Received: 28 May 2017 | Accepted: 17 September 2017
DOI: 10.1111/jen.12462

ORIGINAL CONTRIBUTION

WILEY JOURNAL OF APPLIED ENTOMOLOGY

Efficacy of biopesticides on spotted wing drosophila, *Drosophila suzukii* Matsumura in fall red raspberries

P. D. Fanning | **M. J. Grieshop** | **R. Isaacs**

Department of Entomology, Michigan State University, East Lansing, MI, USA

Correspondence
Philip D. Fanning, Michigan State University, East Lansing, MI, USA.
Email: fanning9@msu.edu

Funding information
National Institute of Food and Agriculture, Grant/Award Number: 2015-34383-23710; USDA-NIFA: IR-4 Minor Pest Crop Management Program, Grant/Award Number: 2015-34383-23710

Abstract

Drosophila suzukii Matsumura is a significant pest of soft-skinned fruit. Larvae of *D. suzukii* develop within the fruit making it unmarketable as fresh berries and increasing the risk of rejection by processors. We evaluated selected biopesticides for control of *D. suzukii* in fall red raspberries, *Rubus idaeus* L. The trial results highlight a small number of biopesticides with the potential to reduce infestation of *Drosophila* larvae in raspberries. In addition to the standard biopesticide spinosad, we found that sabadilla alkaloids and *Chromobacterium subtsugae* both reduced the number of *Drosophila* larvae in raspberry fruit. Treatments that included corn syrup as a feeding stimulant showed no significant difference in their infestation levels compared to treatments without the syrup. In the final week of the 5-week trial, treatments with rotations of either spinosad/*C. subtsugae* or spinosad/sabadilla alkaloids had a 67% and 57% reduction in infestation when compared to untreated raspberries. Treatments of spinosad alone on a 7 day rotation and *C. subtsugae* alone on a 3–5 day rotation both had a 62% and 61% reduction in larval infestation when compared to untreated raspberries. Third instar larvae, the largest and most damaging, were significantly reduced in plots treated with spinosad only, a rotation of spinosad/sabadilla alkaloids and the rotation of spinosad/*C. subtsugae* with corn syrup added when compared to untreated plots. This suggests that either of these biopesticides could be used as effective rotation partners along with spinosad for control of *D. suzukii*. Our results highlight that biopesticides can provide significant reduction in this devastating pest when used alone or in combination, providing options to support resistance management.

KEYWORDS
biopesticides, *Chromobacterium subtsugae*, pest management, *Rubus idaeus*, sabadilla alkaloids, spinosad

1 | INTRODUCTION

Biopesticides are derived from naturally occurring living organisms such as animals, plants and microorganisms (e.g., bacteria, fungi and viruses) and often provide less disruptive control of pests compared to conventional insecticides (Senthil-Nathan, 2015). A review of biopesticides by Copping and Menn (2000) reported increasing interest in these products by growers and producers, particularly those developing environmental friendly approaches to pest management. Many of these biopesticides also get certification by the Organic Materials Review Institute (OMRI) in the United States to meet the regulations set by the National Organic Program (NOP) for use in certified organic production. Biopesticides have important potential uses in settings where there is a high use of conventional insecticides, the use of which might be threatened by the development of insecticide resistance or future restrictions due to human health and environmental concerns (Mazid, Kalida, & Rajkhowa, 2011).

Drosophila suzukii Matsumura is an invasive vinegar fly and a significant pest infesting small fruits and cherries, in the majority of fruit growing regions globally (Asplen et al., 2015; Cini et al., 2014; Walsh et al., 2011). This species differs from most other Drosophila species; the females have a serrated ovipositor allowing them to oviposit in ripening fruit, thus rendering it unmarketable (Walsh et al., 2011). In susceptible crops including soft-skinned berries, millions of dollars of fruit have been put at risk of infestation by this pest (Bolda, Goodhue, & Zalom, 2010; Pfeiffer, Leskey, & Burrack, 2012). In California, which accounts for 74% of all raspberry production in the United States, Farnsworth et al. (2016) calculated revenue losses of $36.4 million, equivalent to 2.07% of their realized revenues for conventional producers, and organic producers had revenue losses of $3.43 million, equivalent to 5.74% of their realized revenues, related to the control of *D. suzukii* between 2009 and 2014. The higher percentage losses in annual revenues for organic producers were due to the higher cost of insecticide inputs, which Farnsworth et al. (2016) calculated increased annual per hectare production costs for conventional and organic producers by $1,161 and $2,933, respectively.

Since the introduction of *D. suzukii*, many growers have changed part of their pest management programmes from the use of selective insecticides applied in response to pest monitoring and scouting, to calendar spray programmes dominated by the use of broad-spectrum insecticides (Diepenbrock, Rosensteel, Hardin, Sial, & Burrack, 2016; Van Timmeren & Isaacs, 2013). The predominant broad-spectrum insecticides used include pyrethroids and organophosphates by conventional berry growers, whereas spinosad is the most commonly used insecticide by organic berry growers. Insecticidal management of *D. suzukii* is challenging, due to its ability to infest ripening fruit in the weeks preceding harvest (Walsh et al., 2011). Thus, growers are restricted to using insecticides with short pre-harvest intervals (PHIs) to ensure fruit can remain free of infestation and also be harvested when appropriate. If the fruit is destined for export markets, it is also important for growers to meet the maximum residual level (MRL) restrictions of the destination country, which are often much lower than the tolerances for domestic distribution (Haviland & Beers, 2012). As many biopesticides do not have residue restrictions, they can help growers meet these MRL restrictions. In addition to concerns surrounding the MRLs, the selection of additional effective insecticides to be included in a rotation is also important for resistance management. Conventional berry growers have a number of chemical classes to incorporate into spray programmes for management of *D. suzukii* (Bruck et al., 2011; Van Timmeren & Isaacs, 2013). However, organically certified growers have a very limited number of choices, and biopesticides may offer an alternative option for meeting the need for control of this pest while decreasing the risk of resistance and avoiding MRL concerns.

The inclusion of a sugar with insecticide applications to act as a phagostimulant has previously been shown to increase feeding in adult *D. suzukii* (Cowles et al., 2015). This increased feeding is due to drosophilids' instinct to feed on a sweet surface when they contact it, regulated by taste receptor neurons in the legs (Thoma et al., 2016). Cowles et al. (2015) reported a > 50% reduction in larval infestation in strawberries from plots treated with spinosad (Entrust) that included sucrose, relative to fruit in plots treated with only spinosad, in five of six sampling dates.

Various biopesticides have the potential for use against *D. suzukii*. *Chromobacterium subtsugae* is thought to have multiple modes of action, including as a repellent and antifeedant, resulting in reduced fecundity and induced mortality in populations of sucking and chewing insects, flies and mites (Marrone Bio Innovation, 2017; Martin, Gundersen-Rindal, Blackburn, & Buyer, 2007). The sabadilla alkaloids, which are derived from the seed of the sabadilla lily, *Schoenocaulon officinale* (Schlecht.) has a mode of action similar to pyrethrins, resulting in paralysis and later death in susceptible organisms upon contact (Dayan, Cantrell, & Duke, 2009). The combination of pyrethrin and azadirachtin provides different modes of action. Pyrethrins act by blocking voltage-gated sodium channels in nerve axons and result in neurotoxic action and death. The azadirachtin in the mixture is extracted from neem seeds, and the extract has antifeedant activity in some insects (Dayan et al., 2009). In addition to reducing feeding, azadirachtin blocks the synthesis and release of moulting hormones (ecdysteroids) from the prothoracic gland, leading to incomplete ecdysis in immature life stages, and a similar mechanism of action was found to lead to sterility in female insects (Isman, 2006). GS-omega/kappa-Hxtx-Hv1a is derived from the venom of *Hadronyche versuta* Rainbow, a species of funnel-web spider native to Australia. A closely related compound, ω-hexatoxin-Hv1a, also acts by blocking the voltage-gated calcium channels of the target insect and has been shown to be lethal to a wide range of insect species including the common housefly *Musca domestica* L. and the house cricket *Acheta domestica* L. but it does not affect vertebrates (Smith, Herzig, King, & Alewood, 2013).

Given the need for alternative modes of action with activity against *D. suzukii*, the objective of this study was to determine the efficacy of biopesticides for management of spotted wing Drosophila in fall red raspberries. This trial included products that are both approved and not yet approved for use in organic production and not yet labelled for use on berry crops. We also compared some of the treatments with and without corn syrup to determine whether this phagostimulant could enhance the efficacy of these biopesticides.

2 | MATERIALS AND METHODS

2.1 | Field set-up

The experiment was conducted during August and September 2016 in a mature planting of red raspberries, *R. idaeus* L. cvs. Heritage and Caroline, located at the Michigan State University Clarksville Research Center in Clarksville, Michigan. The experiment was laid out in a randomized block design with 10 treatments and four replicates per treatment. Each plot consisted of three rows of raspberries, each 18 metres in length and spaced 3 metres apart, giving a total plot size of 162 m^2. The planting was not irrigated throughout the experiment, and the only other chemical treatments were applications of fungicides, consisting of weekly applications of boscalid (Pristine®, BASF Corp., 406.9 g A.I. ha^{-1}) rotated one of the weeks with iprodione (Rovral®, Bayer Crop Science, 1119.43 g A.I. ha^{-1}), applied to all plants.

2.2 | Experimental treatments

A total of six biopesticides: spinosad (Entrust SC, Dow AgroSciences LLC, Indianapolis, IN), *Chromobacterium subtsugae* (Grandevo WDG, Marrone Bio Innovations, Davis, CA), sabadilla alkaloids (Veratran D, Valent USA. Corporation, Walnut Creek, CA), pyrethrins + azadirachtin (Azera, Valent USA. Corporation, Walnut Creek, CA) and GS-omega/kappa-Hxtx-Hv1a (T-Spear, Vestaron Corporation, Kalamazoo MI) were tested against *D. suzukii*, singly, in rotation or in combination. The insecticides were applied at the manufacturer's maximum label rate, and all label restrictions were adhered to, corn syrup (Gordon Food Service, Wyoming, MI) was added at the rate of 12.5% in some treatments containing a corn syrup adjuvant (Table S1). Treatments were applied using a CO_2-powered backpack sprayer operating at 55 PSI in a volume of water equivalent to 114 litres per hectare and equipped with a single head boom and a TeeJet 8003VS spray nozzle. The spray solution was applied to both sides of the rows separately, and all three rows in the plots were treated with their assigned treatment.

In addition to the insecticide treatments, regular harvesting of all plots was conducted in the first couple of weeks of the experiment to remove overripe fruit from all plots, and this was carried out to reduce the resources for *D. suzukii*. Daily temperature (°C) and precipitation (cm) data were collected for the duration of the study, from the nearest Michigan Agriculture Weather Network site, 375 m from the planting.

2.3 | Sampling procedure

To determine the level of pest pressure across the planting, adult *D. suzukii* were sampled in weeks 1, 3 and 5 of the trial. Traps were constructed using 32 oz. deli cups with entry holes around the top, and each trap was baited with 150 ml of yeast-sugar-water mixture. Traps were placed in each plot suspended from a metal stake using a twist tie and positioned within the canopy at fruit height (approximately 0.75 m). At the end of each of the sample weeks, traps were collected, contents were sieved and then washed over a fine gauze. Trap contents were identified as male or female *D. suzukii*, non-target *Drosophila* or other non-target insects.

Fruit infestation was sampled weekly throughout the experiment. On each sampling date, 20–100 g of randomly selected fruit were sampled from each plot, and infestation was determined using a filter-based salt test (Van Timmeren, Diepenbrock, Bertone, Burrack, & Isaacs, 2017). The volume, number and weight of fruit were recorded for each sample, and fruit was then placed in a 16 oz. deli cup and submerged in a strong salt solution (55.5 g/L). Samples were allowed to soak for a minimum of 1 hr, after which the liquid was passed through a coarse sieve (4 mm) to remove large plant material and further sifted through a reusable coffee filter to trap the larvae. The number of first, second and third instar larvae and pupae of *Drosophila* were counted using a stereomicroscope. Observations of phytotoxicity in the plots were made weekly. However, no phytotoxicity was observed in any treatment.

2.4 | Data analysis

Data for fly capture and larval infestation were log and arcsine transformed, respectively, to meet the assumptions of normality and homogeneity of variances. The transformed data were checked for normality using a Kolmogorov–Smirnov test and Levene's tests were used to assess the homogeneity of variances amongst treatment groups. Data for adult captures and fruit infestation were analysed using a repeated measures ANOVA with week and insecticide treatment included as fixed effects. Replicate was included as a random factor in the model. All analyses were performed using R 3.3.2 (R Core Team, 2016). Repeated measures ANOVA was conducted using the "car" package (Healy, 2005). For each week, treatment differences were assessed using an ANOVA, and treatment differences were separated using Tukey's HSD ($p < .05$). For multiple post hoc comparisons, we used Tukey's HSD pairwise comparison tests with the "multcomp" package (Hothorn, Bretz, & Westfall, 2008). When assessing the effect of insecticide treatments on the composition of larval instars in fruit, first and second instars were combined for analysis because those are typically not detectable in berries. The more detectable and economically important third instars were analysed separately.

3 | RESULTS

3.1 | Fly captures

Captures of adult *D. suzukii* were significantly different over the course of the experiment ($F_{2,87} = 5.37$, $p = .006$), but there was no treatment effect on captures over time ($F_{18,87} = 0.92$, $p = .55$). However, fly captures in plots treated with spinosad had numerically lower captures of *D. suzukii* adults compared to those in the untreated control plots. They also had lower captures than plots treated with pyrethrins + azadirachtin and GS-omega/kappa-Hxtx-Hv1a, both of which had corn syrup added as an adjuvant.

3.2 | Larval infestation

Assessment of *Drosophila* larval infestation in fruit revealed significant differences amongst treatments across the whole experiment ($F_{5,177} = 1.28$, $p < .001$). Treatment differences were most evident in plots starting in week 3 ($F_{9,30} = 3.51$, $p < .01$), with plots treated with spinosad alone having significantly lower infestation than untreated plots. Fruit treated with *C. subtsugae* alone had numerically lower, but not significantly lower, infestation by *Drosophila* larva (Table 1).

In week 4 ($F_{9,30} = 3.31$, $p < .01$) and week 5 ($F_{9,30} = 2.34$, $p < .01$), there continued to be significant differences amongst treatments. In both weeks, plots treated with a rotation of spinosad and *C. subtsugae* had significantly lower infestation than untreated plots, causing a 72.3% and 66.7% reduction in infestation, respectively (Table 1). The inclusion of corn syrup as a phagostimulant had no significant effect on infestation in weeks one to three. In week 4, the insecticide treatments excluding corn syrup as a phagostimulant, spinosad/*C. subtsugae* and spinosad/sabadilla alkaloids had 72% and 79% reduction in infestation, respectively, when compared to untreated control plots.

Treatments of a rotation of spinosad/*C. subtsugae* and spinosad/sabadilla including corn syrup as a phagostimulant had 58% and 62% reduction in infestation, respectively, when compared to untreated control plots. In week 5, only the spinosad/*C. subtsugae* rotation

TABLE 1 Mean (±*SE*) number of *Drosophila* larva per 10 fruit in raspberries treated with 10 different biopesticide treatments, assessed using a modified salt test. Values in a column followed by the same letter are not significantly different ($p > .05$, ANOVA, Tukey's HSD test)

Treatment	Week 0-Baseline Mean ± *SE*	Week 1 Mean ± *SE*	Week 2 Mean ± *SE*	Week 3 Mean ± *SE*	Week 4 Mean ± *SE*	Week 5 Mean ± *SE*
Untreated	35.6 ± 2.31 a	46.8 ± 4.97 a	13.7 ± 2.99 a	23.3 ± 5.39 a	17.3 ± 2.81 a	18.3 ± 2.09 a
Spinosad	35.1 ± 5.26 a	26.9 ± 1.49 b	3.7 ± 1.31 a	7.8 ± 1.44 b	4.8 ± 1.17 b	7.0 ± 2.09 ab
C. subtsugae	35.6 ± 9.99 a	41.6 ± 2.40 ab	8.3 ± 1.39 a	11.1 ± 1.30 ab	9.5 ± 3.45 ab	7.2 ± 1.62 ab
Sabadilla alkaloids	28.3 ± 6.24 a	33.6 ± 2.92 ab	8.6 ± 2.10 a	16.4 ± 2.89 ab	12.3 ± 3.15 ab	8.3 ± 0.98 ab
Spinosad/ *C. subtsugae*	48.2 ± 4.66 a	29.5 ± 2.53 ab	5.8 ± 2.16 a	15.2 ± 2.73 ab	4.8 ± 1.77 b	6.1 ± 2.69 b
Spinosad/Sabadilla alkaloids	31.7 ± 6.57 a	32.3 ± 4.25 ab	4.8 ± 1.12 a	13.9 ± 3.98 ab	5.3 ± 1.48 ab	7.8 ± 2.20 ab
Spinosad/ *C. subtsugae**	37.2 ± 4.16 a	32.0 ± 3.46 ab	5.5 ± 2.11 a	14.6 ± 3.15 ab	7.3 ± 2.33 ab	7.5 ± 1.75 ab
Spinosad/Sabadilla alkaloids*	35.3 ± 9.77 a	33.0 ± 5.51 ab	8.7 ± 4.58 a	21.2 ± 3.73 a	6.6 ± 0.92 ab	12.2 ± 2.30 ab
Pyrethrins + azadirachtin*	34.2 ± 2.95 a	40.7 ± 5.10 ab	10.9 ± 1.82 a	24.8 ± 2.15 a	16.1 ± 3.14 ab	16.5 ± 4.80 ab
GS-omega/kappa-Hxtx-Hv1a*	33.7 ± 7.09 a	42.2 ± 4.33 ab	10.3 ± 1.61 a	18.8 ± 2.46 ab	10.1 ± 2.93 ab	10.5 ± 3.35 ab
Statistics	$F_{9,30} = 0.80$ $p < .05$	$F_{9,30} = 2.90$ $p > .05$	$F_{9,30} = 2.01$ $p < .05$	$F_{9,30} = 3.52$ $p > .01$	$F_{9,30} = 3.31$ $p > .01$	$F_{9,30} = 2.34$ $p > .05$

*Treatment included corn syrup at a rate of 12.5% by volume.

treatment without corn syrup had significantly lower levels of infestation than the other treatments (Table 1).

The effect of insecticide treatments on the different life stages of *Drosophila* infesting fruit was assessed during week 4 of the trial (Figure 1). There was a significant difference amongst the insecticide treatments in the number of first and second instars ($F_{9,30} = 2.95$, $p < .05$) and the third instars ($F_{9,30} = 3.45$, $p < .001$) present in fruit. Raspberries treated with a rotation of spinosad/*C. subtsugae* had significantly fewer first and second instars when compared to the untreated control. The reduction of the third instar in comparison with the untreated control was only significant in plots treated with spinosad only, a rotation of spinosad/sabadilla alkaloids, and the rotation of spinosad/*C. subtsugae* with corn syrup added.

4 | DISCUSSION

The current study highlights a small number of biopesticides with the potential to reduce infestation of *D. suzukii* larvae in raspberries. In addition to spinosad, which had previously been shown to be effective for the control of *D. suzukii* (Van Timmeren & Isaacs, 2013), sabadilla alkaloids and *C. subtsugae* when used in rotation with spinosad both numerically reduced the number of *Drosophila* larvae in raspberry fruit. These results expand the number of biopesticides that are active on this pest and can be used for its control within seasonal pest management programmes. There are restrictions on the seasonal limit of spinosad (Entrust SC) for use in fruit crops and directions on the label to rotate to a different chemical class after two applications with this insecticide. This is driven by concerns over the development of resistance amongst *D. suzukii* populations, highlighting the need for selection of effective insecticides to be included in rotation with spinosad. The efficacy of *C. subtsugae* reported here was greatest when included in a rotation with spinosad. Plots treated with this insecticide rotated with *C. subtsugae* had the lowest infestation of all treatments by the end of the experiment, including those treated only with spinosad, indicating that this can be an effective rotation partner. The lack of efficacy observed by GS-omega/kappa-Hxtx-Hv1a and the combination of pyrethrins and azadirachtin indicate that these are not effective for rotation with spinosad against this pest.

The effects of rainfall on the efficacy of treatments were not directly quantified in this experiment. However, rainfall, particularly in the first week of the experiment did coincide with the poor efficacy of insecticides as seen in the consistently high infestation in fruit. The efficacy of spinosad was previously shown to be significantly reduced by simulated rainfall between 12.5 and 25 mm (Gautam et al., 2016). Effective insecticide treatments in this experiment significantly reduced the number of larvae in infested fruit, with some treatments reducing the number of third instar larvae of *D. suzukii* in fruit. Post-harvest cold storage has also been shown to effectively reduce the survival of eggs and second instar larvae infesting raspberries (Aly, Kraus, & Burrack, 2017). Studies by Aly et al. (2017) highlighted differences in survival amongst different larval instar of *D. suzukii* in response to cold storage, with high survival especially third instar larvae in raspberries and blueberry. Therefore, treatments such as spinosad/*C. subtsugae* which reduced larger larva might in combination with post-harvest cold storage effectively reduce the risk of detectable larvae developing in fruit.

The two biopesticides with some efficacy against *D. suzukii* have previously been shown to control a wide range of other insects. The activity of *Chromobacterium subtsugae* has been studied on a number of pest species and has been shown to increase mortality in adults of the Southern green stink bug, *Nezara viridula* L., nymph and adult sweet potato whitefly, *Bemisia tabaci* Gennadius; larval and adult Southern corn rootworm, *Diabrotica undecimpunctata* L., Western corn rootworm *Diabrotica virgifera* LeConte and the Colorado potato beetle, *Leptinotarsa decemlineata* (Say) (Martin et al., 2007). In addition to increasing mortality of adults, *Chromobacterium subtsugae* has been

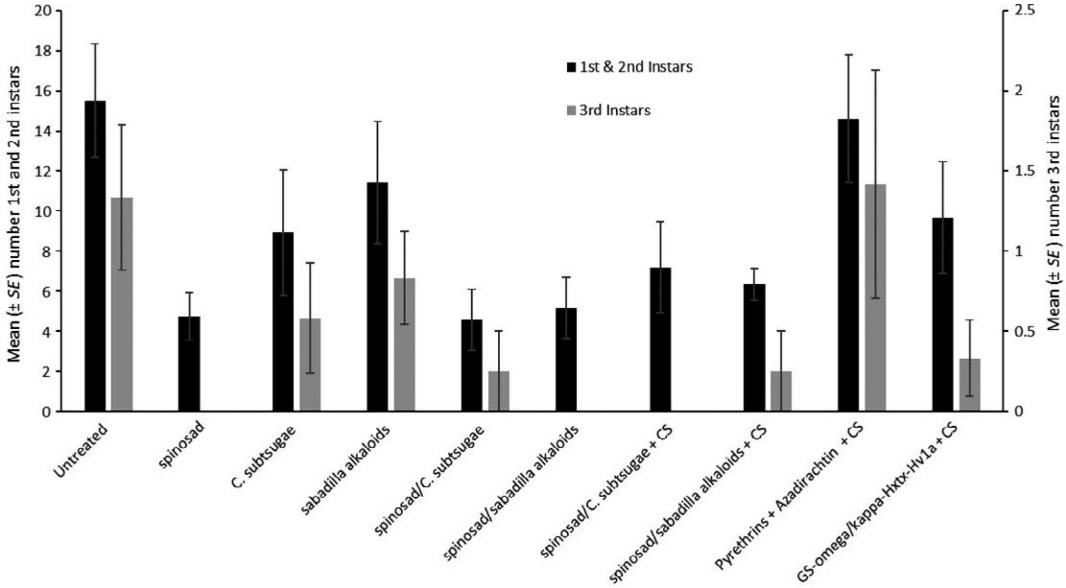

FIGURE 1 Mean (±*SE*) number of larval instars of *Drosophila* per 10 fruit in raspberries treated with 10 different biopesticide treatments, assessed using a modified salt test. Bars within the same series headed with the same letter are not significantly different (Tukey's HSD, $p < .05$)

shown to inhibit feeding by larvae of *D. undecimpunctata* and *L. decemlineata* (Martin, Blackburn, & Shropshire, 2004; Martin et al., 2007). Additionally, Kivett, Cloyd, and Bello (2015) have found suppression of Western flower thrips, *Frankliniella occidentalis* Pergande, in glasshouse experiments with this insecticide. Sabadilla alkaloids, which are not yet labelled on fruit crops, have been shown to be effective in a spray programme for the control of pests of broccoli including swede midge, *Contarinia nasturtii* (Keiffer), diamondback moth, *Plutella xylostella* L. and imported cabbageworm, *Pieris rapae* L., significantly reducing damage in broccoli *Brassica oleracea* var. italica when compared to untreated plants (Seaman, Lange, & Shelton, 2015). The other insecticide tested in the current study sabadilla alkaloids, resulted in numerical but not significantly lower infestation in the fruit. These insecticides might benefit from the inclusion of a spray adjuvant or changes in the current formulation. In the case of GS-omega/kappa-Hxtx-Hv1a, a new liquid formulation is due to be released shortly which may increase effectiveness of the product for control of *D. suzukii*. Spinosad targets binding sites on nicotinic acetylcholine receptors that are distinct from those at which other insecticides exert their activity, leading to disruption of acetylcholine neurotransmission (Sparks, Crouse, & Durst, 2001). The results of the current study highlight two insecticides with different modes of action to spinosad, which can be used as rotational products for resistance management.

The inclusion of a sweetener as a phagostimulant, such as sucrose, has previously been shown to increase the uptake of insecticides (Cowles et al., 2015; Knight, Basoalto, Yee, Hilton, & Kurtzman, 2015); however, in the current study, no benefit of corn syrup was observed on the numbers of *D. suzukii* captured in traps or in the number of *Drosophila* larva in fruit. The reasons for the failure of the inclusion of phagostimulant to reduce infections by *D. suzukii* in this study are unknown; however, the effect of environmental factors such as humidity or the availability of alternative food resources in untreated plots or adjacent to treated plots was not empirically quantified but may result in the reduced efficacy of corn syrup observed in this instance.

Exports of cane berries including raspberries, blackberries, mulberries and loganberries were worth $191 million in 2014, with 90% of these exports from California (Agricultural Issues Center, 2014). Of all Californian exports of cane berries, 85% were to the Canadian market, while the second largest market was Japan at 6%. Spinosad and pyrethrins are the only two active ingredients in the current study to have to establish MRLs, both of which are 1 ppm for the United States and Japan; however, in the case of Canada, pyrethrins have a 1 ppm rate, but spinosad has a lower 0.5 ppm rate (Global MRL, 2017). The other insecticides in this study do not have established MRLs and thus may be valuable for maintaining the residue levels below MRLs for export, particularly *C. subtsugae* which had the lowest infestation when rotated with spinosad.

Recent studies by Leach, Moses, Hanson, Fanning, and Isaacs (2017) have shown that increasing the frequency of harvesting fall red raspberries leads to a reduction in the infestation. In the current study, plots were regularly harvested to remove overripe fruit which can act as a resource for *D. suzukii*. However, to increase the frequency of harvest and maintain a chemical control programme for *D. suzukii* and other pests, products need to be selected with a short PHI. The longest PHI of the insecticides used in this study was spinosad, which has a 1 day PHI, all of the other insecticides tested are no PHI restrictions, with the exception of the sabadilla alkaloids which have no label on caneberries.

5 | CONCLUSION

The current study highlights a number of different biopesticides as rotational products with spinosad for the control of *D. suzukii*. The biopesticides have active ingredients with different modes of action from the current standard of spinosad. Two of these biopesticides, *C. subtsugae* and sabadilla alkaloids, could be important rotational products, to support resistance management and enhance the potential for exporting berries.

ACKNOWLEDGEMENTS

The authors would like to thank the staff at Clarksville Research Center for maintaining the raspberry plantation and the many volunteers from the Isaacs lab for helping with harvesting fruit. Funding for this study was provided by a USDA-NIFA: IR-4 Minor Pest Crop Management Program grant (2015-34383-23710).

AUTHOR CONTRIBUTION

PF, MG and RI, planned experimental design. PF conducted the experiments, statistical analysis and wrote the Manuscript. All authors contributed to the critical evaluation of the manuscript and read and approved it.

ORCID

P. D. Fanning http://orcid.org/0000-0002-6074-0778

REFERENCES

Agricultural Issues Center, California Export Data (2014). University of California. Retrieved from http://aic.ucdavis.edu/pub/exports.html

Aly, M. F., Kraus, D. A., & Burrack, H. J. (2017). Effects of postharvest cold storage on the development and survival of immature *Drosophila suzukii* (Diptera: Drosophilidae) in artificial diet and fruit. *Journal of Economic Entomology*, *110*, 87–93.

Asplen, M. K., Anfora, G., Biondi, A., Choi, D. S., Chu, D., Daane, K. M., … Isaacs, R. (2015). Invasion biology of spotted wing Drosophila (*Drosophila suzukii*): A global perspective and future priorities. *Journal of Pest Science*, *3*, 469–494.

Bolda, M. P., Goodhue, R. E., & Zalom, F. G. (2010). Spotted wing drosophila: Potential economic impact of a newly established pest. *Agric Resour Econom Update*, *13*, 5–8.

Bruck, D. J., Bolda, M. P., Tanigoshi, L., Klick, J., Kleiber, J., DeFrancesco, J., … Spitler, H. (2011). Laboratory and field comparisons of insecticides to reduce infestation of *Drosophila suzukii* in berry crops. *Pest Management Science*, *67*, 1375–1385.

Cini, A., Anfora, G., Escudero-Colomar, L. A., Grassi, A., Santosuosso, U., Seljak, G., & Papini, A. (2014). Tracking the invasion of the alien fruit pest *Drosophila suzukii* in Europe. *Journal of Pest Science*, *87*, 559–566.

Copping, L. G., & Menn, J. J. (2000). Biopesticides: A review of their action, applications and efficacy. *Pest Management Science*, *56*, 651–676.

Cowles, R. S., Rodriguez-Saona, C., Holdcraft, R., Loeb, G. M., Elsensohn, J. E., & Hesler, S. P. (2015). Sucrose improves insecticide activity against *Drosophila suzukii* (Diptera: Drosophilidae). *Journal of Economic Entomology*, *108*, 640–653.

Dayan, F. E., Cantrell, C. L., & Duke, S. O. (2009). Natural products in crop protection. *Bioorganic & Medicinal Chemistry Letters*, *17*, 4022–4034.

Diepenbrock, L. M., Rosensteel, D. O., Hardin, J. A., Sial, A. A., & Burrack, H. J. (2016). Season-long programs for control of *Drosophila suzukii* in southeastern U.S. blueberries. *Crop Protection*, *81*, 76–84.

Farnsworth, D., Hamby, K., Bolda, M. P., Goodhue, R., Williams, J., & Zalom, F. G. (2016). Economic analysis of revenue losses and control costs associated with the spotted wing drosophila (*Drosophila suzukii* (Matsumura)) in the california raspberry industry. *Pest Management Science*, *73*, 1083–1090.

Gautam, B. K., Little, B. A., Taylor, M. D., Jacobs, J. L., Lovett, W. E., Holland, R. M., & Sial, A. A. (2016). Effect of simulated rainfall on the effectiveness of insecticides against spotted wing drosophila in blueberries. *Crop Protection*, *81*, 122–128.

Global M.R.L., (2017). Global Maximum Residue Level database [WWW document]. Retrieved from https://globalmrl.com/

Haviland, D. R., & Beers, E. H. (2012). Chemical control programs for *Drosophila suzukii* that comply with international limitations on pesticide residues for exported sweet cherries. *Journal of Integrated Pest Management*, *3*, 1–6.

Healy, K. (2005). Book review: An R and S-plus companion to applied regression. *Sociological Methods & Research*, *34*, 137–140.

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in general parametric models. *Biometrical Journal*, *50*, 346–363.

Isman, M. B. (2006). Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annual Review of Entomology*, *51*, 45–66.

Kivett, J. M., Cloyd, R. A., & Bello, N. M. (2015). Insecticide rotation programs with entomopathogenic organisms for suppression of western flower thrips (thysanoptera: Thripidae) adult populations under greenhouse conditions. *Journal of Economic Entomology*, *108*, 1936–1946.

Knight, A. L., Basoalto, E., Yee, W., Hilton, R., & Kurtzman, C. P. (2015). Adding yeasts with sugar to increase the number of effective insecticide classes to manage *Drosophila suzukii* (Matsumura)(diptera: Drosophilidae) in cherry. *Pest Management Science*, *72*, 1482–1490.

Leach, H., Moses, J., Hanson, E., Fanning, P. D., & Isaacs, R. (2017). Rapid harvest schedules and fruit removal as non-chemical approaches for managing spotted wing Drosophila. *Journal of Pest Science*, https://doi.org/10.1007/s10340-017-0873-9

Marrone Bio Innovation, (2017). Grandevo product information.

Martin, P. A., Blackburn, M., & Shropshire, A. D. (2004). Two new bacterial pathogens of colorado potato beetle (coleoptera: Chrysomelidae). *Journal of Economic Entomology*, *97*, 774–780.

Martin, P. A., Gundersen-Rindal, D., Blackburn, M., & Buyer, J. (2007). *Chromobacterium subtsugae* sp. Nov., a betaproteobacterium toxic to Colorado potato beetle and other insect pests. *International Journal of Systematic and Evolutionary Microbiology*, *57*, 993–999.

Mazid, S., Kalida, J., & Rajkhowa, R. C. (2011). A review on the use of biopesticides in insect pest management. *International Journal of Science and Advanced Technology*, *1*, 169–178.

Pfeiffer, D. G., Leskey, T. C., & Burrack, H. J. (2012). Threatening the harvest: The threat from three invasive insects in late season vineyards. In N. Bostanian, C. Vincent, & R. Isaacs (Eds.), *Arthropod management in vineyards* (pp. 449–474). Dordrecht, the Netherlands: Springer.

R Core Team (2016). *R: A language and environment for statistical computing*. Vienna, Austria: R foundation for statistical computing. https://www.R-project.Org/.

Seaman, A. J., Lange, H. W., & Shelton, A. M. (2015). Swede midge, diamondback moth, and imported cabbageworm control with insecticides allowed for organic production, 2014. *Arthropod Management Tests*, *40*, E48.

Senthil-Nathan, S. (2015). A review of biopesticides and their mode of action against insect pests. In P. Thangavel & G. Sridevi (Ed.), *Environmental sustainability* (pp. 49–63). New Delhi: Springer.

Smith, J. J., Herzig, V., King, G. F., & Alewood, P. F. (2013). The insecticidal potential of venom peptides. *Cellular and Molecular Life Sciences*, *70*, 3665–3693.

Sparks, T. C., Crouse, G. D., & Durst, G. (2001). Natural products as insecticides: The biology, biochemistry and quantitative structure–activity relationships of spinosyns and spinosoids. *Pest Management Science*, *57*, 896–905.

Thoma, V., Knapek, S., Arai, S., Hartl, M., Kohsaka, H., Sirigrivatanawong, P., … Tanimoto, H. (2016). Functional dissociation in sweet taste receptor neurons between and within taste organs of Drosophila. *Nature Communications*, *7*, 10678.

Van Timmeren, S., & Isaacs, R. (2013). Control of spotted wing drosophila, *Drosophila suzukii*, by specific insecticides and by conventional and organic crop protection programs. *Crop Protection*, *54*, 126–133.

Van Timmeren, S., Diepenbrock, L. M., Bertone, M. A., Burrack, H. J. & Isaacs, R. (2017). A filter method for improved monitoring of drosophila suzukii (diptera: Drosophilidae) larvae in fruit. *Journal of Integrated Pest Management*, *8*, 23–23.

Walsh, D. B., Bolda, M. P., Goodhue, R. E., Dreves, A. J., Lee, J., Bruck, D. J., … Zalom, F. G. (2011). *Drosophila suzukii* (diptera: Drosophilidae): Invasive pest of ripening soft fruit expanding its geographic range and damage potential. *Journal of Integrated Pest Management*, *2*, G1–G7.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Fanning PD, Grieshop MJ, Isaacs R. Efficacy of biopesticides on spotted wing drosophila, *Drosophila suzukii* Matsumura in fall red raspberries. *J Appl Entomol*. 2017;00:1–7. https://doi.org/10.1111/jen.12462