J Pest Sci
DOI 10.1007/s10340-016-0737-8

ORIGINAL PAPER

Current SWD IPM tactics and their practical implementation in fruit crops across different regions around the world

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Received: 28 October 2015 / Revised: 30 January 2016 / Accepted: 1 February 2016

Abstract After its arrival in 2008, the Spotted Wing Drosophila (SWD), *Drosophila suzukii*, has emerged as a harmful invasive insect pest in North America and Europe. This highly polyphagous pest is a major threat to many economically important fruit crops and is also known to develop on a wide variety of natural host plants. In Asia, Europe and North America, different control measures are applied against SWD, such as chemical, biological, and cultural control. Current controls of SWD rely primarily on the application of insecticides, but cultural management tactics such as sanitation and the use of nets provide a good alternative in some crops. Biological control measures, such as conservation of existing natural enemies in invaded areas, introduction of specialized larval parasitoids from Asia for classical biological control and the use of indigenous parasitoids for augmentative control, are currently being investigated and may become an important management tool in the near future for an area-wide control of SWD.

Keywords *Drosophila suzukii* · Biological control · Cultural control · Chemical control

Key message

- *Drosophila suzukii* is a new threat for fruit crop production systems worldwide, and new IPM strategies are urgently needed.
- We summarized the knowledge and practices currently used for integrated pest management (IPM) of SWD around the world, including chemical, cultural and biological control.
- Effective control of SWD in invaded areas will require an area-wide control approach.

Introduction

The Asian Spotted Wing Drosophila (SWD), *Drosophila suzukii* (Diptera: Drosophilidae), is a new threat for fruit crop production systems worldwide. For decades, this insect posed no threat to crop production (Kanzawa 1939), but in 2008, this fly arrived simultaneously in Europe (Italy, Spain) (Calabria et al. 2012; Cini et al. 2014) and North America (Lee et al. 2011) and then more recently in South America (Depra et al. 2014). SWD was not recognized as a serious pest before 2010, but recently increasing damage was noticed in Chinese cherry orchards due to prolonged low-temperature periods in spring, resulting in

Communicated by A. Biondi.

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Published online: 08 February 2016

delayed maturation of fruits and an increase in the production area for late maturing cherry varieties (Yang et al. 2011; Wang et al. 2012; Dai 2013; Guo et al. 2014; Liu et al. 2014; Zhang and Gao 2014; Zhang et al. 2015). The colonization of invaded areas in North America and Europe has been largely facilitated by human activities, particularly the movement of infested fruits, climatic conditions similar to the fly's native range (Wiman et al. 2014) and the absence of natural factors regulating SWD populations effectively.

In contrast to the vast majority of *Drosophila* species, which feed on rotting fruits, *D. suzukii* lay its eggs inside ripening fruits, puncturing the fruit's skin with its unique saw-like ovipositor (Atallah et al. 2014). Damage is mainly caused by larval feeding, resulting in the degradation of fruits. In addition, the puncturing of the fruit skin provides a gateway for secondary infections with bacteria and fungi pathogens or additional pests (de Camargo and Phaff 1957; Molina et al. 1974; Louise et al. 1996; Walsh et al. 2011). This highly polyphagous pest is known to develop in many economically important fruit crops, e.g. blackberries, blueberries, cherries, peaches, raspberries, strawberries, grapes, bayberries and kiwis (Kanzawa 1939; Bolda et al. 2010; Grassi et al. 2011; Lee et al. Lee et al. 2011; Seljak, 2011; Walsh et al. 2011; Bellamy et al. 2013; Liu et al. 2015). In addition, more than 50 wild host plants have been determined in Europe and the US, providing the pest a large reservoir of alternative hosts throughout the seasons (Baroffio Baroffio et al. 2015; Lee et al. 2015; Poyet et al. 2015; Kenis et al. 2016). In the Trento district of Italy, annul losses in small fruit production were assumed €3.3 m per year (De Ros et al. 2013), and in the USA gross revenues for raspberry and strawberry farmers were assumed to decrease by 37 and 20 %, respectively (Goodhue et al. 2011). Estimated annual costs to the US fruit production are more than US$ 500 m (Bolda et al. 2010).

While new control measures are still being developed in Europe and North America, here we summarize knowledge and practices currently used for integrated pest management (IPM) of SWD around the world, including chemical, cultural, and biological control.

Chemical control

Evaluations of the efficacy of insecticides for the control of *D. suzukii* have been undertaken in almost all of the major fruit growing regions where it is now distributed. Trials have included laboratory-based Petri dish experiments along with field evaluations where experimental plots are treated and sampled for control of the fly (Beers et al. 2011; Bruck et al. 2011; Cuthbertson et al. 2014a). Due to there being a zero tolerance within both fresh and processed berry markets against infested fruit, and with many fruit growing areas experiencing high population numbers, growers across the international fruit growing sector take a very proactive approach in trying to control *D. suzukii* in order to protect their individual industries (Van Timmeren and Isaacs 2013). Currently, there is limited published information regarding the levels or extent of insecticide resistance in *D. suzukii* populations, but with it having an almost global invasion of fruit producing areas and the only current viable method of control being insecticide-dependent strategies, no doubt resistance will become a major problem in the foreseeable future. Much information is known in regard to how *D. melanogaster* has developed resistance to insecticides and the associated problems it has caused (Perry et al. 2008; Remnant et al. 2014; Wan et al. 2014).

The current effective insecticides suggested for managing SWD are principally conventional broad-spectrum products which are not always compatible with IPM programmes, such as advanced generation pyrethroids and organophosphates (Beers et al. 2011; Haviland and Beers 2012; Van Timmeren and Isaacs 2013). Neonicotinoids have been used to a limited extent in control strategies because they are perceived to be less effective (Bruck et al. 2011), and, if they are used in foliar sprays, are anticipated to have broad-spectrum effects and negative impacts to beneficial arthropods (James 2003; He et al. 2012). The exception regarding broad-spectrum impacts for insecticides effective against SWD is spinosyns (spinosad and spinetoram; Beers et al. 2011; Bruck et al. 2011; Haviland and Beers 2012; Zhang et al. 2015), which, for resistance management, need to be limited in the number of applications made per year on a given crop. As the current effective pesticide options for managing SWD are limited, it is therefore very important to optimize the use of the insecticides that are available. Within the United States, a total of 18 insecticides are listed for use on blueberry, caneberry, strawberry, grape and stone fruit (Fruit Advisor 2015). These are a mixture of organic and conventional pesticides. Bruck et al. (2011) also screened a wide range of insecticides for efficacy against SWD. In their study, several insecticides including pyrethroids (bifenthrin, beta-cyfluthrin, permethrin, zeta-cypermethrin), organophosphates (malathion, diazinon) and spinosyns (spinosad, spinetoram) provided excellent control of adult *D. suzukii* following direct application. Spinetoram and dimethoate have also been screened for efficacy in Italian cherry orchards (Profaizer et al. 2015). Insecticide screening trials by Cuthbertson et al. (2014a) also confirmed the high efficacy of spinosad and chlorantraniliprole against SWD. Several 'coded' products (potentially awaiting EU/UK registration) have also proved highly efficient against various life stages of SWD following both post- and pre-dipping blueberry treatments (Cuthbertson et al. 2014a; AGS Cuthbertson unpublished data). Gargani et al. (2013)

also undertook berry dipping trials with various organic products; only one product, "Deffort" (Sophora flavescens Aiton, 8 %), a fertilizer liquid based on complexing micronutrients enriched with plant extracts with strong anti-stress action displayed any significant direct toxicity.

Cowles et al. (2015) demonstrated that the addition of sucrose as a phagostimulant improved the activity of several insecticides to target SWD adults and as a result increased protection of fruit from infestation. Their study showed an enhancement in activity of several reduced-risk insecticides, such as spinosyns, cyantraniliprole and acetamiprid, which provided equivalent or superior protection of blueberry and strawberry fruits when compared with application of conventional insecticides. Potential impacts from using sucrose with insecticides on beneficial non-target species and pollinators have yet to be determined. Walse et al. (2012) also demonstrated the potential use of postharvest methyl bromide fumigation for treatment of berries prior to shipment. However, since the early 1990s, this fumigant has been known to break down under the influence of strong UV rays and thus release bromide atoms which deplete the ozone layer (WMO 1995; Dabrowski 2002), and with the phase-out of methyl bromide in industrialized countries in January 2005 (Norman 2005), alternatives to this fumigant are still eagerly sought (Cuthbertson et al. 2013).

Cultural control

Depending on the type of crop, different cultural control methods are currently applied in Asia, Europe and North America. Sanitation is one of the most important cultural control methods to combat SWD around the world (Köppler 2014; Walsh et al. 2011; Tanigoshi et al. 2011; Dreves et al. 2011; Liburd and Iglesias 2013; Shi 2015). During the ripening season, sanitary measures such as clearing ground covering vegetation, removal of dropped and over-ripe fruits have been suggested (Lee et al. 2011; Shi 2015). Larvae inside removed fruits have been effectively killed by solarisation, the use of heat to kill insects. Infested fruits can either be placed on the ground in a sunny location and covered with clear plastic sheeting or placed in sun exposed plastic bags for at least 2 days. Burying infested fruit has been shown to be less effective. Whereas solarisation is effective for berry crops, it is difficult to apply to stone fruits. As viability of SWD eggs is lower under dry, warm conditions (Burrack et al. 2014), cool humid microhabitats should be avoided by pruning to open up the canopy and using wider tree spacing to increase airflow to the canopy and reduce shading. In addition, the use of mulches reducing standing water can further contribute to the reduction of humidity in fruit orchards (Hoashi-Erhardt and Bixby-Brosi 2014). In China, soil tillage in winter is recommended to destroy overwintering habitats of the fly, whereas in spring surrounding ground of cherry trees is supposed to be covered with black plastic fabric, preventing overwintered adults moving up to the tree canopy (Shi and Wang 2015).

Short harvest intervals may further help reduce the number of infested fruits at harvest. When raspberries that had just matured were collected every 2 days in Swiss orchards, only little infestation with SWD was noticed, whereas longer harvest intervals lead to higher infestations due to the larger proportion of over mature fruits (C. Baroffio, unpublished data).

Besides sanitary measures, the use of nets covering fruit bearing trees or shrubs is an effective complementary method to physically exclude SWD. Particularly in cherry crops, nets are among the most important control measures around the world. The recommended mesh size varies between 0.5×0.8, 1×1 and 1×1.6 mm (Grassi and Pallaoro 2012; Gamper 2015; Cormier et al. 2015). Nets with a mesh size of 0.98 mm and 1×1.6 mm provided good control of SWD in blueberries in Asia and Europe, respectively (Kawase et al. 2007; Grassi and Pallaoro 2012; Ioriatti et al. 2015). Nets need to be installed before the fruits begin to ripen to prevent any SWD being trapped inside the nets (Caprile et al. 2013). Lure traps placed inside the nets may serve as additional control. Alternatively, bagging cherry clusters in the early fruit stage with white semitransparent paper bags has been recommended in China (Shi and Wang 2015). Furthermore, it is important to control the climate under the nets to avoid infestation with fungi due to increased humidity.

A wide variety of differently shaped and coloured traps containing attractants, usually a mix of apple cider vinegar, red wine and sugar, have been developed primarily for monitoring SWD populations (Landolt et al. 2012; Wei et al. 2012; Lee et al. 2013; Cha et al. 2014; Grassi and Maistri, 2013; Baroffio et al. 2014; Harris et al. 2014; De Los Santos Ramos et al. 2014; Shi 2015; Burrack et al. 2015). However, some traps can also be used for mass trapping SWD. In Switzerland, commercially available ready-to-use traps ("Riga trap") consist of transparent cups filled with 100 ml of attractant (wine, sugar, wine and fruit vinegar), and covered with a lid with five holes (3 mm) (for details see www.becherfalle.ch). Trials conducted in 2014 showed a significant reduction of SWD populations in raspberries (cv Polka) over a period of three weeks, when traps were placed in shady places at fruit height every 2 metres in the perimeter of the crop (density: 200 traps/ha; costs: 155€/ha). Traps were changed every 3 weeks (Baroffio et al. 2015). In Yunnan, China, sweet lure traps made of 600 ml plastic bottles containing variable mixtures of brown sugar, vinegar, wine and water were used to attract and kill flies in pomegranate orchards. Two opposite holes (2 cm diameter) were drilled near the bottleneck and

the bottom of the trap to allow the flies to enter. Traps were placed in trees every 15–20 m at a height of 1.5 m and monitored daily for a period of 10 days in early September. The best catches (daily average of 19.7 flies) were achieved using a mixture of brown sugar (50 g) vinegar (50 ml), wine (150 ml) and water (300 ml) (Wu et al. 2007). In the Beijing area, slightly modified traps exposed in natural mountain habitats resulted in catches of 310.3 flies per day during the peak flight period (Zhang et al. unpublished data). Traps used in the Beijing area contained the same lure (250 ml) but were made of 1 l plastic containers with 30 small holes (0.5 cm diameter). In two independent studies, it was recommended that the optimal height for hanging traps would be 1.5–2.0 m or 0.8–1.4 m above ground, respectively (Grassi et al. 2009; Guo et al. 2014). Besides lure traps, yellow-green light traps (wavelength 560 nm) or frequency trembler grid lamps (1 per 2000 m^2) have been recommended to trap SWD in Chinese bayberry orchards, but no data on the efficiency of these traps have been reported (Liang et al. 2015).

Biological control

Biological control can be a cost-effective and environmentally safe approach for the management of arthropod pests. Current control programmes for SWD rely primarily on pesticides, and these programmes may be challenged because abundant wild fruits can serve as a reservoir for this highly polyphagous and mobile pest to reinvade managed crops (Lee et al. 2015). Natural enemies may also proliferate in both crop and unmanaged habitats, potentially playing a unique role in lessening the fly populations in crop and uncultivated habitats. A previous review by Asplen et al. (2015) discussed the prospects of biological control of SWD using parasitoids, especially introduced Asian parasitoids. Here, we will focus on new developments and the potential implementation of biological control for SWD by means of parasitoids and other biological control agents (predators, nematodes and pathogens).

Parasitoids play an important role in population regulation of *Drosophila* species (Carton et al. 1986; Fleury et al. 2004). The majority of studies have focused on some common parasitoids such as *Leptopilina heterotoma, L. boulardi* (Hymenoptera: Figitidae) and *Asobara tabida* (Hymenoptera: Braconidae) that attack *Drosophila* larvae living within fermenting substrates, such as rotting fruits (Prévost 2009). Recently, a number of studies have been undertaken in both the USA and Europe to investigate parasitoid species associated with SWD in its invaded regions (Gabarra et al. 2015; Rossi Stacconi et al. 2015; Miller et al. 2015; Wang et al. 2016a) and the suitability of SWD as a host for common Drosophila parasitoids (Chabert et al. 2012; Kacsoh and Schlenke 2012). Two generalist pupal parasitoids, *Trichopria drosophilae* (Diapriidae) and *Pachycrepoideus vindemmiae* (Hymenoptera: Pteromalidae) were found worldwide. Both pupal parasitoids are effective under laboratory conditions; female *P. vindemmiae* and *T. drosophilae* produced a lifetime total of 68.4 and 63.8 offspring on SWD and have an intrinsic rate of increase of 0.14 and 0.12 at 23 °C, respectively (Rossi Stacconi et al. 2015; Wang et al.2016a). Augmentative release in greenhouses also showed that *T. drosophilae* was able to successfully parasitize SWD pupae in strawberry (Trottin et al. 2014). In China, *P. vindemmiae* was mass produced on pupae of *Musca domestica* (Diptera: Muscidae) and released for inundative control of *D. suzukii* in bayberry orchards in the Zhejiang province (Zhou et al. 2014), but with little success.

However, larval parasitoids (e.g. *L. heterotoma*, *L. boulardi* and *A. tabida*) that are commonly associated with other *Drosophila* species appear to be largely unable to develop from SWD larvae, presumably due to their strong host immune response against parasitoids (Kacsoh and Schlenke 2012; Poyet et al. 2013). A recent field survey reported for the first time the presence of trapped *D. suzukii* adults bearing melanized and encapsulated resident parasitoids in North America (Wang et al. 2016b). In contrast, other larval parasitoids, including *Asobara japonica*, *Ganaspis xanthopoda* (Diapriidae), *Leptopilina japonica* and an undescribed species (*Asobara* sp. TK1), utilize SWD as a host in Japan (Mitsui et al. 2007; Ideo et al. 2008; Novkovic et al. 2012; Nomano et al. 2015; Kimura and Novkovic 2015). Furthermore, an *Asobara* sp. TK1 and a strain of *G. xanthopoda* were shown to exhibit a high level of specificity for SWD (Nomano et al. 2015; Kasuya et al. 2013). Recent explorations in South Korea collected 6 different larval parasitoid species (*A. brevicauda*, *A. japonica*, *A. leveri*, *L. japonica*, *L. formosana*, and *G. brasiliensis*) from SWD from infested wild fruits, and parasitism of SWD by these larval parasitoids was as high as 17 % (Daane et al. 2016). *Asobara japonica* was the most widely distributed and abundantly collected species in Japan (Mitsui et al. 2007; Ideo et al. 2008; Murata et al. 2009; Mitsui and Kimura 2010) and South Korea (Daane et al. 2016). This larval parasitoid has shown a high rate of successful development from SWD (Kacsoh and Schlenke 2012) and has a high fecundity (117.4 progeny/female) and intrinsic rate of increase (0.22) when parasitizing SWD (A Biondi, XG Wang, and KM Daane unpublished data). It also showed an innate attraction to volatile cues from different infested host fruits (A Biondi et al. unpublished data). *Ganaspis brasiliensis* and *L. japonica* collected from South Korea also readily developed from SWD when tested in the laboratory (Daane et al. 2016). *Leptopilina japonica* has been observed to parasitize larvae of at least three other *Drosophila* species in Japan (Mitsui and Kimura 2010; Novkovic et al. 2012; Kasuya et al. 2013), but virulence also varied with geographically isolated populations (Kimura and Novkovic 2015). If levels of host specificity are considered

sufficient, introduction of larval SWD parasitoids native to Asia may add a potentially unique role in regulating SWD populations (Daane et al. 2016).

Predatory bugs, such as species of *Orius* (Anthocoridae), have been observed feeding on SWD in raspberries in the USA (e.g. Walsh et al. 2011) and were present in infested fruit samples in Spain (Arnó et al. 2012). Several commercially available *Orius* species have been tested under laboratory conditions. *Orius majusculus* and *O. laevigatus* showed some predatory activity towards SWD larvae but gave no significant suppression of the SWD populations (Cuthbertson et al. 2014b; Malagnini et al. 2014). For example, *O. insidiosus* reduced SWD survival in simple laboratory arenas but not on potted blueberries or bagged blueberry outdoors (Woltz et al. 2015). Other predators such as the beetle *Atheta coriaria* (Staphylinidae) and the bug *Anthocoris nemoralis* (Anthocoridae) also fed on SWD life stages to some extent in laboratory tests (Cuthbertson et al. 2014b; Renkema et al. 2015; Woltz et al. 2015). *Atheta coriaria* did not reduce SWD survival (Woltz et al. 2015), whereas *A. nemoralis* caused 45 % mortality of SWD after five days (Cuthbertson et al. 2014b). *Orius laevigatus* (Malagnini et al. 2014) and the predatory mite, *Hypoaspis miles* (Mesostigmata: Laelapidae) (Cuthbertson et al. 2014b), showed no predatory activity on SWD. Although *A. nemoralis* showed potential for suppressing SWD populations within confined arenas, it is unclear if its predatory efficiency would decrease in the open field situation due to field conditions, such as increased difficulty in catching adult SWD (Cuthbertson et al. 2014b). Overall, none of these predators seemed able to control SWD individually, but they would likely contribute to SWD population suppression additively if they were in the SWD ecosystem (Cuthbertson et al. 2014b).

A few commercially available entomopathogenic nematodes have been screened for control of SWD, including *Steinernema carpocapsae*, *S. feltiae*, *S. kraussei* and *Heterorhabditis bacteriophora*. All showed low infection rates and were not able to affect SWD survival following infested berry dipping experiments (Cuthbertson et al. 2014a; Woltz et al. 2015). However, upon investigating the same nematodes as potential soil drenches against SWD larvae/pupae, *S. kraussei* was shown to cause approximately 55 % pupae mortality, while *H. bacteriophora* provided approximately 95 % larval mortality (AGS Cuthbertson, unpublished data). One unidentified nematode species from a South Korean collection of SWD was found to readily attack SWD in laboratory tests (A Biondi, XG Wang and K Daane, unpublished data). Based on these observations, further screening for more effective nematodes may be warranted and ways to enhance nematode survival in soil under crop plants.

Entomopathogenic fungi have been used successfully to control arthropod pests (Ekesi et al. 2005; Faria and Wraight 2007). The efficacy of several commercially available formulations of entomopathogenic fungi in the genera *Metarhizium*, *Beauveria, Lecanicillium, Isaria* and *Paecilomyces* have been screened against SWD under laboratory conditions (Cuthbertson et al. 2014a; Naranjo-Lázaro et al. 2014; Woltz et al. 2015). Both *L. muscarium* as Mycotal (0.1 % solution) and *B. bassiana* as Naturalis (0.3 % solution) appear to have no marked impact on fly emergence when dipping SWD-infested fruit into field-rate concentrations of the agents, but direct spray of *B. bassiana* caused 44 % adult mortality after 7 days (Cuthbertson et al. 2014a). Mycotrol-O, a *B. bassiana*-based bioinsecticide, showed 80 % adult mortality 10 days after application in strawberries in laboratory cages (Jentsch 2014). Naturalis and another bioinsecticide, Botanigard, which is also based on living spores of *B. bassiana,* showed some suppression of adult SWD (Gargani et al. 2014). The susceptibility of SWD to different strains of *I. fumosorosea* (Pf21, Pf17, Pf15) and of *M. anisopliae* (Ma59) was evaluated through in vitro bioassays and the resulting percentages of fly mortality by Pf21, Pf17 and Ma59, Pf15 were 85, 60, 57 and 12 %, respectively (Naranjo-Lázaro et al. 2014). Woltz et al. (2015) tested *M. anisopliae*, *B. bassiana* and *P. fumosoroseus* as direct sprays on adult SWD and found that only *M. anisopliae* significantly decreased SWD survival. These different results could be due to different strains screened, but the studies suggest that some entomopathogenic fungal strains could be used as biological control agents of SWD. However, there are still obstacles to overcome in the delivery method and lack of persistence of these agents in the field. Entomopathogenic fungi infect their target organisms through the cuticle, and one major constraint is bringing the pathogen into contact with the adult fly in the field (Ekesi et al. 2005). Another potential problem is that fungi such as *M. anisopliae* have low residual activity and no effect on SWD fecundity; they did not kill adult flies quickly enough, and as a result, the next generation of flies began emerging before adult flies that had been treated began to die (Woltz et al. 2015). However, fungi can be easily integrated into existing control strategies, as they may have less effect on natural enemies than on the target pests as compared with conventional insecticides. For example, *M. anisopliae* has been used for the control of tephritid fruit flies in Africa and posed no adverse effect on these flies' parasitoids (Ekesi et al. 2005).

Conclusions

It is likely that we will see a continuous spread of SWD in the coming years due to increased global trade of fruit crops. The control of SWD in fruit orchards will be par-

ticularly challenging because a high number of wild host plants in nearby wood lands, unmanaged private gardens or abandoned orchards provide an enormous refugium for SWD (Lee et al. 2015; Kenis et al. 2016), requiring an area-wide control approach.

Current controls of SWD rely primarily on the application of a range of insecticides such as spinosyns, organophosphates, pyrethroids and neonicotinoids. The rapid turnover of SWD generations requires many chemical interventions at the fruit ripening stage (Bruck et al. 2011; Van Timmeren and Isaacs 2013). Whereas insecticides can be effective, they increase the risk of residues in fruits, promote insect resistance and negatively affect pollinators and natural enemies (Stark and Banks 2003; Desneux et al. 2007). The majority of the screening of chemicals against SWD that has been undertaken has been done so under laboratory conditions. However, laboratory-based data generally become more variable when transferred to the field. Thus, product efficacy testing must be tested on a broader scale before strong conclusions or recommendations to the fruit growing industry can be made. The addition of new insecticides for the control of SWD could further be very disruptive to natural enemies already being used in IPM strategies that were developed over a period of time for management of other pests (Roubos et al. 2014). Future management must also emphasize selective use of risk-reduced pesticides (Biondi et al. 2012) to reduce the negative impact on natural enemies.

At small scale productions, chemical control should be coupled with cultural management tactics (Thistlewood et al. 2012). To date, sanitation is the most important method to combat SWD. Although costly and time consuming, other control measures can only be effective when the crop is "clean", and SWD reservoirs are reduced as much as possible. The use of nets provides a good alternative to chemical control, especially in cherries, blackberries, raspberries and blueberries. In berry crops, mass trapping combined with sanitation can be an efficient strategy; however, the choice of the attractant is critical, and the control may only work if the traps are at least as attractive as the fruits or used prior to start of fruit ripening.

Generalist natural enemies (including indigenous parasitoids and predators) are all likely to contribute to suppression of SWD populations to some degree within the ecosystems occupied by SWD, although their direct impacts on SWD have not yet been demonstrated in the field. Whereas there is a current lack of effective parasitoids attacking SWD larvae in the invaded regions, these species may exist in Asia and current programmes are collecting and screening novel agents. This highlights the importance of conserving all natural enemies, introducing specialized larval parasitoids and continuing investigations into the possible use of augmentative biological control with indigenous or commercially available biological control agents. Research is currently under way to develop these biological control programmes for SWD in the USA and Europe.

Author contribution

TH, PG, AGSC, XGW, KMD, KAH, CB, JZ and ND wrote the manuscript. All authors edited the manuscript and approved the final version.

Acknowledgments Funding for research in the US was supported by California Cherry Board, USDA APHIS (Farm Bill, Fund 14-8130-0463) and the National Institute of Food and Agriculture, USDA SCRI Initiative (Agreement No. 2015-51181-24252). USDA is an equal opportunity employer. Research in Europe has received funding from the European Union's Seventh Framework programme for research, technological development and demonstration under grant agreement numbers 613678 (DROPSA) and 318246 (ASCII).

Compliance with ethical standards

Conflict of interest The authors have declared that no conflict of interest exists.

Research Involving Human Participants and/or Animals This article does not contain any studies with human participants or animals (vertebrates) performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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