipitation as well as to generate information about adult capture patterns across smaller mixed-crop commercial orchards and associated urban landscapes for growers making management decisions based on adult monitoring (most commonly used commercial monitoring tactic) in these settings.

Materials and methods

The study took place at the Wolfskill USDA National Clonal Germplasm Repository near Winters, California, USA. Wolfskill has many small orchard blocks that are comprised of different species, cultivars, and selections of a given type of fruit. Contech® traps [(Contech Enterprises Inc., Victoria, British Columbia, Canada) 210 mL volume clear plastic containers with red screw-top lids, a 4.5 cm red label around the center, and 0.64 cm diameter side entry holes (further described in Lee et al., 2012)] were placed in a single block of cherries (*Prunus* spp.), figs (*Ficus* spp.), mulberries (*Morus* spp.), and plums (*Prunus* spp.) on May 25, 2011 and in a single block of almonds (*Prunus amygdalus*), apricots (*Prunus armeniaca*), grapes (*Vitis* spp.), peaches (*Prunus persica*), persimmons (*Diospyros* spp.), and pomegranates (*Punica granatum*) on June 29, 2011. Additional traps were placed in a citrus (*Citrus* spp.) block and in three evergreen ornamental trees [Portugal Laurel (*Prunus lusitanica*), Common Myrtle (*Myrtus communis*), and a Firethorn (*Pyracantha* sp.) Det. by Thomas J. Zavortink] located near (1 m from the walls) a house on the property on January 4, 2012.

Three traps were placed in each block except for the cherry block, which had four traps. Traps were hung between 1.5 m and 2 m from the ground within the tree canopy in the shade. Traps in the grape block were placed 1 m from the ground inside the canopy in the shade. All traps were spaced more than 9 m from each other and from neighboring blocks (Fig. 1). Traps were baited with approximately 50 mL of 5% acidity apple cider vinegar (Safeway Inc., Pleasanton, CA) and Pure + Clean Palmolive unscented soap (Colgate-Palmolive Co., New York, NY) in solution (4 ml of soap added per 3.78 L of apple cider vinegar). Trap captures were collected and traps were refilled weekly from the date they were first deployed until 26 June 2013. Adult *D. suzukii* were identified and counted using a dissecting microscope (Leica MZ75, Leica Microsystems, Wetzlar, Germany).

The precise stage of fruit that is utilized by *D. suzukii* remains ambiguous for many fruit and most varieties of fruit (Lee et al., 2012); therefore, we used fruit presence in lieu of fruit ripeness. Presence of fruit was recorded weekly for each block and supplemented with data from the Germplasm Resources Information Network online database (USDA, ARS, National Genetic Resources Program, 2013). Fruit was considered present in the blocks when 25% of the trees in the block exhibited hard and green ovaries as large or nearly as large as the ripe fruit. We considered fruiting to be finished when there were no ripe or over-ripe fruit left in the trees. Observations were compiled and the earliest and latest periods of fruit presence from any year were applied to each year to obtain an estimate of potential duration of fruit presence for all years because a complete fruiting season was only observed for 2012. The repository does not use insecticides and employs only limited harvest and sanitation practices so that fallen fruit remains on the orchard floor long after the commercial production season would normally end. Considering the unique circumstances of the repository, resources are present before and after a more traditionally defined period of ripe fruit availability such as the fruiting periods described by Vargas et al. (1990) in a seasonal trapping study of Tephritid fruit flies.

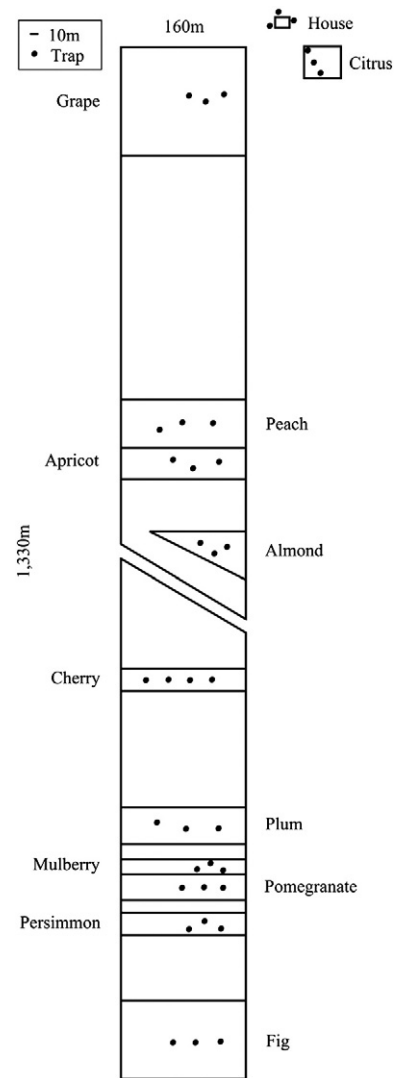


Fig. 1. Wolfskill USDA National Clonal Germplasm Repository in Winters, CA fruit block map and *D. suzukii* trap locations.

Temperature and precipitation data were collected by the California Irrigation Management Information System (CIMIS) station no. 139 in Winters, CA, and downloaded from the University of California Integrated Pest Management Program website (University of California Division of Agriculture and Natural Resources Statewide Integrated Pest Management Program, 2013). This region of California exhibits temperate seasons (winter: December–February; spring, March–May; summer, June–August; fall, September–November) with a Mediterranean climate characterized by hot dry summers and relatively mild winters.

Total *D. suzukii* captured each month was analyzed separately for deciduous and evergreen tree blocks (as trap deployment was not congruent in the two types of blocks) using the Fit model platform of JMP statistical software (JMP version 9.0.0, SAS Institute Inc., Cary, NC). Block (type of fruit in the orchard block), precipitation (mm in a 20 cm diameter gauge), max temperature (mean high temperature for the month in °C), min temperature (mean low temperature for the month in °C), fruit presence (fruit present or absent) and the 2-way interactions of these effects were included in the model, and month was included as a blocking factor for deciduous fruit blocks where fruit presence data was available (grapes were excluded). Interactions and effects that were not significant were dropped from the model. The data was $\log(X + 2)$ transformed to meet the assumption of normality of residual errors as verified with a Shapiro–Wilk test, and was

re-run as a weighted least squares analysis in which the weighting factor was the reciprocal of month residual variance to account for a failed Levene's test of homoscedasticity for the month factor. Mean *D. suzukii* captures across fruit blocks were then compared using Tukey's HSD. For evergreen trees (citrus and house), block (type of fruit in the orchard block), precipitation (mm in a 20 cm diameter gauge), max temperature (mean high temperature for the month in °C), min temperature (mean low temperature for the month in °C), and the 2-way interactions of these were included as effects and month was included as a blocking factor as ripe fruit were present in both blocks throughout the study. Interactions and effects that were not significant were dropped from the model. The data were once again log($X + 2$) transformed to meet the assumption of normality of residual errors as verified with a Shapiro–Wilk test, and was re-run as a weighted least squares method in which the weighting factor was the reciprocal of month residual variance to account for a failed Levene's test of homoscedasticity for the month factor. Mean *D. suzukii* captures were compared across fruit blocks using Tukey's HSD method.

Results

Deciduous blocks

Adult *D. suzukii* males and females were captured in all deciduous blocks where traps were deployed in all years (Figs. 2–3; Table 1). The type of fruit ($F_{8,228} = 12.99, P < 0.0001$), maximum temperature ($F_{1,228} = 17.28, P < 0.0001$), and interaction of type of fruit with fruit presence ($F_{8,228} = 2.13, P = 0.0343$) all significantly impacted the

number of *D. suzukii* adults captured each month in the deciduous fruit blocks, although fruit presence ($F_{1,228} = 0.27, P = 0.6041$) was not significantly independent of fruit type. Among the deciduous fruit blocks, more *D. suzukii* were captured in the cherry and fig blocks, with the fewest captured in almond, apricot, pomegranate, and grape (although excluded from the statistical comparison for lack of data on fruit presence; Figs. 2–3; Table 1).

Because of the significant interaction between fruit type and presence of fruit, it is difficult to tease apart the impact of fruit presence on monthly *D. suzukii* captures. Fruit in the cherry block was present from mid-April to September. High *D. suzukii* weekly trap captures primarily corresponded with the presence of cherry fruit; however, the greatest *D. suzukii* captures were recorded on November 11, 2011 when no cherry fruit were present (Fig. 2). Fruit was present in the fig block from the beginning of April until mid-November. The spring through fall weekly *D. suzukii* trap captures in the fig block corresponded with ripe fig presence; however, high winter trap captures occurred after fig fruit were no longer available (Fig. 2). Fruit was present in the plum block from April to December, and weekly trap captures occurred when plum fruit were present. Greater trap captures were observed earlier in the plum fruiting period (Fig. 2). The mulberry block had fruit present from the beginning of May until mid-November, and most weekly *D. suzukii* trap captures also occurred during this period (Fig. 2). Fruit was present in the peach block from April to late October. The peach block exhibited low weekly trap captures late summer in 2011 followed by increasing fall captures beginning in mid-October and peaking on November 2 when no fruit were present (Fig. 3). Fruit in the apricot block was present from April to

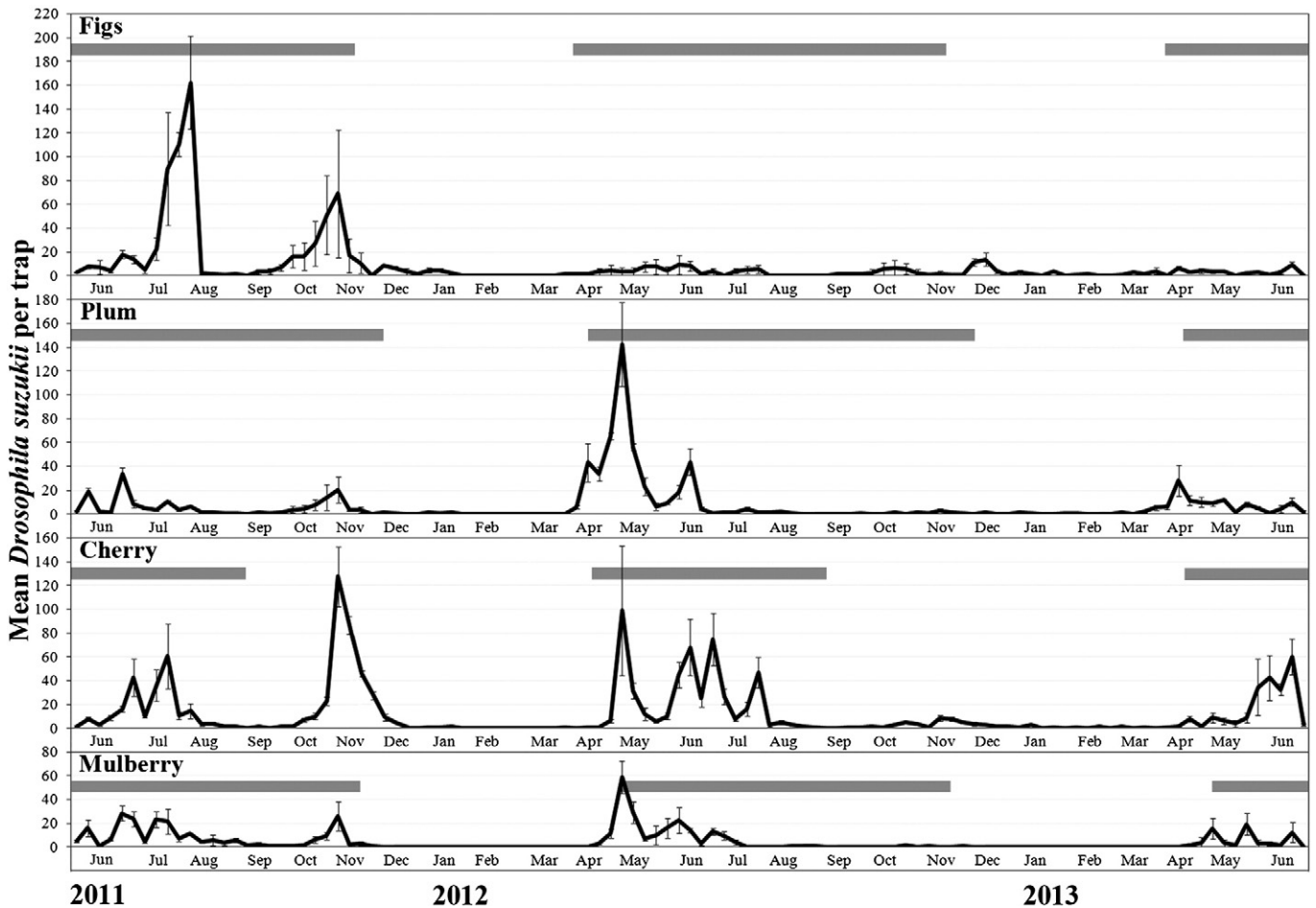


Fig. 2. Weekly mean total *D. suzukii* trap captures and periods when ripe fruit are present (gray bars) on the plant in deciduous fruit blocks where trapping began May 25, 2011.

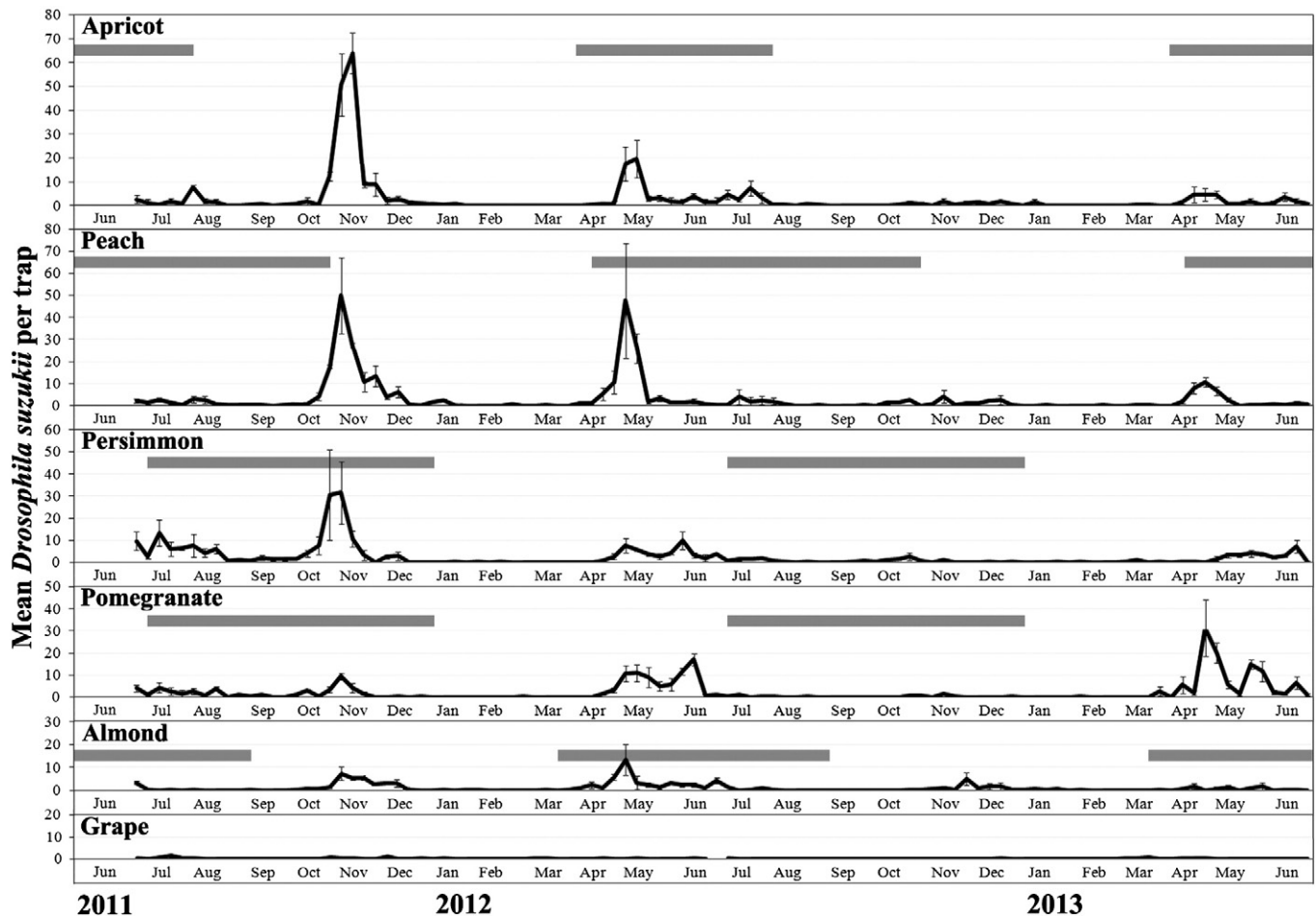


Fig. 3. Weekly mean total *D. suzukii* trap captures and periods when ripe fruit are present (gray bars) on the plant in deciduous fruit blocks where trapping began June 29, 2011.

August, but the greatest weekly trap capture occurred on November 9, 2011, during a period when no apricot fruit were present. This observation is similar to what was observed in the cherry block that same year (Figs. 2 and 3). However, weekly trap captures corresponded with the presence of apricot fruit in both 2012 and 2013. Fruit was present in the persimmon block from the beginning of July to January, the latest start of fruit ripening among the deciduous fruit types in this study except for pomegranates, which also began ripening in July. Weekly trap captures in the persimmon block began prior to the presence of

persimmon fruit, from late May to mid-August (Fig. 3). As in the persimmon block, fruit was present in the pomegranate block from July to January, and *D. suzukii* trap captures began before pomegranate fruiting in both 2012 and 2013, with most of the total captures occurring during that period (Fig. 3). Although almond fruit is not considered a potential host due to lack of soft flesh and was intended in this study as a non-host control, modest spring and early summer trap captures occurred when immature almond fruit were present, although fall captures occurred when no fruit were present (Fig. 3). *D. suzukii* trap captures were numerically lowest in the grape block (not included in statistical analysis as the period of fruiting for the grape block was not recorded). Weekly trap captures were consistently low such that no high capture periods could be discerned (Fig. 3).

For climatic data, only maximum temperature was found to have a significant impact on monthly *D. suzukii* trap captures in the deciduous fruit blocks. Daily average maximum temperatures were highest from July through September and lowest from December through early February (Table 2). The latter period also tended to have the lowest weekly trap captures in all of the deciduous fruit blocks (Figs. 2–3). Unseasonable rainfall events occurred during the last week of May through mid-June 2011, with additional precipitation events occurring from October through early December (Table 2). June and November were the wettest months in 2011 (Table 2). Precipitation continued from January until mid-April 2012, with March being the wettest spring month. Typically dry conditions for the area occurred from mid-April into October 2012, with precipitation resuming from mid-October to the end of December, and precipitation was much greater and more frequent than the same period in 2011 (Table 2). Precipitation was lower

Table 1

Mean \pm SE adult *D. suzukii* captured for all months (*N*) of trap deployment in each deciduous fruit orchard block and evergreen tree block.

Deciduous trees				Evergreen trees			
Block	<i>N</i>	Mean \pm SE	Tukey's HSD ¹	Block	<i>N</i>	Mean \pm SE	Tukey's HSD ¹
Cherry	26	202.8 \pm 56.2	A	House	18	160.8 \pm 88.9	A
Fig	26	105.2 \pm 32.7	A	Citrus	18	101.6 \pm 42.1	B
Plum	26	90.3 \pm 31.5	AB				
Mulberry	26	57.7 \pm 17.4	BC				
Peach	25	37.2 \pm 13.4	BC				
Apricot	25	34.4 \pm 15.1	C				
Persimmon	25	31.0 \pm 8.0	BC				
Pomegranate	25	28.3 \pm 9.0	C				
Almond	25	12.4 \pm 3.5	C				
Grape	25	1.28 \pm 0.3	–				

¹ Different letters denote a significant difference ($P < 0.05$) in Block means separated by Tukey's HSD.

Table 2

Mean \pm SE maximum and minimum temperature ($^{\circ}$ C) and mean \pm SE precipitation (mm in a 20 cm diameter gauge) for each month as recorded by CIMIS station no. 139 in Winters, CA.

Year	Month	Precipitation (mm)	Max temp ($^{\circ}$ C)	Min temp ($^{\circ}$ C)	
2011	May	0.45 \pm 0.25	22.18 \pm 0.87	8.97 \pm 0.55	
	June	1.50 \pm 0.81	28.06 \pm 1.18	12.69 \pm 0.60	
	July	0.00 \pm 0.00	32.27 \pm 0.58	14.43 \pm 0.41	
	August	0.00 \pm 0.00	33.02 \pm 0.28	12.40 \pm 0.24	
	September	0.00 \pm 0.00	32.89 \pm 0.66	13.26 \pm 0.31	
	October	0.53 \pm 0.31	25.47 \pm 0.65	9.29 \pm 0.58	
	November	1.14 \pm 0.50	16.15 \pm 0.61	3.79 \pm 0.57	
	December	0.34 \pm 0.34	15.36 \pm 0.42	0.09 \pm 0.79	
	2012	January	2.98 \pm 1.71	16.14 \pm 0.61	0.80 \pm 0.58
		February	1.09 \pm 0.74	17.07 \pm 0.67	3.93 \pm 0.59
		March	3.77 \pm 1.45	16.57 \pm 0.63	5.44 \pm 0.60
		April	1.55 \pm 0.82	22.14 \pm 0.97	8.46 \pm 0.73
May		0.00 \pm 0.00	27.63 \pm 0.75	10.37 \pm 0.38	
June		0.01 \pm 0.01	29.93 \pm 0.89	13.33 \pm 0.48	
July		0.00 \pm 0.00	32.77 \pm 0.63	13.02 \pm 0.34	
August		0.00 \pm 0.00	34.95 \pm 0.53	13.25 \pm 0.44	
September		0.00 \pm 0.00	32.83 \pm 0.30	10.70 \pm 0.25	
October		0.28 \pm 0.19	25.52 \pm 0.94	9.85 \pm 0.42	
November		3.76 \pm 1.61	18.99 \pm 0.65	6.08 \pm 0.65	
December		5.21 \pm 1.81	12.89 \pm 0.65	3.29 \pm 0.73	
2013	January	0.56 \pm 0.36	13.91 \pm 0.56	0.06 \pm 0.72	
	February	0.12 \pm 0.12	17.88 \pm 0.53	1.97 \pm 0.46	
	March	0.63 \pm 0.32	21.15 \pm 0.56	6.01 \pm 0.53	
	April	0.44 \pm 0.40	25.42 \pm 0.81	10.39 \pm 0.57	
	May	0.57 \pm 0.56	27.78 \pm 0.74	12.48 \pm 0.51	
	June	0.07 \pm 0.05	29.98 \pm 0.95	14.32 \pm 0.38	

from January through April 2013 than during the same period in the previous year, with brief periods of rainfall occurring in early April and again in early May.

Evergreen *D. suzukii* trap captures

In the evergreen blocks (citrus and fruiting ornamentals), only the type of fruit ($F_{1,35} = 14.92$, $P = 0.0008$) was significantly related to the number of *D. suzukii* captured each month. Fruit was present throughout the year in both of the evergreen blocks, and therefore we were not able to perform a statistical correlation between trap captures and fruit presence. In the house block, *P. lusitanica* began fruiting in April. Although the end of the *P. lusitanica* fruiting period was not recorded, fruit was present in August 2013 and not present in December 2012. The beginning of *M. communis* fruiting was also not recorded, but many cultivars are reported to begin fruiting in November (Mulas et al., 2008) and fruit was observed until mid-April 2013. The beginning of the fruiting period for the *Pyracantha* sp. was not recorded but it is typical for fruit to ripen in members of this genus in late summer (Pers. comm. Thomas J. Zavortink), and fruit was observed remaining on the *Pyracantha* sp. until April 2013. Weekly trap captures tended to occur while fruit were present on *M. communis* and *Pyracantha* sp. (Fig. 4). The seasonal pattern of weekly trap captures in the house and citrus blocks differed from that of the deciduous fruit in that high weekly captures occurred in December and January (Fig. 4). Different species of ripe citrus were present throughout the study.

Discussion

Captures of insects in attractive traps depend on many environmental and behavioral factors and are not necessarily reflective of population density (Byers, 2012); nor do captures imply utilization of proximal resources (Turchin and Odendaal, 1996; Campbell et al., 2002). Little is known of the dispersal range of *D. suzukii*, and captures in proximal blocks are not necessarily discrete populations, but rather might be individuals in a much larger metapopulation encompassing a number of

hosts in the landscape. The host quality and stage of ripeness potentially utilized by *D. suzukii* is not known for many of the fruits included in this study. Additionally, the distance that *D. suzukii* adults may travel to these hosts, the impact of neighboring fruit blocks, and the radius of attraction for the traps that were used is unknown. Given that the Wolfskill repository is comprised of many potential hosts in relatively small orchard blocks and the individual blocks contain fruit of a wide maturity range, there are likely a number of sources of attractive volatiles that would compete with the apple cider vinegar we used as a trap lure (Cha et al., 2012; Landolt et al., 2012). Indeed, the volatile compounds from neighboring blocks may compete with and mask the effect of the individual fruit species and trap efficiency may also influence trap capture. The Contech® traps were used for monitoring because they were the first *D. suzukii* traps commercially available to growers; however, these traps were later shown to capture fewer *D. suzukii* than experimental trap designs in a multiple trap comparison study initiated during the second year of our research (Lee et al., 2012). Although capturing fewer adult flies, grower monitoring programs may continue using commercial traps baited with apple cider vinegar for presence/absence sampling of *D. suzukii* due to availability and ease of purchase and use of this type of trap and lure.

D. suzukii trap captures in the deciduous fruit blocks appeared inconsistently related to fruit presence and more closely related with time of year; however, time of year could not be included as a statistical factor in this study due to the uneven sampling periods across years. Though high trap captures for many of the deciduous blocks fell within periods of fruit presence, this relationship often varied among the blocks. For example, in the cherry and apricot blocks, high weekly *D. suzukii* trap captures were observed both during periods of fruit presence and also during periods of fruit absence in fall, while trap captures in the persimmon and pomegranate blocks began long before fruit were present. Almond fruit are not considered hosts for *D. suzukii*, yet modest trap captures occurred in this block both in the spring when fruits were present and again during fall when no fruit was present. This is consistent with other *Prunus* spp., which have extrafloral nectaries that may provide a resource for adult *D. suzukii* at times of the year when suitable host fruit are not present for them to oviposit (Chin et al., 2013). Blossoms may also provide a resource for adult and larval *D. suzukii* via nectar, microbial resources, or feeding directly on the fleshy parts of the flower. Indeed, adult *D. suzukii* have been collected and reared from Japanese Snowbell *Styrax japonicus* blossoms collected from riparian areas in Japan (Mitsui et al., 2010). Although the number of *D. suzukii* captured as well as the duration of trap capture periods varied among the deciduous fruit blocks, the overall pattern was remarkably similar across these blocks with two annual flight periods observed: one lasting from April through August and the other occurring late fall and early winter. The fall peak was distinctly more pronounced in 2011 than in 2012. Trap captures were suppressed from August through September in all blocks monitored, which may be due to high temperatures. David et al. (2005) found male sterility in *Drosophila* spp. at extreme temperatures, with thermal heat sterility thresholds varying by species from 23 $^{\circ}$ C to 31 $^{\circ}$ C, and Kinjo et al. (2014) found *D. suzukii* that mated at 31 $^{\circ}$ C produced infertile eggs. Indeed, *D. suzukii* adult captures in blueberries in Japan became negligible when the average temperature exceeded 28 $^{\circ}$ C or daily temperature exceeded 33 $^{\circ}$ C for 8 hours or more (Kinjo et al., 2014). August and September were the warmest months of both 2011 and 2012, with mean maximum monthly temperatures of 32 $^{\circ}$ C–33 $^{\circ}$ C (Table 2), which is above the male sterility range for other *Drosophila* spp. Furthermore, *D. suzukii* is thought to show reduced activity at temperatures above 30 $^{\circ}$ C (Walsh et al., 2011). One peculiar observation is the high *D. suzukii* trap captures observed in all of the deciduous fruit blocks from November 2 to 9, 2011, which represented the greatest weekly trap capture for all years in the cherry, apricot, peach, and persimmon blocks. There were corresponding trap captures in all blocks as well during November 2012 but the number of adult *D. suzukii* captured were decidedly low by comparison.

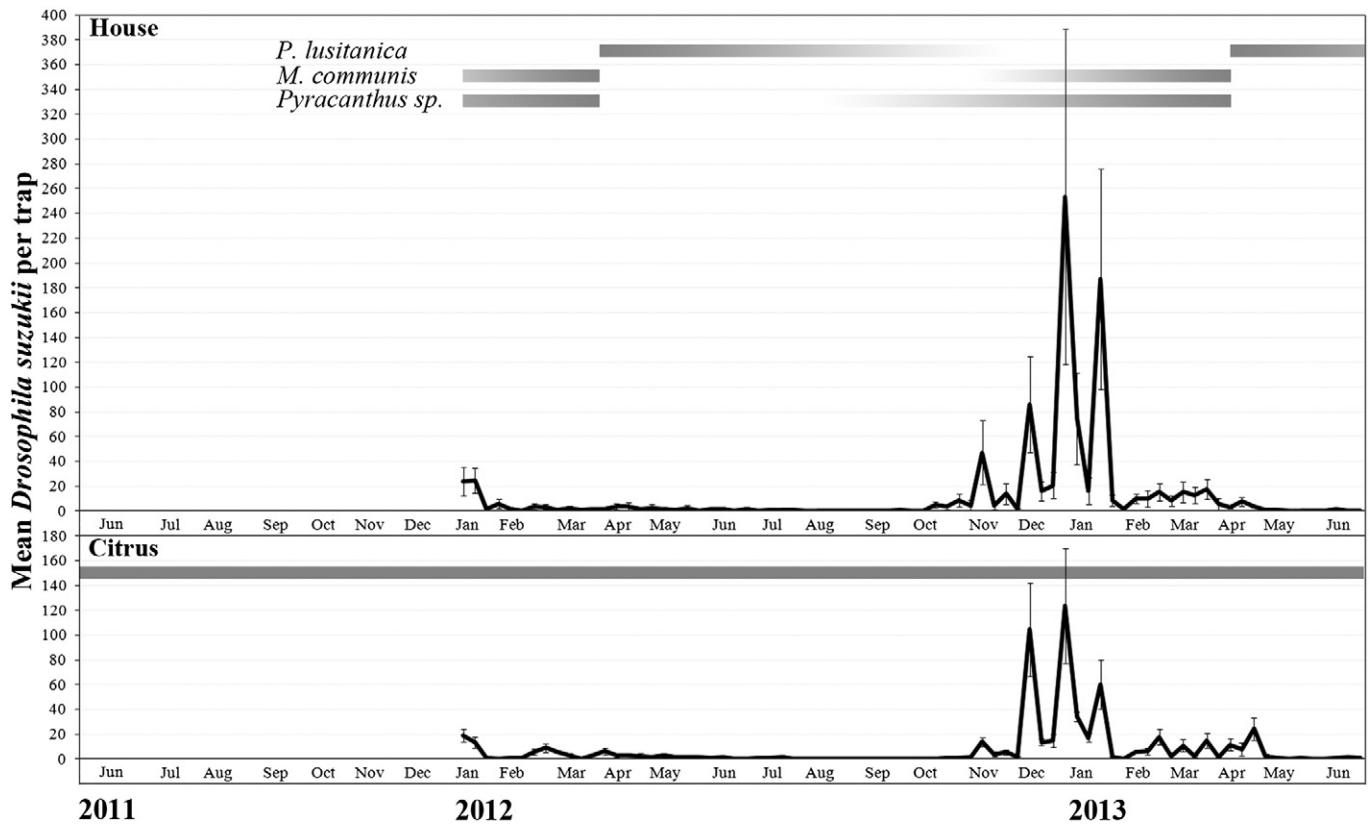


Fig. 4. Weekly mean total *D. suzukii* trap captures and periods when ripe fruit are present (gray bars) on the plant in evergreen fruit blocks. Periods when ripe fruit were present were not systematically observed for the ornamental landscape plants *Prunus lusitanica*, *Myrtus communis*, and *Pyracantha* sp., and their presence was assumed from other studies (note lighter gray for areas of uncertainty).

Additional trap captures were observed in December 2012 through early February 2013 in most blocks, with higher captures recorded in the evergreen fruit blocks. Climatic conditions often influence insect trap captures, and may explain seasonal patterns of *D. suzukii* trap captures observed here. Captures began to increase at the beginning of October in both 2011 and 2012 when the daily minimum temperatures dropped below 10 °C for the first time during the fall. The November captures in both years was followed with a subsequent rapid decline that occurred following the first 0 °C daily minimum temperature. The lower November captures observed in 2012 may be due to greater precipitation occurring in that month relative to 2011, although trap captures continued beyond November in 2012 and monthly precipitation was not a significant effect in our comparison of monthly trap captures (Table 2). Our observations support a *D. suzukii* trapping study conducted at multiple US locations in 2010 that showed an interaction between captures and ambient temperature (Dalton et al., 2011) with fall peak captures observed on November 17 in both California's San Joaquin Valley and in Wasco Co., OR; on November 24 in Benton Co., WA; and on October 26 in Allegan Co., MI. One might expect local climatic factors to explain anomalous trap captures such as reported for these fall peaks in 2010 and our observations in 2011 and 2012; however, they are uncannily similar across a broad latitudinal, altitudinal, and climatic area; suggesting that an additional factor may be at work.

It is possible that high fall *D. suzukii* trap captures, when larval food resources are presumed to no longer be available in the orchard or vineyard sites where the traps are placed, might suggest a behavior related to overwintering success. Many insects select special microhabitats to enhance winter survival and must reach this overwintering site before the onset of severe weather (Danks, 1978). Therefore, it may be that the general decrease in fall temperatures along with a decrease in host and non-host food resources for their larvae stimulate *D. suzukii* to begin searching for additional resources or for sheltered overwintering

sites before the onset of colder winter months. Adult movement associated with this activity would increase encounters with traps that are baited with a food-lure resulting in increased captures in all blocks that contain these traps similar to what we observed in November 2011 and 2012, and in the Dalton et al. (2011) study.

In our study, captures in the fall occurred in the deciduous fruit blocks and decreased just as *D. suzukii* captures began to increase in the evergreen blocks. Similarly, as winter ends and spring begins, captures decreased in the evergreen blocks and resumed in the deciduous fruit blocks. Indeed, the house and citrus blocks are unique in that they shared large *D. suzukii* captures in the winter while captures were absent or very low in all of the other blocks. This may be because man-made structures and evergreen trees provide some shelter from unfavorable winter conditions (Johnson et al., 1975; Kimura, 2004). Dominiak et al. (2006) showed that urban areas provided warmer and moister environments than surrounding rural areas, the effect of which increased survival of the Queensland fruit fly (*Bactrocera tryoni*) during periods when natural climatic conditions would have otherwise suppressed their densities. Also, the citrus and ornamental plants in these blocks are evergreen, which would provide additional shelter and favorable microclimates (Johnson et al., 1975), while the deciduous fruit blocks are relatively barren at that time. Furthermore, fruit is present in both the house and citrus blocks throughout the winter, which may add to their attractiveness to *D. suzukii*. Decante and van Helden (2008) found that adult green leafhoppers (*Empoasca vitis*), a vineyard pest, are found in evergreen trees and on alternative hosts during the winter when the vineyards lack foliage. The ornamental plant species present in the house block have not been mentioned as host plants in the literature, but their fruit may prove to be hosts or may have plant-associated yeasts or nectar resources that serve as an attractant or food source for *D. suzukii* (Cha et al., 2012; Hamby et al., 2012). Although the skin of citrus fruit is likely too thick for *D. suzukii*

oviposition (Bellamy et al., 2013; Burrack et al., 2013; Atallah et al., 2014), fallen, split fruit are present that could serve as a winter food source. *D. suzukii* have been observed using split citrus as a resource in Kern Co., CA orchards (Pers. comm. David Haviland). Interestingly, the total *D. suzukii* captured in our study during the winter period (predominantly comprised of the house and citrus trap captures) were comparable to the total *D. suzukii* that were captured throughout the previous year in all the deciduous fruit blocks.

The period and intensity of the *D. suzukii* capture oscillations during the winter in the house and citrus blocks were also interesting. In Japan, only the adult stage was noted to overwinter (Kanzawa, 1939; Lee et al., 2011). However, oscillations in the house and citrus blocks are approximately congruent with generation time and winter reproduction may be responsible for the weekly patterns of *D. suzukii* adult trap captures in lieu of or in addition to the impact of local climatic factors. Dalton et al. (2011) showed that all life stages could survive short periods of freezing temperatures. It is possible that the more favorable California climate and availability of fallen citrus fruits and fruiting ornamentals could enable *D. suzukii* to remain active and reproducing in the winter.

Conclusion

The Wolfskill germplasm repository site is representative of a landscape consisting of small mixed-crop orchards and urban plantings that contain multiple known and potential host plants within relatively close proximity, and are likely to contain food and perhaps shelter for *D. suzukii* throughout the year. Our results show that *D. suzukii* adults are active at some level throughout most of the year in California, and may be present over the winter in evergreen ornamental plants around structures and evergreen crop plants such as citrus. This presents a significant concern considering the abundant overwintering sites with proximal hosts, non-hosts, or anthropogenic resources often present in urban landscapes. These sites may serve as overwinter reservoirs that sustain individuals able to migrate into surrounding crops in the spring, and sources of the devastatingly large fruit infestations noted by home gardeners. Monthly *D. suzukii* trap captures varied by fruit block for all blocks sampled in this study, which provides insight for trap deployment in a mixed fruit setting. Rather than trapping in an economically susceptible host crop, early spring (February–April) monitoring may be improved by deployment in nearby evergreen fruiting ornamentals or citrus.

Acknowledgments

The authors would like to thank Doris Yu, Helen T. Nguyen, and Mitchell J. Bamford for their assistance in fieldwork and data collection, and Thomas J. Zavortink for his plant identifications. We would especially like to thank John Preece, Howard Garrison, and Salvador Rivas of the USDA National Clonal Germplasm Repository at Wolfskill. This work was supported by USDA-NIFA SCRI Competitive Research grant number 51181-21167 awarded to Frank G. Zalom.

References

- Atallah, J., Teixeira, L., Salazar, R., Zaragoza, G., Kopp, A., 2014. The making of a pest: the evolution of a fruit-penetrating ovipositor in *Drosophila suzukii* and related species. *Proc. R. Soc. B* 281, 20132840.
- Bellamy, D.E., Sisterson, M.S., Walse, S.S., 2013. Quantifying host potentials: indexing postharvest fresh fruits for spotted wing drosophila, *Drosophila suzukii*. *PLoS ONE* 8, e61227. <http://dx.doi.org/10.1371/journal.pone.0061227>.
- Bolda, M.P., Goodhue, R.E., Zalom, F.G., 2010. Spotted wing drosophila: potential economic impact of a newly established pest. *Agric. Resour. Econ. Update* 13, 5–8.
- Burrack, H.J., Fernandez, G.E., Spivey, T., Kraus, D.A., 2013. Variation in selection and utilization of host crops in the field and laboratory by *Drosophila suzukii* Matsumura (Diptera: Drosophilidae), an invasive frugivore. *Pest Manag. Sci.* <http://dx.doi.org/10.1002/ps.3489>.
- Byers, J.A., 2012. Estimating insect flight densities from attractive trap catches and flight height distributions. *J. Chem. Ecol.* 38, 592–601.
- Campbell, J.F., Mullen, M.A., Dowdy, A.K., 2002. Monitoring stored-product pests in food processing plants with pheromone trapping, contour mapping, and mark-recapture. *J. Econ. Entomol.* 95, 1089–1101.
- Cha, D.H., Adams, T., Rogg, H., Landolt, P.J., 2012. Identification and field evaluation of fermenting volatiles from wine and vinegar that mediate attraction of spotted wing drosophila, *Drosophila suzukii*. *J. Chem. Ecol.* 38, 1419–1431.
- Chin, S., Lutz, S., Wen, J., Potter, D., 2013. The bitter and the sweet: inference of homology and evolution of leaf glands in *Prunus* (Rosaceae) through anatomy, micromorphology, and ancestral-character state reconstruction. *Int. J. Plant Sci.* 174, 27–46.
- 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. Insectol.* 65, 149–160.
- Dalton, D.T., Walton, V.M., Shearer, P.W., Walsh, D.B., Caprile, J., Isaacs, R., 2011. Laboratory survival of *Drosophila suzukii* under simulated winter conditions of the Pacific Northwest and seasonal field trapping in five primary regions of small and stone fruit production in the United States. *Pest Manag. Sci.* 67, 1368–1374.
- Danks, H.V., 1978. Modes of seasonal adaptation in the insects. I. Winter survival. *Can. Entomol.* 110, 1167–1205.
- David, J.R., Araripe, L.O., Chakir, M., Legout, H., Lemos, B., Pétavy, G., Rohmer, C., Joly, D., Moreteau, B., 2005. Male sterility at extreme temperatures: a significant but neglected phenomenon for understanding *Drosophila* climatic adaptations. *J. Evol. Biol.* 18, 838–846.
- Decante, D., van Helden, M., 2008. Spatial and temporal distribution of *Empoasca vitis* within a vineyard. *Agric. For. Entomol.* 10, 111–118.
- Dominiak, B.C., Mavi, H.S., Nicol, H.I., 2006. Effect of town microclimate on the Queensland fruit fly *Bactrocera tryoni*. *Aust. J. Exp. Agric.* 46, 1239–1249.
- Goodhue, R.E., Bolda, M., Farnsworth, D., Williams, J.C., Zalom, F.G., 2011. Spotted-wing drosophila infestation of California strawberries and raspberries: economic analysis of potential revenue losses and control costs. *Pest Manag. Sci.* 67, 1396–1402.
- Hamby, K.A., Hernández, A., Boundy-Mills, K., Zalom, F.G., 2012. Yeast associations of spotted wing drosophila (*Drosophila suzukii*, Diptera: Drosophilidae) in cherries and raspberries. *Appl. Environ. Microbiol.* 78 (14), 4869–4873.
- Hauser, M., 2011. A historic account of the invasion of *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae) in the continental United States, with remarks on their identification. *Pest Manag. Sci.* 67, 1352–1357.
- Johnson, F.L., Bell, D.T., Sipp, S.K., 1975. A comparison of urban and forest microclimates in the midwestern United States. *Agric. Meteorol.* 14, 335–345.
- Kanzawa, T., 1936. Studies on *Drosophila suzukii* Mats. *J. Plant Protect. (Tokyo)* 23, 66–70 (127–132, 183–191. Abstract in *Rev. Appl. Entomol.* 24, 315).
- Kanzawa, T., 1939. Studies on *Drosophila suzukii* Mats. Yamanshi Prefecture Agricultural Experimental Station, Kofu, Japan (49 pp. Abstract in *Rev. Appl. Entomol.* 29, 622).
- Kimura, M.T., 2004. Cold and heat tolerance of drosophilid flies with references to their latitudinal distributions. *Oecologia* 140, 442–449.
- Kinjo, H., Kunimi, Y., Nakai, M., 2014. Effects of temperature on the reproduction and development of *Drosophila suzukii* (Diptera: Drosophilidae). *Appl. Entomol. Zool.* 49, 297–304.
- Landolt, P.J., Adams, T., Rogg, H., 2012. Trapping spotted wing drosophila, *Drosophila suzukii* (Matsumura) (Diptera: Drosophilidae), with combinations of vinegar and wine, and acetic acid and ethanol. *J. Appl. Entomol.* 136, 148–154.
- Lee, J.C., Bruck, D.J., Dreves, A.J., Ioriatti, C., Vogt, H., Baufield, P., 2011. In focus: spotted wing drosophila, *Drosophila suzukii*, across perspectives. *Pest Manag. Sci.* 67, 1349–1351.
- Lee, J.C., Burrack, H.J., Barrantes, L.D., Beers, E.H., Dreves, A.J., Hamby, K.A., Haviland, D.R., Isaacs, R., Richardson, T.A., Shearer, P.W., Stanley, C.A., Walsh, D.B., Walton, V.M., Zalom, F.G., Bruck, D.J., 2012. Evaluation of monitoring traps for *Drosophila suzukii* (Diptera: Drosophilidae) in North America. *J. Econ. Entomol.* 105, 1350–1357.
- Lee, J.C., Shearer, P.W., Barrantes, L.D., Beers, E.H., Burrack, H.J., Dalton, D.T., Dreves, A.J., Gut, L.J., Hamby, K.A., Haviland, D.R., Isaacs, R., Nielsen, A.L., Richardson, T., Rodriguez-Saona, C.R., Stanley, C.A., Walsh, D.B., Walton, V.M., Yee, W.L., Zalom, F.G., Bruck, D.J., 2013. Trap designs for monitoring *Drosophila suzukii* (Diptera: Drosophilidae). *Environ. Entomol.* 42, 1348–1355.
- Mitsui, H., Beppu, K., Kimura, M.T., 2010. Seasonal life cycles and resource uses of flower- and fruit-feeding drosophilid flies (Diptera: Drosophilidae) in central Japan. *Entomol. Sci.* 13, 60–67.
- Mulas, M., Francesconi, A.H.D., Perinu, B., 2008. Myrtle (*Myrtus communis* L.) as a new aromatic crop: cultivar selection. *J. Herbs Spices Med. Plants* 9, 127–131.
- National Agricultural Pest Information System (NAPIS), 2013. Survey Status of Spotted Wing Drosophila—*Drosophila suzukii* (2010 to present)[website] Purdue University, (URL <http://pest.ceris.purdue.edu/map.php?code=IOAPUA&year=3year>).
- Poyet, M., Eslin, P., Héraude, M., Le Roux, V., Prévost, G., Gilbert, P., Chabrier, O., 2014. Invasive host for invasive pest: when the Asiatic cherry fly (*Drosophila suzukii*) meets the American black cherry (*Prunus serotina*) in Europe. *Agric. For. Entomol.* 16, 251–259.
- Tochen, S., Dalton, D.T., Wiman, N., Hamm, C., Shearer, P.W., Walton, V.M., 2014. Temperature-related development and population parameters for *Drosophila suzukii* (Diptera: Drosophilidae) on cherry and blueberry. *Environ. Entomol.* 43, 501–510.
- Turchin, P., Odendaal, F.J., 1996. Measuring the effective sampling area of a pheromone trap for monitoring population density of southern pine beetle (Coleoptera: Scolytidae). *Environ. Entomol.* 25, 582–588.
- University of California Division of Agriculture and Natural Resources Statewide Integrated Pest Management Program, 2013. [website] UC IPM Online. <http://www.ucipm.ucdavis.edu/calludt/cgi/WXDESCRIPTION?MAP=solano.html&STN=WINTERS.A>.
- USDA-ARS, 2013. Germplasm Resources Information Network—(GRIN)[Online Database] National Germplasm Resources Laboratory, Beltsville, Maryland (URL http://www.ars-grin.gov/cgi-bin/npgs/html/site_crops.pl?DAV).

- Vargas, R.I., Stark, J.D., Nishida, T., 1990. Population dynamics, habitat preference, and seasonal distribution patterns of oriental fruit fly and melon fly (Diptera: Tephritidae) in an agricultural area. *Environ. Entomol.* 19, 1820–1828.
- Walsh, D.B., Bolda, M.P., Goodhue, R.E., Dreves, A.J., Bruck, D.J., Walton, V.M., O'Neal, S.D., Zalom, F.G., 2011. *Drosophila suzukii* (Diptera: Drosophilidae): invasive pest of ripening soft fruit expanding its geographic range and damage potential. *J. Integr. Pest Manag.* 2, 1–7.
- Wilson, H.E., Hamby, K.A., Zalom, F.G., 2013. Host susceptibility of 'French Prune' *Prunus domestica* to *Drosophila suzukii* (Diptera: Drosophilidae). *Acta Hortic.* 985, 249–254.
- Yu, D., Zalom, F.G., Hamby, K.A., 2013. Host status and fruit odor response of *Drosophila suzukii* (Diptera: Drosophilidae) to figs and mulberries. *J. Econ. Entomol.* 106, 1932–1937.