



Drosophila suzukii (Diptera: Drosophilidae): Invasive Pest of Ripening Soft Fruit Expanding its Geographic Range and Damage Potential

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ABSTRACT. Spotted wing drosophila, *Drosophila suzukii* Matsumura, a native of eastern and southeastern Asia, is a pest of small and stone fruits. First detected in California in 2008, the insect is now found across the Pacific Coast states. Its penchant for attacking healthy, ripening fruit (as opposed to overripe and rotting fruit favored by other so-called “vinegar flies”) makes it a potential economic threat to a host of soft- and thin-skinned fruit crops including cherry, raspberry, blackberry, blueberry, strawberry, peach, plums, pluots, nectarines, juice grape, table grape, and wine grape. Coordinated research projects to determine host preference, seasonal phenology, biology, and management options are taking place among entomologists in Washington, Oregon, and California. A description of the pest and initial findings on its biology, life history, known and expected geographic range, management and monitoring techniques, and economic considerations are presented and discussed.

Key Words: *Drosophila suzukii*, vinegar fly, spotted wing drosophila, small fruit, stone fruit

Of the ≈1,500 species of *Drosophila* (Markow and O'Grady 2006) commonly known as vinegar flies, *Drosophila suzukii* Matsumura (Diptera: Drosophilidae), known as cherry drosophila in Japan and now commonly called spotted wing drosophila in the United States, is one of only two species (the other being *Drosophila pulchrella* Tan, found in tree fruit in Japan) known to oviposit in healthy (whole) fruit as opposed to fruit that is damaged or overripe (Sasaki and Sato 1995, 1996). Two unique characteristics of *D. suzukii* make it a particularly onerous pest: its propensity for favoring ripening (as opposed to overripe) fruit (Mitsui et al. 2006) and the prominent serrated ovipositor of the female, which upon insertion can cause physical damage to the host fruit. Very often oviposition wounds, including those caused by *Drosophila* flies, provide access to secondary infection by both insects and pathogens including fungi, yeasts, and bacteria causing additional losses (De Camargo and Phaff 1957, Molina et al. 1974, Louise et al. 1996). Eggs develop into larvae within the fruit, causing it to become soft and rot rapidly, resulting in reduced crop yields and significant financial losses.

Drosophila suzukii was first observed in mainland Japan in 1916 and later observed in 1930–1931 in other parts of what was then the Japanese empire, including parts of today's Korea and China (Kanzawa 1936, 1939). There it was found on wild strawberry and cultivated cherry. While initial infestations were confused with those by cherry fruit fly, it was soon apparent that *D. suzukii* had the potential to severely impact the Japanese cherry industry. Kanzawa's observations on the general biology and habits of *D. suzukii*, as well as his initial experiments with trapping and control of the fly, formed the basis for subsequent studies and are cited extensively throughout this paper. *Drosophila suzukii* continues to be a pest in Japanese soft and stone fruits (Sasaki and Sato 1995, 1996).

This paper seeks to define the pest and present historic and recent findings on its biology, life history, known and expected geographic range, management and monitoring techniques, and economic considerations.

Range Expansion and Introduction to North America

In the decades since the initial Asian observations, *D. suzukii* has been recorded in China, Myanmar, India, Italy, Thailand, Spain, and Russia (Toda 1987, Oku 2003, Hauser et al. 2009). It has been established in Hawaii since at least 1980 (Kaneshiro 1983). The first detected North American mainland invasion of *D. suzukii* was in Santa Cruz County, CA, in August 2008, on strawberries and caneberries (Bolda et al. 2010). In May 2009, economically damaging infestations were detected in cherry orchards in the Santa Clara Valley, and from Yolo to Stanislaus counties in California (Bolda et al. 2010). Further trapping and identification efforts in the fall of 2009 confirmed *D. suzukii* presence over a wide geographic range, including the entire length of California's coastal counties, western Oregon, the Columbia River Gorge, counties throughout western Washington, and north into British Columbia (Bolda et al. 2010, D.B.W. unpublished data, V.M.W. unpublished data). The first detection in Washington State occurred in strawberries at the Washington State University Puyallup Research and Extension Center on August 10, 2009; by the end of the year, *D. suzukii* had been positively identified in 10 Washington State counties (D.B.W. unpublished data). Oregon's first detection was made by a u-pick grower of blueberries in early August 2009; additional observations were confirmed in 16 Oregon counties on domestic and volunteer caneberries and stone fruits (V.M.W. unpublished data). It was also identified in Florida in August 2009 in rural Hillsborough County, where a single male fly was captured in each of two traps located about three miles apart (E2009-5702 and E2009-5703, collected by K.A. Miller, United States Department of Agriculture [USDA]). Twenty-four Florida counties have subsequently confirmed the fly. In February and March 2010, adult *D. suzukii* were routinely detected in apple cider vinegar traps placed in citrus orchards with fallen citrus fruit near Bakersfield in California's San Joaquin Valley, subsequently attacking the very early cherry fruit in adjacent orchards before harvest in late April through May (D. Haviland, University of California Cooperative Extension, personal communication).

Table 1. Egg size measurement (millimeters)

		Length	Width	Egg stalk
May (cherry)	Avg	0.62	0.18	0.65
	Max	0.64	0.21	0.72
	Min	0.56	0.19	0.51

Translated from Kanzawa (1939).

Table 2. Larvae size measurement (millimeters)

		First instar	Second instar	Third instar
Oct. (grape)	Length	0.67	2.13	3.94
	Width	0.17	0.40	0.88

Translated from Kanzawa (1939).

Description of the Pest

Kanzawa (1939, also identified as “Kamizawa” in some journals and reports) compiled an extensive early database on *D. suzukii*, cataloguing egg, larva, pupa, and adult sizes (Tables 1–4). He described the eggs as half transparent, milky white, and glossy, with transparency increasing and the developing larva becoming visible toward emergence. Larvae emerge milky white with visible internal

organs and black mouthparts; visible respiratory ducts evolve from silvery white, inconspicuous products at the first instar to branched, open, and emerging to the larva’s exterior by the third instar. The pupae were described as grayish yellow with soft pupal cases initially, later hardening and turning brown. A characteristic dark spot on the leading edge of the males’ wings began developing 10 hours after adult emergence but took 2 days to become obvious.

Life Cycle

Kanzawa (1939) observed the life cycle of the fly in captivity (Table 5). He kept oviposition records and found the most active period of the 10 generations studied to be the span between the fifth and sixth generations, during the peaks of the cherry and grape seasons and at the most highly preferred temperature for *D. suzukii*, 20–25°C. In his initial overwintering studies, only the adult life stage successfully survived winter. More recently, it has been observed that adults emerging from pupal cases during the early part of winter survived as adults (V.M.W., unpublished data). Only females survived extended cold periods in this study. Mitsui et al. (2010) found that *D. suzukii* adults collected in autumn were reproductively immature, suggesting winter reproductive diapause. Our findings on the development and life history of *D. suzukii* are summarized as follows.

Adult. Adult *D. suzukii* are small (2–3 mm) flies with red eyes and a pale brown or yellowish-brown thorax and abdomen (Figs. 1 and 2).

Table 3. Pupal size measurement (millimeters)

		Male				Female			
		Length	Width	Length of respiratory organ	Length of respiratory organ’s base	Length	Width	Length of respiratory organ	Length of respiratory organ’s base
Oct. (grape)	Avg	2.9	0.99	0.29	0.14	3.18	1.06	0.32	0.14
	Max	3.10	1.20	0.30	0.15	3.35	1.10	0.35	0.15
	Min	2.75	0.85	0.25	0.10	2.95	0.95	0.28	0.13

Translated from Kanzawa (1939).

Table 4. Imago (adult) size measurement (millimeter)

		Males			Females		
		Body length	Wing span	Wing length	Body length	Wing span	Wing length
June (cherry)	Avg	2.25	5.75	2.25	2.5	6.75	2.75
	Max	2.5	6.5	2.5	3.0	7.5	3.0
	Min	2.0	5.0	2.0	2.0	6.0	2.5
Oct. (grape)	Avg	3.0	5.95	2.3	4.0	7.5	3.1
	Max	3.5	6.7	2.7	4.5	8.3	3.5
	Min	2.5	5.2	2.0	3.5	6.7	2.7

Translated from Kanzawa (1939).

Table 5. Captivity observations

Generation	Date (mo/d)				Length of period (d)				Lifespan	Bait
	Oviposition	Hatch	Pupation	Emergence	Egg	Larva	Pupa	Emergence to oviposition		
1	—	—	6/7	6/13	—	—	6	—	—	Cherry
2	6/16	6/18	6/23	6/29	2	5	6	—	—	Cherry
3	7/1	7/2	7/7	7/11	1	5	4	2	12	Cherry
4	7/13	7/14	7/19	7/23	1	5	4	1	11	Cherry
5	7/24	7/25	—	8/2	1	—	—	1	10	Plum
6	8/6	8/7	8/12	8/18	1	5	6	4	16	Cherry
7	8/20	8/21	8/26	9/1	1	5	6	2	14	Grape
8	9/2	9/4	9/9	9/15	2	5	6	1	14	Grape
9	9/18	9/20	9/24	10/1	2	4	7	3	16	Grape
10	10/4	10/5	10/15	10/25	1	10	10	3	24	Grape
11	11/2	11/4	11/24	—	2	20	—	8	—	Grape

Translated from Kanzawa (1939).

These data were taken from experiments conducted in 1934. Ten pairs from each generation were observed, with earliest emergence reported in the table. Materials and methods were 8.7 cm diam glass enclosures 18.5 cm tall with gauze at the bottom and the mouth of the enclosure and bait hung from the top.



Fig. 1. Adult female *Drosophila suzukii*. (Photo courtesy Martin Hauser)



Fig. 2. Adult male; note dark spots on wing tips. (Photo courtesy Martin Hauser)

They have black stripes on the abdomen and males have a distinguishing dark spot on the leading edge near the tip of each wing. The spot may play a role in courtship but results are ambiguous for flies under diurnal light cycles (Fuyuma 1979). The female's serrated ovipositor (Fig. 3) is able to penetrate the skin of most thin-skinned fruit, leaving a small depression, scar, or "sting" on the fruit's surface (Fig. 4). A female lays $\approx 1\text{--}3$ eggs per oviposition site, averaging 380 eggs in her lifetime. The number of eggs laid may depend on fruit maturity and eggs tend to be randomly distributed on cherry fruit (Mitsui et al. 2006). Multiple clutches of larvae are quite possible on



Fig. 3. Serrated ovipositor of *D. suzukii*. (Photo courtesy Martin Hauser)

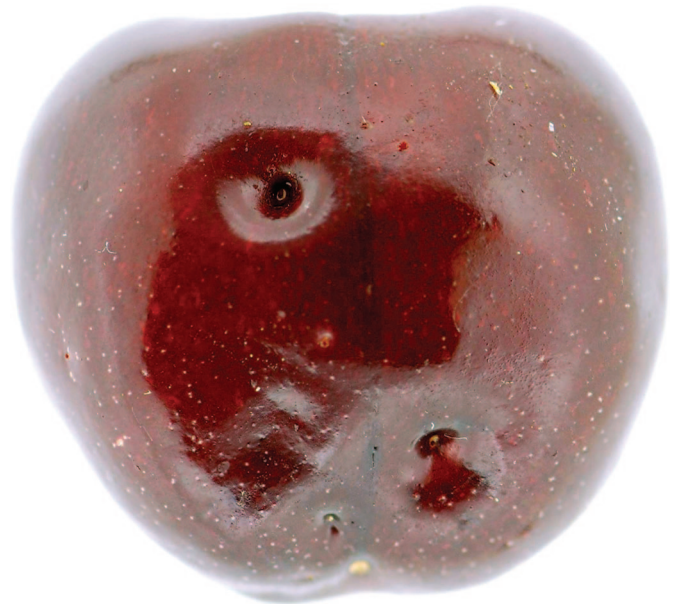


Fig. 4. Oviposition scars on a cherry. (Photo courtesy Martin Hauser)

the same fruit because many females may visit the same piece of fruit. Anecdotal observations have indicated that oviposition is most likely when fruits are entering peak ripeness and marketability. Initial research supports this: where red raspberries were observed and oviposition measured, no green fruit contained eggs, $\approx 5\%$ of green/pink and pink fruit contained eggs, and $\approx 80\%$ of ripe (not over-ripe) fruit contained eggs (Tanigoshi et al. 2010).

Egg. The egg develops and subsequently hatches inside the fruit in which it has been laid. Eggs are translucent, milky-white, and glossy; the milky quality diminishes toward emergence, and larvae become more visible.

Larva. Larval development occurs inside the fruit. Larvae are milky-white and cylindrical with black mouthparts; they are ≈ 0.67 mm in length at emergence and may grow to 3.5 mm. Internal organs of the larvae are visible, particularly after it has consumed some of the fruit in which it resides. The larva develops through three instars, feeding upon the host fruit until it exits to pupate. This feeding creates brown, soft, sunken areas on the fruit, compromising its marketability and creating opportunity for other pests such as other vinegar flies and for infection by fungal and bacterial disease pathogens (Fig. 5).

Pupa. Pupae are initially grayish yellow with soft cases, gradually becoming brownish, then yellowing and hardening. Pupation occurs both inside and outside of the fruit, however pupation within the fruit is more common.

Host Range

Kanzawa observed that the fly oviposited most often on cherries, peaches, plums, persimmons, strawberries, and grapes in Japan, but



Fig. 5. Infested blueberry (right) exhibits soft, sunken areas two weeks after exposure to *D. suzukii* when compared with control blueberry (left). (Photo courtesy Vaughn Walton)

was also opportunistic and would feed on other fruits dropped on the ground that spoiled or fermented. In the absence of preferred fruit, he found *D. suzukii* would feed upon oak tree sap. *Drosophila suzukii* has now been documented in apricots, blackberries, blueberries, cherries, figs, grapes, hardy kiwis, nectarines, peaches, pears, persimmons, plums, pluots, raspberries, and strawberries; it has additionally been observed feeding upon injured or culled fruit including apples and oranges. Primary concerns in the Pacific Coastal states of Washington, Oregon, and California are the small fruits blueberry, blackberry, raspberry, marionberry, boysenberry, and strawberry, and the stone fruits cherry and peach; wine and juice grapes are also of concern.

The wide variety of documented hosts, plus the presence throughout the Pacific Coastal states of ornamental and native fruiting plants (e.g., wild rose, dogwood, snowberry, crab apple, flowering cherry) that may serve as alternate hosts and that ripen at different times throughout the year, exacerbates cause for concern about the spread and potential pest status of *D. suzukii*. In addition, adult *D. suzukii* have been observed in the upper reaches of trees and ovipositing in some species of flowers in the absence of preferred hosts. Mitsui et al. (2010) found that *D. suzukii* bred on *Stylax* flowers at the end of May and the start of June, when the fruiting season of wild *Prunus* starts. Nishiharu (1980) observed this fly bred (rarely) on *Camellia japonica* L. flowers in early spring in southern Japan. Toda (1987) reported finding *D. suzukii* most often at a height between 9 and 11 m in the forest trees, but does not suggest why the flies might dwell so high in the canopy. In the Seattle, WA, region, high numbers of *D. suzukii* were reported in the upper one-fourths of a fruit tree where aphids and honeydew were prevalent. We speculate that the adults are staying alive there until preferred fruit hosts are available. The pest's mobility and its utilization of a range of agricultural, home landscape, and native plants make educational outreach and eventual control challenging.

Potential Geographic Range in North America

Drosophila suzukii prefers a moderate climate such as that along the Pacific Coast, but Kanzawa (1939) observed it surviving and thriving in relatively cold areas of northern Japan. Mitsui et al. (2010) suggested that the fly may migrate to avoid resource poor conditions. Based on the fly's expansion in 2009 and a preliminary Maxent climate matching model by Martin Damus of the Canadian Food Inspection Agency (Damus 2009), range expansion might be anticipated throughout the Pacific Coast from Northern Baja California to Central British Columbia (Fig. 6). Inland, preliminary Climex modeling using the pest's native range and extrapolated to North America indicates that much of the United States from roughly east of the Mississippi River might be suitable for *D. suzukii* to complete its life cycle (Damus 2009).

Climatic Limitations. *D. suzukii* are most active at 20°C (68°F) and activity becomes reduced at temperatures above 30°C (86°F). David et al. (2005) found thermal heat sterility thresholds variable from 23°C in heat-sensitive *Drosophila* spp. to 31°C in heat-tolerant species; *D. suzukii* seem to be toward the heat-tolerant end of the spectrum, with frequent anecdotal reports of sterility in males at temperatures above 30°C. Eggs, larvae and adults can die at temperatures below freezing, but this does not necessarily mean a whole population will be eradicated at low temperatures because *D. suzukii* is firmly established on the island of Hokkaido in Japan where winters average -12 to -4 °C. Kimura (2004) found the cold LT_{50} for female *D. suzukii* originating from Sapporo to be -1.6 °C and the hot LT_{50} to be 32.6°C. For males, the temperatures were -0.1 °C and 32.6°C, respectively. Temperatures were similar for *D. suzukii* originating from Tokyo. Kimura (1988) reported that the adult stage is more tolerant to cold than other drosophilid developmental stages except in those species that overwinter in the larval or pupal stage.

Preliminary findings from research conducted in Oregon in the winter of 2009–2010 suggest that some percentage of *D. suzukii*

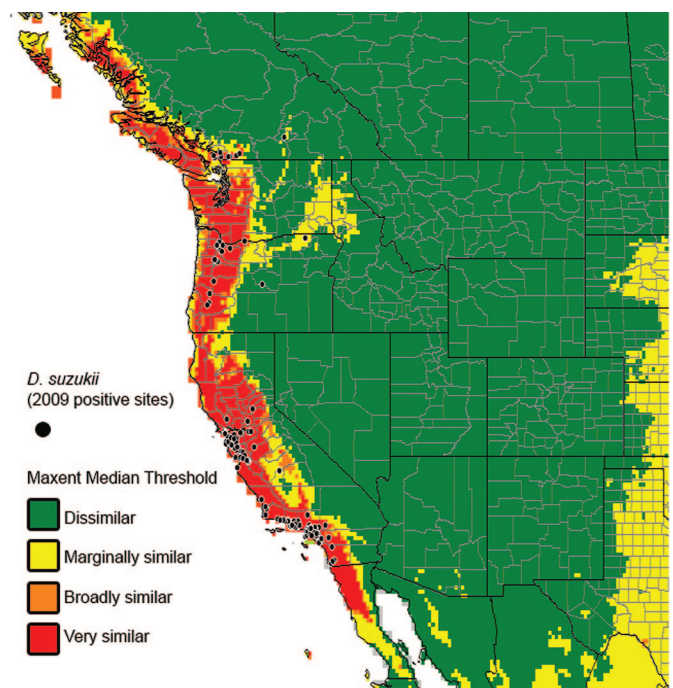


Fig. 6. Possible distribution of *D. suzukii* in the western United States and Canada based on Maxent climatic matching with native and introduced distribution. (Figure courtesy M. Damus, Canadian Food Inspection Agency)

larvae, pupae, and adults have the potential to survive fluctuating overwintering conditions for periods up to 60 days. Adults were able to withstand longer periods of cold than larvae or pupae (A.J.D., unpublished data). In these preliminary, replicated studies, laboratory-reared subject pests were placed in 15 cm vials with moisture and a cornmeal-yeast-based media and exposed to fluctuating outdoor temperatures from late January through late March. The temperatures ranged from 0.72°C to 17.0°C and averaged 8.6°C with an average relative humidity of 82% in protected pockets of leaf fall for exposure periods of 2, 7, 14, 30, and 60 days. Six percent of the larvae and 13% of pupae survived to adulthood, while 39% of adults survived over the 60-day exposure period. Surviving adult females were able to oviposit. When flies were acclimated before direct exposure to outdoors and the amount of moisture accumulating in the vials was regulated to prevent condensation and subsequent drowning of *D. suzukii*, survival increased. However, when exposing pupae and adults to constant cold temperatures in lab studies, higher mortality rates occurred at colder temperatures (V.M.W., unpublished data). Individuals were acclimated to respective constant temperatures during a 2-week period, after which they were subjected to five temperatures of which 10°C was the highest for 6 weeks (42 days). Surviving individuals were then subjected to 10°C for an additional 42 days followed by another 22 days at 20°C. Less than 2% of adult females survived the total trial period of 120 days.

In addition to temperature sensitivities, vinegar flies in general are very sensitive to desiccation, and will die within 24 hours in the absence of water. Other *Drosophila* spp., most notably *D. melanogaster* Meigen, have been shown to exhibit differentiation in tolerance to cold as well as desiccation depending upon climatic conditions (Davidson 1990). Bradley et al. (1999) demonstrated that desiccation resistance could evolve over time among successive generations of *D. melanogaster*. While similar studies have not been conducted on *D. suzukii*, the relationship of the species is known to be close: Harr et al. (2000) identified the two as belonging to a monophyletic clade and Schmidt et al. (1993) confirmed the two as having a homologous sex-peptide.

Degree-day models for *D. suzukii* are under development for the Pacific Coast states and Canada (Damus 2009, Coop 2010). Kanzawa (1939) observed *D. suzukii* lifespans (from egg through oviposition) ranging from 10 to 24 days, with seven of the eight generations for which lifespan was recorded being 16 days or fewer (Table 5). Recent laboratory observations of the *D. suzukii* life cycle document development from egg to egg-laying female as 12–15 days at 18.3°C (65°F). Another study at 21.1°C (70°F) found it took a little more than a week. Kanzawa's early observations across a wide geographic range in Asia indicated that the number of generations could range from 3 to 13 annually, depending upon a variety of climatic factors. *Drosophila suzukii* is believed to complete up to 10 generations per year in California. Based on degree-day models, it is estimated that 3–9 generations may develop annually within its current range in the Western United States and Canada. Coop (2010) developed a preliminary degree-day model as a framework for asking questions about *D. suzukii* biology and for guiding research projects. The model is based on a combination of local data, Sasaki and Sato (1995) and Kanzawa's (1939) research findings. Coop estimates a lower threshold of 10°C and an upper threshold of 30°C, beginning January 1 using a single sine curve calculation method. Initial spring activity is predicted to begin at 250DD, 50% egg laying on 490DD, and an accumulation of 744DD for development of egg to adult in the first generation.

Monitoring and Management

Kanzawa experimented with a variety of baits (molasses, grape wine, rice wine, cherry wine, acetic acid, citronella oil, geranium oil, sugar, and cherry juice, in various combinations) and trap densities, and also tested the efficacy of several chemical control regimens. He found that camphor oil was the most efficacious of the treatments he employed, followed by nicotine sulfate, pyrethroid soap, kerosene emulsion, and neoton. No treatment totally prevented oviposition, however. Kanzawa also explored the efficacy of natural enemies on *D. suzukii*, but his laboratory experiments with parasitoid wasps (*Proctotrypoidea* Diapriidae *Phaenopria* sp.), had minimal impact on pest mortality. Mitsui et al. 2007 evaluated dominant parasitoids attacking frugivorous Drosophilidae species in Japan. They determined that *Asobara* (Braconidae, Alysiinae), *Leptopilina*, and *Ganaspis* species (Figitidae, Eucolidae) were distributed throughout Japan. Other parasitoids showed rather restricted distributions; *Asobara tabida* Nees, *A. rossica* Belokobylskij, *A. rufescens* Foerster, and *Leptopilina heterotoma* Thomson occurred mainly in northern to central parts of the main islands, *Ganaspis xanthopoda* Ashmead from central to southern parts of the main islands, *A. leverii* Nixon in a southern part of the main islands, and *A. pleuralis* Ashmead, *L. victoriae* Nordlander, and *Ganaspis* sp. mainly in the subtropical islands. They concluded that host use considerably varied among parasitoid species, especially in the subtropical islands.

Trapping/Monitoring. Growers of known *D. suzukii* host fruits are encouraged to monitor for the presence of the pest before initiating control measures. No species-specific commercial traps are currently available, but traps used for other vinegar flies should attract *D. suzukii* as well. Emerging recommendations in the Pacific Coast states involve use of bucket-style traps or quart containers with ≈5-to-10 mm-diameter mesh or holes baited with an attractant. Baits currently in use include mixtures of yeast, sugar, and water; fruit purees; various distillates from apple cider vinegar to wine; ethanol, acetic acid, and phenylethanol 1:22:5; and Yellow Muse from AgBio. Other baits that may potentially attract *D. suzukii* and require testing include the commercial lure for *D. melanogaster*; a yellowjacket lure known as Invite; ammonium acetate crystals; and methyl salicylate. The yeast-sugar-water mixture creates CO₂ and is highly attractive. Use of apple cider vinegar is also widely suggested because it has the advantage of longevity in the field as well as being transparent enough for easy fly identification. A small drop of dish soap added to the apple cider vinegar as a surfactant or placement of a sticky card within the trap

results in more fly captures (not because the soap or the card attract more flies, but these elements increase the traps' success at holding flies that enter the traps). Traps for *D. suzukii* seem to perform best when deployed in the cooler, shadier areas of the field or orchard. Scouts are sometimes encouraged to count male *D. suzukii* only, as they are easier to positively identify. One example of a trap is shown in Fig. 7.

Cultural Management. While no set management program has yet been determined for *D. suzukii*, a successful one will be similar to that used for other *Drosophila* species except that there is a need to keep the flies at low densities when ripening fruit, not just overripe fruit, are present. Grower focus should include proactive control of adult vinegar flies before they mate and lay eggs, and sanitation targeted toward eliminating breeding sites in overripe fruit where *D. suzukii* can complete its life cycle. There are no registered insecticides that will control maggots within fruit, so chemicals must target adult control. Essential components of a management program will likely include basic sanitation and attention to timely harvest intervals before fruit reaches peak susceptibility to *D. suzukii*.

Sanitation measures include removal and destruction of both infested fruit and any ripe, overripe and rotten fruit at the crop site that can serve as a host. Methods for fruit removal will vary based upon the host crop, size of operation, the number of harvests taken by crop, and the economics of the situation, but growers in general are encouraged to remove cull piles and to deal with fallen fruit in some fashion. Research is underway to evaluate solarizing, burying, bagging, crushing, and spraying infested fruit to discourage *D. suzukii* colonization. Removal/destruction of overripe/rotting fruit will be especially important if a nearby susceptible crop will soon be ripening. Regarding harvest intervals, it is important to remember that extending harvest intervals, as may occur for a processing crop, may result in larger populations, more fruit damage, and a greater risk for future infestations of fruit crops that will be harvested later in the area.

Backyard gardens are considered an important part of an areawide approach to *D. suzukii* management. Coordinated efforts by Cooperative Extension personnel in California, Washington, Oregon, Idaho, and British Columbia are underway to educate homeowners and regional pest control boards about monitoring (how to and when), pest identification, sanitation, mass trapping, pest exclusion (i.e., covering fruiting plants with netting before oviposition), methods for checking fruit for infestation (e.g., fruit dunk flotation), and appropriate use of insecticides. A mapping and reporting program of fly numbers for noncommercial gardeners is also underway.

Biological Control. Parasitoid wasps (Braconidae and Cynipidae) are thought to be the primary Hymenopteran families targeting *Drosophila* spp. and have potential as biocontrol agents against *D. suzukii*



Fig. 7. *Drosophila suzukii* trap deployed in a cherry orchard. (Photo courtesy Dan Groenendale)

(Kanzawa 1939, Janssen 1989, Driessen and Hemerik 1991). For instance, some cynipid parasitoids are known as exclusively primary parasitoids of *Drosophila* spp. (Dubuffett et al. 2009). A search of literature on *Drosophila* parasitoids revealed more than 10 genera belonging to three Families of Hymenoptera. Timing of emergence and other factors have yet to be evaluated and little is known about the potential contribution these parasitoids can make to an integrated management system.

The role of other beneficial organisms including predators, parasitoids, and pathogens has yet to be assessed. *Orius*, a generalist predator in wildlands and agroecosystems, was observed feeding on *D. suzukii* larvae in backyard raspberries in the fall 2009 (A.J.D., unpublished data). Preliminary studies in the laboratory indicate that *Orius insidiosus* Say can feed on *D. suzukii* larvae infesting blueberries (J.L. and D.J.B., unpublished data).

Chemical Management. Several insecticide classes have proven effective against *D. suzukii* including spinosyns, organophosphates, pyrethroids, and neonicotinoids. Longest-duration control was achieved with malathion and diazinon, with reports of good duration from zeta-cypermethrin, cyfluthrin, beta-cyfluthrin, spinetoram, and beta-cyfluthrin plus imidacloprid as well. Permethrin, imidacloprid, thiomethoxam, esfenvalerate, lambda-cyhalothrin, and some formulations of spinosad have proven effective but with a shorter duration of control (D.J.B. and J.G., unpublished data). Several studies have shown that there are no organic insecticides as effective and persistent against *D. suzukii* as the conventional products. The spinosad formulation GF-120 has no knock-down activity, but will suppress populations over time. However, efficacy of GF-120 was variable when populations increased and attractiveness of the product decreased as the fruiting season progressed. Pyganic and Entrust have a degree of efficacy, but residual impact is limited to 1–3 days. Horticultural oils, azadirachtin, Organocide, and Ecotrol offered no significant control in California field trials. Recent laboratory trials in Oregon supported early reports that the organophosphates diazinon and malathion had the longest residual activity against *D. suzukii*, and indicated that zeta-cypermethrin had the longest residual efficacy of the pyrethroids tested (D.J.B., unpublished data). In these same trials, spinetoram had residual activity comparable to zeta-cypermethrin; this was supported by results from field trials conducted in California.

Drosophila suzukii's preference for ripening fruit presents timing difficulties with respect to preharvest intervals and pollinator protection. The most effective time for applying controls is when the fruit is ripe or very nearly ripe, necessitating chemicals with a shorter preharvest interval. Growers of bee-pollinated crops may find that they need to remove their bees slightly earlier than optimum to spray late-flowering fruit before *D. suzukii* infestation if bee kills are to be minimized. For short-residual insecticides, evening applications may be recommended. Research is underway both in the laboratory and in the field to determine the time of oviposition, taking factors including fruit coloration, sugar levels, pH, and firmness into consideration.

Economics

While it is difficult to estimate economic damage because of significant gaps in scientific knowledge about *D. suzukii*'s biology and control, yield loss estimates from 2009 observations range from negligible to 80%.

The majority of United States small fruit production occurs in the Pacific Coast states. In 2008, California, Oregon, and Washington accounted for virtually all commercial United States raspberry and blackberry production, 84% of the value of commercial cherry production, 83% of the value of strawberry production, and 26% of the value of blueberry production. For these five crops as a group, 76% of the total value of United States commercial production is grown in these three states, or \$2.6 billion of value. Table 6 reports the value of production by state for each crop, and the share of each state's production in the national total (USDA NASS 2009).

Table 6. Revenue losses because of *D. suzukii*, assuming 20% yield loss

	California	Oregon	Washington	Three-state total
Strawberries				
Total farmgate value ^a	1,544.7	16.8	10.1	1,571.5
Share of U.S. production	82%	1%	1%	83%
Total losses	308.9	3.4	2.0	314.3
Blueberries (cultivated)				
Total farmgate value	49.1	49.4	43.4	141.9
Share of U.S. production	9%	9%	8%	26%
Total losses	9.8	9.9	8.7	28.4
Raspberries and blackberries				
Total farmgate value	179.5	41.7	92.1	313.3
Share of U.S. production	57%	13%	29%	100%
Total losses	35.9	8.3	18.4	62.7
Cherries				
Total farmgate value	194.5	58.7	297.1	550.3
Share of U.S. production	30%	9%	45%	84%
Total losses	38.3	9.9	57.8	105.9
All above crops				
Total farmgate value	1,967.9	166.5	442.6	2,577.0
Share of U.S. production	58%	5%	13%	76%
Total losses	393.0	31.4	86.9	511.3

Calculations based on USDA National Agricultural Statistics Service 2009 data for 2008.

^aFarmgate values and total losses given in \$million.

Very little is known about the aggregate potential for crop damage because of *D. suzukii*. Bolda et al. (2010) offered a benchmark estimate that specifies identical yield losses across crops and regions. Assuming a yield loss of 20% for all crops, production of these five crops in these three states could sustain \$511 million in damages annually because of *D. suzukii*. Closure of markets because of quarantine and postharvest fumigation of fruit shipped from *D. suzukii* infested regions will also impact grower returns.

Future and Next Steps

As we enter into the 2010 season, the fact is that we do not know what to expect of *D. suzukii* in the Pacific Coast states or other areas of North America. Area-wide monitoring is taking place throughout California, Washington, and Oregon as well as in southern British Columbia. Upper Midwestern states including Michigan, Atlantic Coast states such as North Carolina and Virginia, and southern sections of Canadian provinces including Ontario are taking an active interest in tracking the pest in case it should appear in their growing regions. The full range of *D. suzukii* crop hosts is unknown, as is the fly's ultimate geographic/climatic range. Cooperative projects involving Western states and Canada are underway to address knowledge gaps and prepare recommendations for dealing with this invasive new pest.

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References Cited

- Bolda, M. P., R. E. Goodhue, and F. G. Zalom. 2010.** Spotted wing drosophila: potential economic impact of a newly established pest. *Agricultural Resource Economics*. Update, University of California Giannini Foundation of Agricultural Economics 13: 5–8.
- Bradley, T. J., A. E. Williams, and M. R. Rose. 1999.** Physiological responses to selection for desiccation resistance in *Drosophila melanogaster*. *American Zoologist* 39: 337–345.
- Coop, L. 2010.** Online phenology and degree-day model for agricultural and

- decision-making in the US. Integrated Plant Protection Center, Botany & Plant Pathology Dep. Oregon State University, Corvallis, Oregon. (<http://uspest.org/risk/models?spp=swd>).
- Damus, M. 2009.** Some preliminary results from Climex and Maxent distribution modeling of *Drosophila suzukii*. Version 2. CFIA Plant Health Risk Assessment, Ottawa, Canada. (<http://swd.hort.oregonstate.edu/files/files/DrosophilaSuzukiiInfestationModel.pdf>).
- David, J. R., L. O. Araripe, M. Chakir, H. Legout, B. Lemos, G. Pétavy, C. Rohmer, D. Joly, and B. Moreteau. 2005.** Male sterility at extreme temperatures: a significant but neglected phenomenon for understanding *Drosophila* climatic adaptations. *Journal of Evolutionary Biology* 18: 838–846.
- Davidson, J. K. 1990.** Nonparallel geographic patterns for tolerance to cold and desiccation in *Drosophila melanogaster* and *Drosophila simulans*. *Australian Journal of Zoology* 38: 155–161.
- De Camargo, R., and H. J. Phaff. 1957.** Yeasts occurring in *Drosophila* flies and in fermenting tomato fruits in Northern California. *Journal of Food Science* 22: 367–372.
- Driessen, G., and L. Hemerik. 1991.** Aggregative responses of parasitoids and parasitism in populations of *Drosophila* breeding in fungi. *Oikos* 61: 96–107.
- Dubuffet, A., D. Colinet, C. Anselme, S. Dupas, Y. Carton, and M. Poirié. 2009.** Variation of *Leptopilina boulardi* success in *Drosophila* hosts: what is inside the black box? *Advances in Parasitology* 70: 147–88.
- Fuyuma, Y. 1979.** A visual stimulus in the courtship of *Drosophila suzukii*. *Experientia* 35: 1327–1328.
- Harr, B., B. Zangerl, and C. Schlötterer. 2000.** Removal of microsatellite interruptions by DNA replication slippage: phylogenetic evidence from *Drosophila*. *Molecular Biology and Evolution* 17: 1001–1009.
- Hauser, M., S. Gaimari, and M. Damus. 2009.** *Drosophila suzukii* new to North America. *Fly Times* 43: 12–15. (www.nadsdiptera.org/News/FlyTimes/issue43.pdf).
- Janssen, A. 1989.** Optimal host selection by *Drosophila* parasitoids in the field. *Functional Ecology* 3: 469–479.
- Kaneshiro, K. Y. 1983.** *Drosophila* (Sophophora) *suzukii* (Matsumura). *Proceedings of the Hawaiian Entomology Society* 24: 179.
- Kanzawa, T. (aka “Kamizawa, T.) 1936.** Studies on *Drosophila suzukii* Mats. *Journal of Plant Protection (Tokyo)* 23: 66–70, 127–132, 183–191. (abstr.) *Review of Applied Entomology* 24: 315.
- Kanzawa, T. 1939.** Studies on *Drosophila suzukii* Mats. Kofu, Yamanashi Agricultural Experiment Station 49 pp. (abstr.) in *Reviews of Applied Entomology* 29: 622.
- Kimura, M. T. 2004.** Cold and heat tolerance of drosophilid flies with reference to their latitudinal distributions. *Oecologia* 140: 442–449.
- Kimura, M. T. 1988.** Adaptations to temperate climates and evolution of over-wintering strategies in the *Drosophila melanogaster* species group. *Evolution* 42: 1288–1297.
- Louise, C., M. Girard, G. Kuhl, and M. Lopez-Ferber. 1996.** Persistence of *Botrytis cinerea* in its vector *Drosophila melanogaster*. *Phytopathology* 86: 934–939.
- Markow, T. A., and P. M. O’Grady. 2006.** *Drosophila*: a guide to species identification and use (Chapt. 1, p. 13). Academic, London, United Kingdom.
- Mitsui, H., K. Beppu, and M. T. Kimura. 2010.** Seasonal life cycles and resource uses of flower- and fruit-feeding drosophilid flies (Diptera: Drosophilidae) in central Japan. *Entomological Science* 13: 60–67.
- Mitsui, H., K. H. Takahashi, and M. T. Kimura. 2006.** Spatial distributions and clutch sizes of *Drosophila* species ovipositing on cherry fruits of different stages. *Population Ecology* 48: 233–237.
- Mitsui, H., K. Van Achterberg, G. Nordlander, and M. T. Kimura. 2007.** Geographical distributions and host associations of larval parasitoids of frugivorous Drosophilidae in Japan. *Journal of Natural History* 41: 1731–1738.
- Molina, J. J., M. D. Harisson, and J. W. Brewer. 1974.** Transmission of *Erwinia carotovora* var. *atropeptica* by *Drosophila melanogaster* Meig. *American Potato Journal* 51: 245–250.
- Nishiharu, S. 1980.** A study of ecology and evolution of Drosophilid flies with special regard to imaginal and larval feeding habits and seasonal population fluctuations. Science thesis, Tokyo Metropolitan University of Tokyo.
- Oku, T. 2003.** SWD: *Drosophila suzukii* (Matsumura) (p. 381). In *Japan Agricultural Pest Encyclopedia*. Zenkoku Nosen Kyoiku Kyokai.
- Sasaki, M., and R. Sato. 1995.** Bionomics of the cherry drosophila, *Drosophila suzukii* Matsumura (Diptera: Drosophilidae) in Futeushima prefecture (Japan). *Annual Report of the Society of Plant Protection of North Japan* 46: 164–172.
- Sasaki, M., and R. Sato. 1996.** Bionomics of *Drosophila pulchrella* Tan, Hus et Sheng (Diptera: Drosophilidae) in Fukushima prefecture (Japan). *Tohoku Agriculture Research* 49: 161–162.
- Schmidt, T., Y. Choffat, M. Schneider, P. Hunziker, Y. Fuyuma, and E. Kubil. 1993.** *Drosophila suzukii* contains a peptide homologous to the *Drosophila melanogaster* sex-peptide and functional in both species. *Insect Biochemistry and Molecular Biology* 23: 571–579.
- Tanigoshi, L. K., B. S. Gerdeman, and G. H. Spitzer. 2010.** 2010 spotted wing drosophila (SWD) recommendations for red raspberry in Washington State. Washington State University Mount Vernon NW Research Center Spotted Wing *Drosophila* Updates Website. (www.mountvernon.wsu.edu/ENTOMOLOGY/pests/SWD.html). Accessed 8-16-10).
- Toda, M. J. 1987.** Vertical microdistribution of Drosophilidae (Diptera) within various forests in Hokkaido. III. The Tomakomai Experiment Forest, Hokkaido University. *Research Bulletin of College Experimental Forests* 44: 611–632.
- (USDA) U.S. Department of Agricultural National Agricultural Statistics Service. 2009.** Noncitrus fruits and nuts 2008 summary. Publication Fruit and Nuts 1–3 (09). U.S. Department of Food Agriculture of National Agricultural Statistics Service, Washington, DC.

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