Effects of Spray Volume and Application Frequency on Insecticide Efficacy Against Adult Western Flower Thrips (*Frankliniella Occidentalis*) under Greenhouse Conditions

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Abstract. The western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is a major insect pest of greenhouse-grown horticultural crops. Western flower thrips causes direct and indirect damage by feeding on plant leaves, flowers, and fruits, and by transmitting viruses that can result in greenhouse producers experiencing substantial economic losses. Consequently, insecticides are used to suppress western flower thrips populations. However, issues associated with applying insecticides may affect the suppression of western flower thrips populations. Therefore, experiments were conducted under greenhouse conditions to determine the effects of the spray volume applied and application frequency on insecticide efficacy against western flower thrips adults located in transvaal daisy, *Gerbera jamesonii*, cut flowers. Four spray volumes (5.0, 10.0, 12.5, and 25.0 mL), two application frequencies (one or two spray applications), and three insecticides [spinosad (Conserve), chlorfenapyr (Pylon), and flonicamid (Aria)], each with a different mode of action, were tested. The insecticide treatments had the greatest effects on the mean percent mortality of western flower thrips adults regardless of spray volume or application frequency. However, in Expt. 3, the 5.0- and 10.0-mL spray volumes resulted in a higher mean percent mortality of western flower thrips adults than the 2.5-mL spray volume. Spinosad and chlorfenapyr resulted in a mean percent mortality of more than 72% for western flower thrips adults, whereas flonicamid resulted in mean percent mortality between 40% and 91%. Our study demonstrates that certain insecticides are more effective against western flower thrips adults located in transvaal daisy flowers than others, which will help greenhouse producers effectively manage western flower thrips populations.

Western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is an insect pest of horticultural crops worldwide (Cloyd, 2009; Kirk, 2002; Moudén et al., 2017; Reitz, 2009; Robb and Parrella, 1995). Western flower thrips feeds

on more than 250 plant species within 60 different families (Tommasini and Maini, 1995). Their feeding is associated with direct and indirect damage (Allen and Broadbent, 1986; Chisholm and Lewis, 1984; Harrewijn et al., 1996; Pappu et al., 2009). Adults and larvae cause direct damage by feeding on plants using their piercing-sucking mouthparts (Harrewijn et al., 1996; Hunter and Ullman, 1989). Direct damage is associated with leaf, flower, and fruit scarring, distortion and discoloration of flowers, fruit deformation, sunken leaf tissues, and a characteristic “silvering” of leaves and flowers (Childers, 1997; Chisholm and Lewis, 1984; Cloyd, 2009; van Dijken et al., 1994). Indirect damage is associated with adults vectoring the tospoviruses, *Tomato spotted wilt virus* and *Impatiens necrotic spot virus* (Allen and Broadbent, 1986; Daughtrey et al., 1997; Kirk, 2002; Mound, 1995; Pappu et al., 2009). Direct and indirect damage can result in substantial economic losses for producers of greenhouse-grown horticultural crops (Goldbach and Peters, 1994; Reitz and Funderburk, 2012).

Insecticides are commonly used to suppress western flower thrips populations because greenhouse producers have minimal tolerance for any damage to leaves or flowers (Cloyd, 2009; Kontsedalov et al., 1998; Loughner et al., 2005; Moudén et al., 2017; Osborne and Oetting, 1989; Reitz and Funderburk, 2012). However, several factors can influence the effectiveness of insecticide applications, including spray coverage (Dibble, 1962; Martini et al., 2012; McClure, 1977; Shelton et al., 2003, 2006; Tipping et al., 2003), application frequency (Ajeigbe and Singh, 2006; Story and Sundstrom, 1986), and insecticide resistance (Bielza et al., 2007; Cloyd, 2016; Immaraju et al., 1992; Jensen, 2000; Loughner et al., 2005; Zhao et al., 1995). The failure of insecticides to suppress western flower thrips populations may be associated with insecticide resistance; however, application factors, such as spray coverage and application frequency, may also influence the suppression of western flower thrips populations (Cloyd, 2016; Shelton et al., 2006).

Despite the importance of application factors, no greenhouse studies have been conducted to assess the effects of spray volume (which is associated with the coverage of plant parts—leaves, stems, and flowers) and application frequency of insecticides against western flower thrips. Therefore, the objective of our study was to determine if spray volume and application frequency affect the efficacy of insecticides against western flower thrips adults (based on the percent mortality) located in transvaal daisy flowers by conducting a series of controlled greenhouse experiments.

Materials and Methods

Western flower thrips colony

A laboratory colony of western flower thrips has been maintained for more than 10 years inside Glad (The Glad Products Company, Oakland, CA) plastic containers [20.4 × 14.4 × 9.4 cm (length × width × height)] with No-Thrips insect screening (mesh = 150 × 150 µm: Green-Tek Inc., Janesville, WI) at 24 to 27 °C, 50% to 60% relative humidity, and constant light in a laboratory of the Department of Entomology at Kansas State University (Manhattan, KS). Green bean (*Phaseolus vulgaris*) pods, purchased from a local supermarket, were changed every 2 to 3 d. The green bean pods served as a food source for western flower thrips larvae and adults and as oviposition sites for adult females. Bee pollen (Prairie Harvest; Kansas Wildflower Pollen, Wilson, KS) was also provided as a food source for the larvae and adults. Specimens used in the research are deposited as voucher number 262 at the Kansas State University Museum of Entomological and Prairie Arthropod Research (Manhattan, KS).

Plant material and procedures

Yellow transvaal daisy, *Gerbera jamesonii*, cut flowers were obtained from a wholesale broker (Koehler & Dramm of Missouri,

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Fig. 1. Pooled mean ($\pm$ SEM) percent mortality of adult western flower thrips, *Frankliniella occidentalis*, in Expt. 1 after exposure to one and two spray applications at 25.0 mL of spray solution per cut flower of transvaal daisy, *Gerbera jamesonii*, associated with the following treatments: 1) spinosad (Conserve) at 0.81 mL/946 mL ($n = 132$); 2) chlorfenapyr (Pylon) at 0.38 mL/946 mL ($n = 181$); 3) flonicamid (Aria) at 0.15 g/946 mL ($n = 129$); and 4) water control ($n = 150$). Means followed by the same letter are not significantly different ($P > 0.05$) based on Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

Kansas City, MO) and used in a series of greenhouse experiments conducted from Apr. 2019 through Feb. 2020. The experiments tested the effects of spray volume and application frequency on insecticide efficacy associated with western flower thrips adults. No pesticides were applied to the cut flowers before receipt; therefore, pesticide residues did not affect the survival of western flower thrips adults. Transvaal daisy has been used as a model host flower in previous studies (Cloyd and Raudenbush, 2014; Willmott et al., 2013) due to their susceptibility to western flower thrips (Daughtrey et al., 1997), and because the disc florets provide a natural habitat for western flower thrips (Cloyd, 2009). Individual transvaal daisy cut flowers can be isolated from other cut flowers to avoid cross-contamination among experimental units. In addition, western flower thrips adults do not leave after they are established in the cut flowers (Cloyd and Gillespie, 2012; Willmott et al., 2013).

After arrival, flower stems were excised 5 to 6 cm below the base of the flower and placed into 22-mm borosilicate glass vials (Research Products International Corp., Mt. Prospect, IL) containing tap water. The glass vials were inserted in 250-mL plastic containers with sand (Quikrete Premium Play Sand). The sand inside the plastic container held the glass vial with tap water in an upright position throughout the course of each ex-

periment. One transvaal daisy cut flower was placed in each glass vial containing tap water. All plastic containers with cut flowers inside the glass vials were positioned on a wire-mesh bench in a research greenhouse under a 50% black knit shade cloth (Hummert International, Earth City, MO) held in place by an open frame composed of polyvinyl chloride piping. The black knit shade cloth helped preserve the longevity of the cut flowers by protecting them from direct sunlight. Plastic containers holding a cut flower were placed at least 20 cm apart from each other on the wire-mesh bench to further mitigate the possibility of western flower thrips adults moving among the cut flowers. The glass vials holding the cut flowers were filled with tap water as needed for each experiment.

For all experiments, each cut flower was artificially infested with 15 to 20 western flower thrips adults (between 16 and 25 d post-eclosion) obtained from the laboratory colony. Western flower thrips adults were aspirated into 9-dram (33 mL) plastic vials. Each plastic vial was placed above the center of a transvaal daisy cut flower and lightly tapped until all the adults were dispersed on the cut flower. Western flower thrips adults were allowed to acclimate for 1 to 2 d before the designated treatments were applied to the cut flowers. Environmental conditions inside the greenhouse for all experiments were 22 to

24 °C, relative humidity between 60% and 70%, and natural daylight.

All insecticide treatments were mixed in 946 mL of tap water, and spray applications were performed for all cut flowers using a 946-mL plastic spray bottle (Spraymaster; Delta Industries, King of Prussia, PA). Experiments were conducted to evaluate spray volume, with one spray application of the designated treatment to each cut flower, and the effect of application frequency (one or two spray applications using a consistent spray volume). All cut flowers were treated with the spray nozzle $\approx$ 25 cm away from the top of each cut flower.

For all experiments, there were four treatments including three insecticides registered for and commonly used against western flower thrips in greenhouses and a water control. Experiments were set up as a completely randomized design. One transvaal daisy cut flower was considered an experimental unit. The three insecticides and application rates were as follows: spinosad (Conserve SC; Dow AgroSciences LLC, Indianapolis, IN) at 11.0 fl oz/100 gallons (0.81 mL/946 mL); chlorfenapyr (Pylon; BASF Corp., Research Triangle Park, NC) at 5.2 fl oz/100 gallons (0.38 mL/946 mL); and flonicamid (Aria; FMC Corporation, Philadelphia, PA) at 2.1 oz/100 gallons (0.15 g/946 mL). Each insecticide has a different mode of action (Insecticide Resistance Action Committee, 2019).

In the spray volume experiments, all cut flowers were treated on the same day. At 4 or 5 d after the treatments were applied, the cut flowers were harvested and placed in plastic petri dishes (diameter, 14 cm) with lids and then destructively sampled under laboratory conditions. Each cut flower was destructively sampled over a 22- × 28-cm white piece of paper. The numbers of live, dead, and total western flower thrips adults associated with each cut flower were recorded. Western flower thrips adults that moved across the paper were counted as live, whereas adults that did not move were counted as dead. The percent mortality was calculated by dividing the number of dead western flower thrips adults by the total number recovered from each cut flower and multiplying by 100.

In the application frequency experiments, all cut flowers were treated on the same day. At 4 or 5 d after the first spray application, cut flowers designated to receive one spray application were harvested and placed in plastic petri dishes (14 cm diameter) with lids and destructively sampled under laboratory conditions, and the numbers of live, dead, and total western flower thrips adults associated with each cut flower were recorded. Afterward, cut flowers designated to receive two spray applications were treated a second time. At 4 or 5 d after the second spray application, the numbers of live, dead, and total western flower thrips adults associated with the remaining cut flowers were recorded. The percent mortality was calculated by dividing the number of dead western flower

Fig. 2. Pooled mean ($\pm$ SEM) percent mortality of adult western flower thrips, *Frankliniella occidentalis*, in Expt. 2 after exposure to one spray application and three spray volumes of 5.0, 12.5, and 25.0 mL per cut flower of transvaal daisy, *Gerbera jamesonii*, associated with the following treatments: 1) spinosad (Conserve) at 0.81 mL/946 mL ($n = 105$); 2) chlorfenapyr (Pylon) at 0.38 mL/946 mL ($n = 104$); 3) flonicamid (Aria) at 0.15 g/946 mL ($n = 64$); and 4) water control ($n = 96$). Means followed by the same letter are not significantly different ($P > 0.05$) based on Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

Fig. 3. Pooled mean ($\pm$ SEM) percent mortality of adult western flower thrips, *Frankliniella occidentalis*, in Expt. 3 after exposure to one spray application at spray volumes of 2.5, 5.0, and 10.0 mL per cut flower of transvaal daisy, *Gerbera jamesonii*, associated with the following treatments: 1) spinosad (Conserve) at 0.81 mL/946 mL ($n = 212$); 2) chlorfenapyr (Pylon) at 0.38 mL/946 mL ($n = 231$); 3) flonicamid (Aria) at 0.15 g/946 mL ($n = 162$); and 4) water control ($n = 287$). Means followed by the same letter are not significantly different ($P > 0.05$) based on a Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

thrips adults by the total number recovered from each cut flower and multiplying by 100.

Expt. 1: Effect of application frequency on western flower thrips adults in transvaal daisy cut flowers. There were five replicates per treatment combination for a total of 40 experimental units (cut flowers). Cut flowers were exposed to one or two spray applications using a spray volume of 25.0 mL per cut flower for each spray application. All cut flowers were initially treated; then, those cut flowers designated to receive one spray application were destructively sampled after 5 d. The cut flowers designated to receive two spray applications were treated a second time; then, they were destructively sampled 5 d later.

Expt. 2: Effect of spray volume on western flower thrips adults in transvaal daisy cut flowers. There were five replicates per treatment combination for a total of 60 experimental units (cut flowers). Three different spray volumes were used: 5.0, 12.5, and 25.0 mL per cut flower. Each cut flower was treated once; then, all cut flowers were destructively sampled after 5 d.

Expt. 3: Effect of spray volume on western flower thrips adults in transvaal daisy cut flowers. There were four replicates per treatment combination for a total of 48 experimental units (cut flowers). Four replicates were used instead of five because of the limited number of western flower thrips adults available from the laboratory colony (900 western flower thrips adults needed for five replicates compared with 720 western flower thrips adults needed for four replicates). Three different spray volumes were used: 2.5, 5.0, and 10.0 mL per cut flower. Lower spray volumes were used based on 100% mortality of western flower thrips adults associated with the spinosad and chlorfenapyr treatments in Expt. 2. Treatments were applied once to each cut flower; then, the cut flowers were destructively sampled after 4 d.

Expt. 4: Effect of application frequency on western flower thrips adults in transvaal daisy cut flowers. There were five replicates per treatment combination for a total of 40 experimental units (cut flowers). A spray volume of 5.0 mL per cut flower was used for each spray application based on 100% mortality of western flower thrips adults for the spinosad and chlorfenapyr treatments in Expt. 1. All cut flowers were initially treated with the first spray application; then, the cut flowers that received one spray application were destructively sampled after 4 d. The cut flowers designated to receive two spray applications were treated a second time; then, they were destructively sampled after 4 d.

Expt. 5: Effect of spray volume on western flower thrips adults in transvaal daisy cut flowers. There were four replicates per treatment combination for a total of 48 experimental units (cut flowers). Three different spray volumes were used: 2.5, 5.0, and 10.0 mL per cut flower. The treatments were applied once to all cut flowers; then, the cut flowers were destructively sampled after 4 d.

Expt. 6: Effect of application frequency on western flower thrips adults in transvaal

Fig. 4. Pooled mean ($\pm$ SEM) percent mortality of adult western flower thrips, *Frankliniella occidentalis*, in Expt. 3 after exposure to one spray application of spinosad (Conserve) at 0.81 mL/946 mL, chlorfenapyr (Pylon) at 0.38 mL/946 mL, flonicamid (Aria) at 0.15 g/946 mL, and a water control at spray volumes of 2.5 ($n = 327$), 5.0 ($n = 270$), or 10.0 mL ($n = 295$) per cut flower of transvaal daisy, *Gerbera jamesonii*. Means followed by the same letter are not significantly different ($P > 0.05$) based on Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

daisy cut flowers. There were five replicates per treatment combination for a total of 40 experimental units (cut flowers). Each treatment was applied at a spray volume of 5.0 mL per cut flower, which was the same spray volume used in Expt. 4. All cut flowers were initially treated; then, those cut flowers designated to receive one spray application were destructively sampled after 4 d. The cut flowers designated to receive two spray applications were treated a second time; then, the cut flowers were destructively sampled after 4 d.

Statistical analysis

There were two factors for each experiment: treatment (four levels) and spray volume (three levels) or application frequency (two levels). The percent mortality estimates of western flower thrips adults were subjected to a two-way analysis of variance with treatment and spray volume or application frequency as the main effects. Data were analyzed using PROC GLIMMIX in a SAS software program (SAS Institute, 2012); significant treatment means were separated using Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$. Pairwise comparisons were conducted using Tukey's HSD adjustment to avoid type I error rate inflation.

Results

Expt. 1: Effect of application frequency on western flower thrips adults in transvaal

daisy cut flowers. The number of spray applications (one or two) at 25.0 mL did not significantly affect the mean percent mortality of western flower thrips adults ($P > 0.05$). Consequently, the data were pooled within treatment for further analysis. There was a significant treatment effect on the mean percent mortality of western flower thrips adults ($F = 220.27$; $df = 3, 31$; $P < 0.0001$), whereby all three insecticide treatments resulted in percent mortality of more than 90% for western flower thrips adults. The mean percent mortality of western flower thrips associated with the insecticide treatments was significantly higher than the water control, but there were no significant differences among the three insecticide treatments (Fig. 1).

Expt. 2: Effect of spray volume on western flower thrips adults in transvaal daisy cut flowers. The spray volume (5.0, 12.5, or 25.0 mL) did not significantly affect the mean percent mortality of western flower thrips adults ($P > 0.05$). Consequently, the data were pooled within treatment for further analysis. There was a significant treatment effect on the mean percent mortality of western flower thrips adults ($F = 74.55$; $df = 3, 50$; $P < 0.0001$), whereby the spinosad and chlorfenapyr treatments resulted in percent mortality of more than 90% for western flower thrips adults. The mean percent mortality of western flower thrips adults for flonicamid was significantly lower at $\approx 60\%$.

The mean percent mortality of western flower thrips adults associated with the three insecticide treatments was significantly higher than the water control (Fig. 2).

Expt. 3: Effect of spray volume on western flower thrips adults in transvaal daisy cut flowers. There was a significant treatment effect ($F = 105.95$; $df = 3, 33$; $P < 0.0001$) and a significant effect of spray volume [2.5, 5.0, or 10.0 mL ($F = 11.28$; $df = 2, 33$; $P = 0.0002$)] associated with the mean percent mortality of western flower thrips adults. Consequently, the data were pooled within treatment and spray volume because the two-way interaction between treatment and spray volume was not significant ($P > 0.05$). Spinosad resulted in the highest mean percent mortality for western flower thrips adults, followed by chlorfenapyr and flonicamid (Fig. 3). The mean percent mortality of western flower thrips adults associated with the three insecticide treatments was significantly higher than the water control (Fig. 3). In addition, the 5.0- and 10.0-mL spray volumes resulted in a significantly higher mean percent mortality for western flower thrips adults than the 2.5-mL spray volume (Fig. 4).

Expt. 4: Effect of application frequency on western flower thrips adults in transvaal daisy cut flowers. There was a significant treatment effect ($F = 245.68$; $df = 3, 28$; $P < 0.0001$) as well as a significant effect of the number of applications at 5.0 mL [one or two applications ($F = 23.52$; $df = 1, 28$; $P < 0.0001$)] associated with mean percent mortality of western flower thrips adults. Consequently, the data were pooled within treatment and number of applications because the two-way interaction between treatment and number of applications was not significant ($P > 0.05$).

Spinosad resulted in a significantly higher mean percent mortality of western flower thrips adults than flonicamid, but was not higher than that of chlorfenapyr. Chlorfenapyr was not significantly different from spinosad and flonicamid (Fig. 5). The mean percent mortality of western flower thrips adults associated with the three insecticide treatments was significantly higher than the water control (Fig. 5). Furthermore, two spray applications ($82.5\% \pm 6.3\%$; $n = 208$) induced a significantly higher mean percent mortality of western flower thrips adults than one spray application ($72.0\% \pm 7.5\%$; $n = 330$).

Expt. 5: Effect of spray volume on western flower thrips adults in transvaal daisy cut flowers. The spray volume (2.5, 5.0, or 10.0 mL) did not significantly affect the mean percent mortality of western flower thrips adults ($P > 0.05$). Consequently, the data were pooled within treatment for further analysis. There was a significant treatment effect on the mean percent mortality of western flower thrips adults ($F = 128.6$; $df = 3, 33$; $P < 0.0001$), with the spinosad and chlorfenapyr treatments resulting in western flower thrips adult mortality of more than 88%. The mean percent mortality of western flower thrips adults for flonicamid was

Fig. 5. Pooled mean ($\pm$ SEM) percent adult mortality of western flower thrips, *Frankliniella occidentalis*, in Expt. 4 after exposure to one and two spray applications at 5.0 mL of spray solution per cut flower of transvaal daisy, *Gerbera jamesonii*, associated with the following treatments: 1) spinosad (Conserve) at 0.81 mL/946 mL ($n = 136$); 2) chlorfenapyr (Pylon) at 0.38 mL/946 mL ($n = 172$); 3) flonicamid (Aria) at 0.15 g/946 mL ($n = 126$); and 4) water control ($n = 104$). Means followed by the same letter are not significantly different ($P > 0.05$) based on Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

Fig. 6. Pooled mean ($\pm$ SEM) percent mortality of adult western flower thrips, *Frankliniella occidentalis*, in Expt. 5 after exposure to one spray application and three spray volumes of 2.5, 5.0, and 10.0 mL per cut flower of transvaal daisy, *Gerbera jamesonii*, associated with the following treatments: 1) spinosad (Conserve) at 0.81 mL/946 mL ($n = 160$); 2) chlorfenapyr (Pylon) at 0.38 mL/946 mL ($n = 258$); 3) flonicamid (Aria) at 0.15 g/946 mL ($n = 117$); and 4) water control ($n = 200$). Means followed by the same letter are not significantly different ($P > 0.05$) based on Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

significantly lower at $\approx 60\%$ (Fig. 6). The mean percent mortality of western flower thrips adults associated with the three insecticide treatments was significantly higher than the water control (Fig. 6).

Expt. 6: Effect of application frequency on western flower thrips adults in transvaal daisy cut flowers. There was a significant treatment effect ($F = 166.79$; $df = 3, 28$; $P < 0.0001$) as well as a significant effect of number of applications at 5.0 mL [one or two applications ($F = 30.31$; $df = 1, 28$; $P < 0.0001$)] on the mean percent mortality of western flower thrips adults. In addition, the two-way interaction between treatment and number of applications was significant ($F = 4.93$; $df = 3, 28$; $P = 0.0071$). Spinosad resulted in a significantly higher mean percent mortality of western flower thrips adults than flonicamid and chlorfenapyr after one application (Fig. 7). The mean percent mortality of western flower thrips adults with chlorfenapyr and flonicamid was significantly higher after two applications than after one application (Fig. 7). The mean percent mortality of western flower thrips adults associated with all three insecticide treatments and the number of applications was significantly higher than the water control (Fig. 7).

Discussion

This study demonstrated that certain insecticides are more effective against western flower thrips adult populations than others, regardless of the spray volume and application frequency. It is important to note that the western flower thrips colony used in our study had never been exposed to insecticides, which may explain why western flower thrips adults were highly susceptible to spinosad and chlorfenapyr compared with field populations of western flower thrips adults that are routinely exposed to insecticides.

The continual use of insecticides with the same mode of action can promote the development of resistance in western flower thrips populations, especially if insecticides are used in succession (Bielza, 2008; Kontsedalov et al., 1998; Loughner et al., 2005). Consequently, to avoid insecticide resistance, greenhouse producers must develop rotation programs that abstain from using insecticides with the same mode of action (Cloyd, 2016; Gao et al., 2012; Loughner et al., 2005; Mouden et al., 2017). In fact, many insecticide labels contain information regarding the number of applications that are allowed within a growing season or cropping cycle; this information is provided to mitigate resistance.

Studies have shown that insect pest mortality can be increased by thorough spray coverage of plant parts (leaves, stems, and flowers) with insecticides (Dibble, 1962; Martini et al., 2012; McClure, 1977; Murphy et al., 1998; Shelton et al., 2003; Tipping et al., 2003). Western flower thrips occupy disc florets (small tubular flowers located in the center of the flower head of certain plants in the Asteraceae or Compositae family),

Fig. 7. Mean ($\pm$ SEM) percent mortality of adult western flower thrips, *Frankliniella occidentalis*, in Expt. 6 after exposure to one and two spray applications at 5.0 mL of spray solution per cut flower of transvaal daisy, *Gerbera jamesonii*, associated with the following treatments: 1) spinosad (Conserve) at 0.81 mL/946 mL [n = 71 (one application), n = 64 (two applications)]; 2) chlorfenapyr (Pylon) at 0.38 mL/946 mL [n = 102 (one application), n = 92 (two applications)]; 3) fonicamid (Aria) at 0.15 g/946 mL [n = 91 (one application), n = 50 (two applications)]; and 4) water control [n = 158 (one application), n = 99 (two applications)]. Means followed by the same letter within treatments and across number of applications are not significantly different ($P > 0.05$) based on Tukey's honestly significant difference test. Vertical bars represent the standard error of the mean (SEM).

unopened buds, and developing leaves, which can decrease exposure to contact insecticides (Cloyd, 2009; Loughner et al., 2005). Western flower thrips adults may be more exposed to insecticide treatments in the flowers of transvaal daisy, as in our study, due to restricted movement within the flowers compared with western flower thrips adults located on plant leaves (upper and lower sides). In our study, we found that the spray volume did not influence the mean percent mortality of western flower thrips adults in transvaal daisy flowers, except in Expt. 3, in which the 5.0- and 10.0-mL spray volumes resulted in higher mean percent mortality of western flower thrips adults than the 2.5-mL spray volume.

Spinosad and chlorfenapyr were more effective against western flower thrips adults than fonicamid based on the mean percent mortality of western flower thrips adults. The higher efficacy of spinosad and chlorfenapyr may be associated with their modes of action. For example, fonicamid is a selective feeding blocker (IRAC designation 29) causing starvation by inhibiting the ingestion of phloem (Cho et al., 2011; Morita et al., 2014). However, this mode of action may increase the time required to kill western flower thrips adults, especially in cut flowers. Cut flowers were destructively sampled 4 or

5 d after the final spray application, which may not have been enough time for fonicamid to induce sufficient mortality of western flower thrips adults. In contrast, spinosad acts on the nicotinic acetylcholine receptors in the central nervous system (Geng et al., 2013; Watson et al., 2010), and chlorfenapyr uncouples oxidative phosphorylation in the mitochondria, which disrupts cellular adenosine triphosphate (ATP) production (Raghavendra et al., 2011; Yu, 2008). The modes of action of spinosad (IRAC designation 5) and chlorfenapyr (IRAC designation 13) may result in faster mortality of western flower thrips adults than fonicamid.

Spinosad is highly toxic to nonresistant populations of western flower thrips (Jones et al., 2005; Loughner et al., 2005; Warnock and Cloyd, 2005; Willmott et al., 2013). The current study confirms the ability of spinosad to suppress susceptible populations of western flower thrips adults. Spinosad applications resulted in a mean mortality rate $>95\%$ for western flower thrips adults in all experiments, even when applied at 2.5 mL. Spinosad can provide suppression of insect pests for up to 28 d after an application (Tomkins et al., 1999).

Further studies are warranted to compare the effects of insecticide spray volume and application frequency on laboratory-reared

and field populations of western flower thrips. This would involve comparing how insecticide spray volume and application frequency affects laboratory reared populations vs. field populations of western flower thrips that greenhouse producers are more likely to encounter. In addition, studies associated with application factors that compare plants with different architectures (simple vs. complex) are warranted.

The application of insecticides is the primary strategy used against western flower thrips (Bielza et al., 2007; Cloyd, 2009; Kontsedalov et al., 1998; Mouden et al., 2017; Reitz and Funderburk, 2012). Therefore, improving application factors and developing rotation programs that use effective insecticides with different modes of action will result in increased mortality, which will help greenhouse producers manage western flower thrips populations. Consequently, this will lower insecticide inputs and labor costs and preserve existing effective insecticides.

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