Predation Efficacy of Rove Beetle (Coleoptera: Staphylinidae) Adults in Response to Western Flower Thrips (Thysanoptera: Thripidae) Pupal Stage, Predator–Prey Ratio, and Searchable Area[1]

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Abstract The rove beetle, *Dalotia coriaria* (Kraatz) (Coleoptera: Staphylinidae), is a soil-dwelling predator that preys upon insect pests residing in growing media. Minimal information exists addressing its predation on western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), below-ground life stages. Two laboratory experiments were conducted to assess the effects of western flower thrips pupal stage, predator–prey ratio, and searchable area on predation efficacy of rove beetle adults. In Experiment 1, predation was recorded in response to two thrips pupal stages (prepupae and pupae); three predator–prey ratios (1:5, 1:10, 1:15) and predator–prey ratios that were 2, 3, and 4 times greater. Experiment 2 was designed to assess predation in response to those predator–prey ratios along with searchable areas in 15.2- and 11.5-cm-diameter containers. Response was measured by capturing thrips adults on yellow sticky cards (YSC) as they emerged from pupation. The estimated mean probability of thrips adults captured on the cards was significantly higher for the 1:5 (61.1%) than for the 1:10 (39%) and 1:15 (34.7%) predator–prey ratios. The estimated mean probability of thrips adults captured on the cards for 2 times the predator–prey ratio (57%) was significantly higher than 3 times (37.2%) and 4 times (40.6%) the ratios. A significantly higher estimated mean probability of thrips adults was captured on the cards in the 15.2-cm-diameter containers than in the 11.5-cm-diameter containers. We conclude that a predator–prey ratio of 1:15 would result in fewer rove beetle adults needed to reduce western flower thrips prepupae/pupae stages and subsequent adult populations.

Key Words biological control, soil-dwelling predator, below-ground life stages, growing medium

Western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is an important insect pest associated with greenhouse-grown horticultural crops including ornamentals and vegetables (Cloyd 2009; Kirk 2002; Lewis 1997). Western flower thrips can cause direct and indirect plant damage (Chisholm and Lewis 1984; Harrewijn et al. 1996; Hunter and Ullman 1989; Pappu et al. 2009), resulting in substantial economic losses (Goldbach and Peters 1994; Reitz and Funderburk 2012). Consequently, greenhouse producers rely on regular

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applications of insecticides to suppress western flower thrips populations below damaging levels (Cloyd 2009; Kontsedalov et al. 1998; Loughner et al. 2005).

Western flower thrips populations have developed resistance to insecticides associated with many chemical classes due to the intensive selection pressure from repeated insecticide applications (Bielza et al. 2007; Brødsgaard 1994; Immaraju et al. 1992; Jensen 2000; Kay and Herron 2010; Loughner et al. 2005; Zhao et al. 1995). Therefore, biological control may be a viable alternative plant protection strategy to manage western flower thrips populations (Cloyd 2009; Reitz 2009).

The predatory rove beetle, *Dalotia coriaria* (Kraatz) (Coleoptera: Staphylinidae), is a potential biological control agent of western flower thrips (Carney et al. 2002) that is commercially available from most biological control suppliers (Jandricic et al. 2005; Warner and Getz 2008). *Dalotia coriaria* larvae and adults prey upon a number of greenhouse insect pests including the pupal stages of the western flower thrips and the larval stages of shore flies (*Scatella* spp.) and fungus gnats (*Bradysia* spp.) (Carney et al. 2002; Echegaray et al. 2015; Helyer et al. 2014; Jandricic et al. 2006).

Predation efficacy is a measurement designed to evaluate the ability of a predator to suppress/regulate prey populations, which is important in selecting biological control agents (Farhadi et al. 2011). The low tolerance for plant damage and the ability of most greenhouse insect and mite pests to increase populations rapidly exacerbate the importance of determining appropriate predator–prey ratios that will sufficiently suppress/regulate pest populations. Consequently, studies have evaluated predator–prey ratios for various predators and prey (Cheng et al. 2012; Echegaray et al. 2015; Gaudchau 1982; Gilkeson and Hill 1987, Herrick and Cloyd 2017, 2018, Hill 1987, Opit et al. 2004). Furthermore, different incremental increases in the predator–prey ratio may also influence predation efficacy (Echegaray et al. 2015; Herrick and Cloyd 2018).

Western flower thrips late second-instar larvae migrate downward on plants or drop onto the growing medium surface to pupate (Helyer et al. 1995; Holmes et al. 2012; Kirk 1996; Manners et al. 2013; Tommasini and Maini 1995; Wiethoff et al. 2004). The development duration of western flower thrips prepupae is 2–3 d; that of the pupae is 1–2 d before emerging as adults (Zhang et al. 2007). Because exposure time of prepupae to rove beetle adults, prior to western flower thrips adult emergence, is longer than that of pupae, rove beetle adults may have more time (about 1 d) to forage for western flower thrips prepupae than pupae. As such, predation efficacy may be influenced by duration of a specific western flower thrips pupal stage (prepupae or pupae). Therefore, to account for the effect of different exposure time of western flower thrips pupal stages on rove beetle adult predation, pupal stage was included in this study as a factor that could potentially affect predation efficacy. Furthermore, the searchable area may also affect predation efficacy of *D. coriaria* on soil-dwelling prey, which has been investigated in previous studies associated with fungus gnat, *Bradysia* sp. nr. *coprophila* (Lintner) (Diptera: Sciaridae), larvae (Echegaray et al. 2015; Herrick and Cloyd 2017, 2018).

However, minimal information is available on how the aforementioned factors influence rove beetle adult predation efficacy. Therefore, the objective of our study was to evaluate the effects of western flower thrips pupal stage, predator–prey ratio, and searchable area on predation efficacy of rove beetle adults.

Materials and Methods

Insect colonies. A western flower thrips colony was maintained under laboratory conditions (20–24°C, 50–60% relative humidity [RH], and constant light) in Glad® plastic containers (20.4 × 14.4 × 9.4 cm [length × width × height]; The Glad Products Co., Oakland, CA) with a 9.5-cm-diameter opening in the lid covered with No-Thrips insect screening (mesh size: 0.15 × 0.15 mm) (Greentek®; Janesville, WI). Green beans (*Phaseolus vulgaris* L.) were purchased from a local supermarket, soaked in soapy water (1.5 mL Dawn Ultra dishwashing liquid; Procter & Gamble; Cincinnati, OH) in a 9.4-L plastic container (40.2 × 26.4 × 12.8 cm [l × w × h]; Rubbermaid Home Products; Wooster, OH) for 20 min in tap water, then triple-rinsed with tap water and allowed to air dry. The green beans were provided as food and oviposition sites for adults as well as a food source for larvae. Green beans were replaced every 2–3 d.

A rove beetle colony was maintained in growing medium in 7.6-L plastic rectangular containers (34.8 × 24.7 × 12.4 cm [l × w × h]; Rubbermaid Home Products) under laboratory conditions of 20–24°C, 45–60% RH, and constant darkness. The preparation of the substrate was as follows: a 6.0-L plastic container (28.5 × 11.0 cm [diameter × height]; Rubbermaid Home Products) was filled with Sunshine LC1 RSi Professional Growing Mix (SunGro Horticulture, Inc., Bellevue, WA) growing medium consisting of 70–80% Canadian sphagnum peat moss, perlite, 0.0001% silicone dioxide, and dolomitic limestone.

The growing medium was moistened with approximately 200 mL of tap water. The plastic container with growing medium was then heated for 25 min in a microwave set at full-power (1,200 W output). After the growing medium cooled, 1.8 L of tap water was applied to the growing medium and thoroughly mixed. About 3.0 L of the sterilized growing medium was placed into each 7.6-L container. Approximately 15 g of dry oats (*Avena sativa* L.) (The Quaker Oats Co., Chicago, IL) were placed, every 4–5 d, onto the growing medium surface in a line (lengthwise) within each 7.6-L container. About 15 mL of tap water was applied every 1–2 d onto the oats using a 946-mL plastic spray bottle (Delta Industries, King of Prussia, PA) to maintain constant moisture. Western flower thrips and rove beetle specimens used in this study are deposited as voucher numbers 237 and 220, respectively, in the Kansas State University Museum of Entomological and Prairie Arthropod Research (Manhattan, KS).

Rove beetle adult preparation. Five third-instar rove beetle larvae were placed into a Gladware container (7.8 × 5.1 cm [d × h]; The Glad Products Co.) with 20 mL of moistened growing medium and 3–4 pieces of oats. A total of 20 Gladware containers with third-instar larvae were prepared following the aforementioned method and then placed into an environmental growth chamber (Conviron® Controlled Environments Inc., Pembina, ND) set at 21–27°C and constant darkness. Rove beetle adults were observed 7 d later with most adults emerging after 11 d (Y.L., pers. comm.). Newly emerged adults (1–3 d old) were individually placed in 9-dram plastic vials with lids using a moistened soft-bristled brush. All plastic vials containing rove beetle adults were returned to the environmental growth chamber, and the adults were starved for 24 h. The sex ratio of rove beetle adults was 1:1 (♀:♂).

Baseline conditions for Experiment 1. Approximately 1.2 L of sterilized Sunshine LC1 RSi Professional Growing Mix growing medium was placed into each 15.2-cm-diameter container (Dillen Products Inc., Middlefield, OH). The drainage holes in the bottom were covered with No-Thrips insect screening to prevent thrips and rove beetle adults from escaping. Twenty western flower thrips prepupae or pupae were positioned on the growing medium surface of each container. Each 15.2-cm container was covered with No-Thrips insect screening and a yellow sticky trap (YSC) (7.7 × 10.4 cm [l × w]; Pestrap Phytotronics, Inc., Earth City, MO) was affixed onto the inside center of the screening to capture emerging western flower thrips adults. The experiment was arranged as a completely randomized design with 10 replications per pupal stage (prepupae or pupae). Twenty, 15.2-cm containers were prepared and held at laboratory conditions of 20–24°C, 50–60% relative humidity, and a 16:8-h (light:dark) photoperiod. The number of western flower thrips adults captured on the YSC was recorded 17 d after the experiment was initiated.

Baseline conditions for Experiment 2. The procedures were similar to those described above for Experiment 1 except that the recovery rate of western flower thrips adults was evaluated in 15.2- and 11.5-cm-diameter containers. Ten 15.2- and 11.5-cm-diameter containers were prepared and 20 western flower thrips prepupae were positioned on the growing medium surface of each container.

Experimental procedures. Two independent experiments were conducted under laboratory conditions. Each experiment was arranged as a randomized complete block design, with experimental round (day) as a blocking factor. Each experiment was completed in 5 experimental rounds, 1 per day, with each experimental round involving 18 treatment combinations (described below).

In Experiment 1, predation efficacy of rove beetle adults was evaluated in 15.2-cm-diameter containers (1,834.82 cm^3 with 1.2 L of growing medium) using a three-way factorial treatment structure consisting of all combinations of two western flower thrips pupal stages (prepupae and pupae); three predator–prey ratios (1:5, 1:10, and 1:15); and 2, 3, and 4 times those predator–prey ratios (1:5, 1:10, and 1:15) (Table 1). In Experiment 2, rove beetle adult predation was assessed based on a three-way factorial treatment structure including all combinations of two searchable areas (15.2-cm-diameter containers [1,834.82 cm^3 with 1.2 L of growing medium] and 11.5-cm diameter containers [701.79 cm^3 with 0.4 L of growing medium]); three predator–prey ratios (1:5, 1:10, and 1:15); and 2, 3, and 4 times the predator–prey ratios (1:5, 1:10, and 1:15) (Table 2).

In Experiment 1, approximately 1.2 L of sterilized Sunshine LC1 RSi Professional Growing Mix growing medium was placed into each 15.2-cm container. In Experiment 2, to account for different searchable areas, two container sizes were used: 15.2- and 11.5-cm diameter. About 1.2 L and 0.4 L of sterilized Sunshine LC1 RSi Professional Growing Mix growing medium were placed into each 15.2- and 11.5-cm container, respectively. A section of green bean (5 cm in length) was placed on the growing medium surface beside the inside rim of each container to provide a food source for western flower thrips adults that emerged.

The pupal stages reside at a depth of 1.0–5.0 mm, although this is contingent on the growing medium (Helyer et al. 1995), with studies indicating that pupation can occur at a depth of 1.5–2.0 cm (Deligeorgidis and Ipsilandis 2004; Tommasini and Maini 1995). Furthermore, prepupae and pupae can be distributed throughout the growing medium via cracks and crevices present on the growing medium surface

Table 1. Predator–prey ratios and 2, 3, and 4 times the predator–prey ratios (1:5, 1:10, and 1:15) associated with the number of rove beetle (RB), *Dalotia coriaria*, adults released and initial number of western flower thrips (WFT), *Frankliniella occidentalis*, prepupae (PP) or pupae (P) in each 15.2-cm container (1,834.82 cm^3 with 1.2 L of growing medium) on each day (1, 2, 3, 4, or 5) for Experiment 1.

Times the Predator–Prey Ratios	Predator–Prey Ratios					
	1:5		1:10		1:15	
	RB	WFT PP/P	RB	WFT PP/P	RB	WFT PP/P
2	2	10	2	20	2	30
3	3	15	3	30	3	45
4	4	20	4	40	4	60

(Y.L., pers. comm.). Thus, no additional growing medium was needed to cover the prepupae or pupae. Western flower thrips prepupae or pupae, from established laboratory colonies, were observed under a dissecting microscope (Nikon SMZ1000; BioQuip Products, Inc., Rancho Dominguez, CA) and collected using a moistened soft-bristled brush. The prepupae and pupae were then positioned on the growing medium surface. After 1–2 h, a predetermined number of newly emerged rove beetle adults, based on the designated treatments, were released into each container. Only western flower thrips prepupae were used in Experiment 2, based on the results from Experiment 1, where predation efficacy of rove beetle adults was not significantly different between western flower thrips prepupae and pupae.

Table 2. Predator–prey ratios and 2, 3, and 4 times the predator–prey ratios (1:5, 1:10, and 1:15) associated with the number of rove beetle (RB), *Dalotia coriaria*, adults released and initial number of western flower thrips (WFT), *Frankliniella occidentalis*, prepupae (PP) in each 15.2-cm container (1,834.82 cm^3 with 1.2 L of growing medium) or 11.5-cm container (701.79 cm^3 with 0.4 L of growing medium) on each day (1, 2, 3, 4, or 5) for Experiment 2.

Times the Predator–Prey Ratios	Predator–Prey Ratios					
	1:5		1:10		1:15	
	RB	WFT PP	RB	WFT PP	RB	WFT PP
2	2	10	2	20	2	30
3	3	15	3	30	3	45
4	4	20	4	40	4	60

Each container was covered with No-Thrips insect screening that was hot-glued to the edge of the container; this provided ventilation and prevented rove beetle and western flower thrips adults from escaping. For each experimental round (day), a total of 18, 15.2-cm containers for Experiment 1, and 9, 15.2-cm and 9, 11.5-cm containers for Experiment 2 were prepared and maintained in the laboratory at 20–24°C, 50–60% RH, and a 16:8-h (light:dark) photoperiod.

Rove beetle adults tend to reside in the growing medium; however, adults can fly and will disperse within a greenhouse away from the original release site (Helyer et al. 2003). Therefore, to prevent rove beetle adults from being captured on the YSC prior to western flower thrips adult emergence, YSC were affixed on the inside center of the No-Thrips insect screening within the containers 5 d after the experiment was initiated. One YSC was used for each 15.2-cm container and a one-half section of a YSC for each 11.5-cm container. Simultaneously, green beans were removed from the containers, and approximately 15 g of oats were placed on the growing medium surface as a food source for rove beetle adults to ensure adult survival after completing Experiment 1. To maintain constant moisture, 15 mL of tap water was applied to the oats through the No-Thrips insect screening using a 946-mL plastic spray bottle every 1–2 d. In Experiment 2, no oats were placed on the growing medium surface after removing the green beans.

The number of western flower thrips and rove beetle adults captured on the YSC was recorded 17 d after initiating the experiments. The number of western flower thrips adults captured on the YSC was used as an indirect assessment of predation efficacy which, in turn, was quantified by the binomial probability of western flower thrips adults captured on the YSCs.

To confirm rove beetle adult survival during the experiment, the growing medium in each 15.2-cm container was placed into a 9.4-L plastic rectangular container. About 0.8 L of tap water was added to each 9.4-L container to saturate the growing medium, causing rove beetles to emerge from the growing medium (Y.L., pers. comm.). Then, approximately 15 g of oats were placed on the growing medium surface as a food source for rove beetle adults. The 9.4-L containers were covered using modified lids with insect screening (mesh size: 0.2×0.8 mm) (Greentek). The number of rove beetle adults in each 9.4-L container was counted 24 h after the growing medium was saturated. Recovery of rove beetle adults at the end of the experiment was based on the number of adults captured on YSC and the number of adults recovered from the growing medium. In Experiment 2, the number of rove beetle adults recovered at the end of experiment was based on the number of adults captured on YSCs.

Statistical analysis. For each experiment, a generalized linear mixed model assuming a binomial distribution was fitted to the response variable defined as the number of western flower thrips adults captured on the YSC from the initial number of western flower thrips pupal stage in the container. A logit link function was used to estimate the probability of western flower thrips adults captured on the YCSs, which was an indicator of predation efficacy.

In Experiment 1, the linear predictor in the model included the fixed effects of western flower thrips pupal stage; predator–prey ratio; and 2, 3, and 4 times those initial predator–prey ratios as well as all two- and three-way interactions. In Experiment 2, the fixed effects in the linear predictor consisted of predator–prey ratio; 2, 3, and 4 times the initial predator–prey ratios; and searchable area as well

as all two- and three-way interactions. For both experiments, random effects associated with the linear predictor included the blocking effect of experimental round (day) and an effect of the container as the unit of observation, defined as the cross product of experimental round (day) and treatment combination. This specification was needed to account for over-dispersion in the data, as observed in preliminary analyses.

Over-dispersion was evaluated using the maximum-likelihood based fit statistic Pearson chi-square/degrees of freedom (df). For the two experiments, the final model used for inference showed no evidence of over-dispersion. Estimation was conducted using residual pseudo-likelihood. Degrees of freedom were approximated and estimated standard errors were adjusted using Kenward-Roger's procedure. The statistical model was fitted using the PROC GLIMMIX procedure (SAS Institute 2012) implemented using Newton-Raphson with ridging as the optimization technique. Pairwise comparisons were conducted using Tukey-Kramer's or Bonferroni's adjustments for multiple testing, as appropriate in each case, to avoid inflation of type I error.

Results

Baseline conditions for Experiment 1. When no rove beetle adults were released, the estimated mean probability of western flower thrips adults captured on the YSC ranged from 98.2% to 99.4% for prepupae and 89.2% to 97.9% for pupae. The high recovery of western flower thrips adults in the absence of rove beetle adults suggests that natural mortality of western flower thrips pupal stage and mortality caused by handling technique were minimal; therefore, a correction factor was not needed. Furthermore, descriptive statistics of rove beetle adults recovered at the end of the experiment (17 d) confirmed their general presence and survival during the experimental period (Table 3).

Predation efficacy of rove beetle adults associated with western flower thrips pupal stage; predator–prey ratio; and 2, 3, and 4 times the initial predator–prey ratios (Experiment 1). No significant two- or three-way interactions were detected among pupal stage; predator–prey ratio; or 2, 3, and 4 times those predator–prey ratios, on the estimated mean probability of western flower thrips adults captured on the YSC (western flower thrips pupal stage $\times$ predator–prey ratio interaction: $F = 0.73$; df $= 2$, 66.02; $P = 0.48$; western flower thrips pupal stage $\times$ 2, 3, and 4 times the predator–prey ratio interaction: $F = 2.15$; df $= 2$, 66.36; $P = 0.12$; predator–prey ratio $\times$ 2, 3, and 4 times the predator–prey ratio interaction: $F = 0.93$; df $= 4$, 65.77; $P = 0.45$; and western flower thrips pupal stage $\times$ predator–prey ratio $\times$ 2, 3, and 4 times the predator–prey ratio interaction: $F = 0.23$; df $= 4$, 65.75; $P = 0.92$).

Furthermore, there was no evidence of any main effect differences between prepupae and pupae on the estimated mean probability of western flower thrips adults captured on the YSC ($F = 0.00$; df $= 1$, 66.65; $P = 0.98$). However, a main effect of predator–prey ratio was detected ($F = 7.25$; df $= 2$, 66.06; $P = 0.0014$). Regardless of pupal stage, the estimated mean probability of western flower thrips adults captured on the YSC was significantly higher at the 1:5 predator–prey ratio (61.1% [48.5, 72.4%]; mean (95% confidence interval) than the 1:10

Table 3. Mean (minimum, maximum) number of rove beetle, *Dalotia coriaria*, adults recovered at the end of Experiment 1 associated with the predator–prey ratios and 2, 3, and 4 times the predator–prey ratios for all treatment combinations of western flower thrips (WFT), *Frankliniella occidentalis*, pupal stages (prepupae [PP] and pupae [P]), three predator–prey ratios (1:5, 1:10, and 1:15); and 2, 3, and 4 times the predator–prey ratios (1:5, 1:10, and 1:15).

Times the Predator–Prey Ratios	Predator–Prey Ratios					
	1:5		1:10		1:15	
	WFT PP	WFT P	WFT PP	WFT P	WFT PP	WFT P
2	1.4 (1, 2)	1.6 (0, 2)	2.0 (2, 2)	1.6 (1, 2)	1.6 (1, 5)	1.4 (1, 2)
3	1.8 (1, 2)	2.0 (1, 3)	2.6 (2, 3)	1.8 (0, 3)	2.2 (2, 3)	2.4 (0, 3)
4	2.8 (0, 4)	3.6 (3, 4)	2.4 (1, 4)	3.0 (2, 4)	2.6 (0, 4)	3.4 (2, 4)

ratio (39% [28.1, 51.2%] ($t = 2.96$, df = 72, $P = 0.01$) and 1:15 ratio (34.7% [24.7, 46.3% ($t = 3.62$, df = 69.07, $P = 0.002$). However, the latter two predator–prey ratios were not significantly different from each other ($t = 0.65$, df = 59.06, $P = 0.80$) (Fig. 1).

A main effect of 2, 3, and 4 times the predator–prey ratio was also identified for the estimated mean probability of western flower thrips adults captured on the YSC ($F = 3.99$; df = 2, 66.36; $P = 0.02$). At 2-times the predator–prey ratio, the estimated

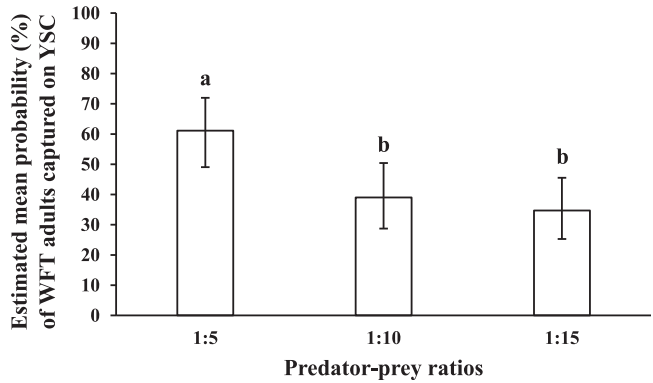

Fig. 1. Estimated mean probability (95% confidence intervals) of western flower thrips (WFT), *Frankliniella occidentalis*, adults captured on yellow sticky cards (YSC) associated with three predator–prey ratios (1:5, 1:10, and 1:15) in Experiment 1. Estimated means followed by different letters indicate significant differences (Tukey-Kramer's adjusted $P < 0.05$).

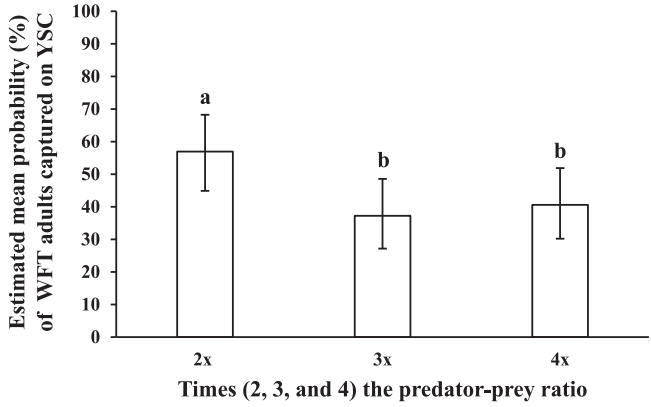

Fig. 2. Estimated mean probability (95% confidence intervals) of western flower thrips (WFT), *Frankliniella occidentalis*, adults captured on yellow sticky cards (YSC) associated with 2, 3, and 4 times the predator–prey ratio (1:5, 1:10, and 1:15) in Experiment 1. Estimated means followed by different letters indicate significant differences (Tukey-Kramer's adjusted $P < 0.05$).

mean probability of western flower thrips adults captured on the YSC (57% [44.3, 68.8%]) was significantly higher than 3 times (37.2% [26.6, 49.3%]) ($t = 2.66$, df = 70.62, $P = 0.03$) and 4 times (40.6% [30, 52.3%]) ($t = 2.21$, df = 68.15, $P = 0.04$) the predator–prey ratio. However, the latter two were not significantly different from each other ($t = -0.49$, df = 61.39, $P = 0.88$) (Fig. 2).

Baseline conditions for Experiment 2. When no rove beetle adults were released, the estimated mean probability of western flower thrips adults captured on the YSC ranged from 84.1% to 90.2% for the 11.5-cm containers and 87.3% to 94.2% for the 15.2-cm containers. Furthermore, the estimated mean probability of western flower thrips adults captured on the YSC without rove beetle adults suggests that natural mortality of western flower thrips prepupae and mortality caused by handling technique were not contributing factors inhibiting prepupae from developing into pupae and then adults. Moreover, descriptive statistics of rove beetle adults recovered at the end of the experiment (17 d) confirmed their general presence and survival during the experimental period (Table 4).

Predation efficacy of rove beetle adults associated with western flower thrips pupal stage; predator–prey ratio; and 2, 3, and 4 times the predator–prey ratio (Experiment 2). A significant three-way interaction was detected among predator–prey ratio; 2, 3, and 4 times the predator–prey ratio; and searchable area ($F = 3.21$; df = 4, 72; $P = 0.02$). To explain this interaction, we evaluated the simple effects of searchable area on the estimated mean probability of western flower thrips adults captured on the YSC within combinations of predator–prey ratios and 2, 3, and 4 times the predator–prey ratios (Fig. 3).

The estimated mean probability of western flower thrips adults captured on the YSCs, for the 1:5 predator–prey ratio, based on 4 times the predator–prey ratio, was

Table 4. Mean (minimum, maximum) number of rove beetle, *Dalotia coriaria*, adults captured on the yellow sticky cards at the end of Experiment 2 associated with the predator–prey ratios and 2, 3, and 4 times the predator–prey ratios for all treatment combinations of two searchable areas (11.5-cm containers [701.79 cm^3 with 0.4 L of growing medium] and 15.2-cm containers [1,834.82 cm^3 with 1.2 L of growing medium]), three predator–prey ratios (1:5, 1:10, and 1:15); and 2, 3, and 4 times the predator–prey ratios (1:5, 1:10, and 1:15).

Times the Predator–Prey Ratios	Predator–Prey Ratios					
	1:5		1:10		1:15	
	11.5-cm Containers	15.2-cm Containers	11.5-cm Containers	15.2-cm Containers	11.5-cm Containers	15.2-cm Containers
2	0.5 (0, 1)	1.2 (0, 2)	1.2 (0, 2)	1.2 (0, 2)	1.7 (1, 2)	1.0 (0, 2)
3	1.5 (0, 3)	2.5 (1, 3)	1.2 (0, 3)	1.7 (0, 2)	1.6 (1, 3)	1.2 (0, 3)
4	1.8 (0, 4)	1.3 (0, 2)	2.2 (1, 4)	1.8 (0, 4)	1.8 (1, 3)	1.7 (1, 3)

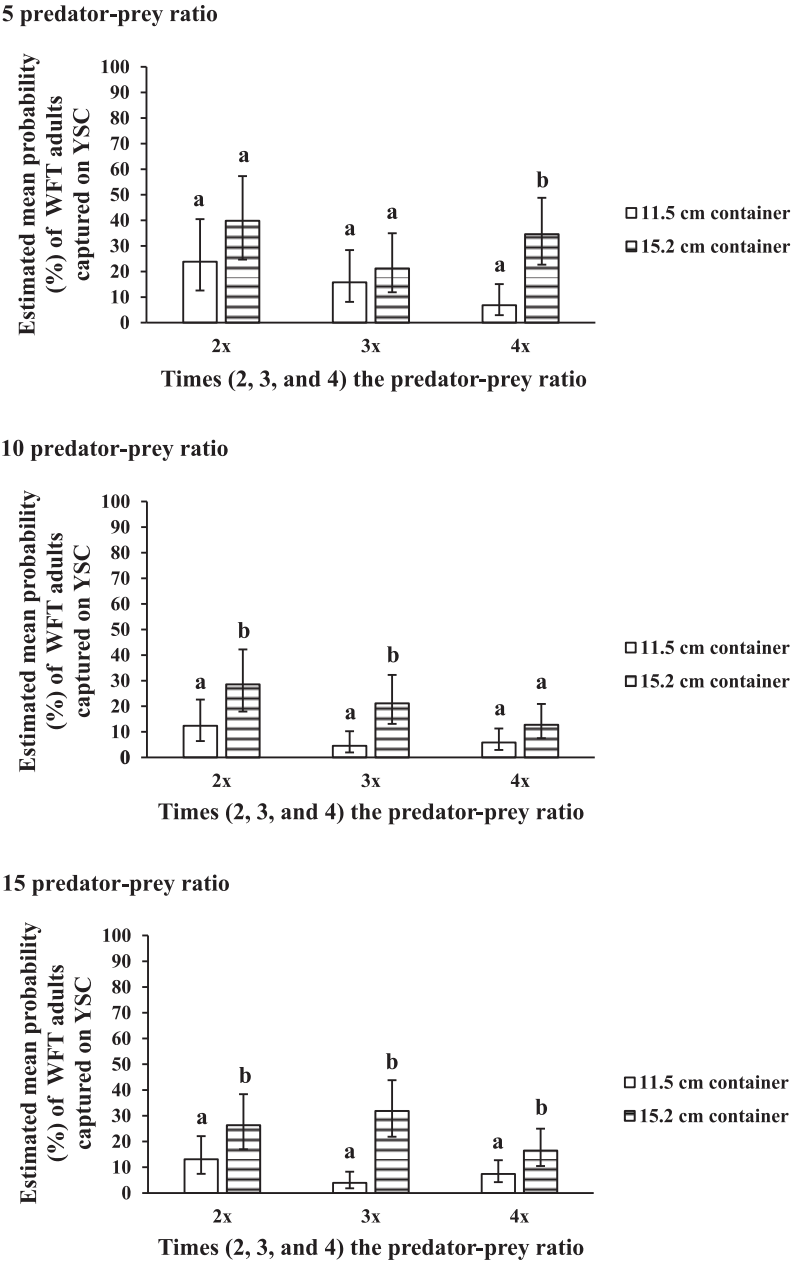

Fig. 3. Estimated mean probability (95% confidence intervals) of western flower thrips (WFT), *Frankliniella occidentalis*, adults captured on yellow sticky cards (YSC) for two searchable areas (11.5-cm containers [701.79 cm^3 with 0.4 L of growing medium] and 15.2-cm containers [1,834.82 cm^3 with 1.2 L of growing medium]) within all

significantly higher in the 15.2-cm containers than in 11.5-cm containers. However, this difference in searchable area was not significant for 2 or 3 times the predator–prey ratio (Fig. 3A). In contrast, at the 1:10 predator–prey ratio, the effects of searchable area on the estimated mean probability of western flower thrips adults captured on the YSC was significant for 2 and 3 times, but not 4 times the predator–prey ratio (Fig. 3B). Finally, at the 1:15 predator–prey ratio, the estimated mean probability of western flower thrips adults captured on the YSC in the 15.2-cm containers was significantly higher than in the 11.5-cm containers across 2, 3, and 4 times the predator–prey ratios (Fig. 3C).

Discussion

This study is the first to assess the effect of western flower thrips pupal stage, predator–prey ratio, and searchable area on predation of western flower thrips by the rove beetle, *D. coriaria*. The study demonstrated that the estimated mean probability of western flower thrips adults captured on YSC was higher for the 1:5 predator–prey ratio than the 1:10 and 1:15 predator–prey ratios. In addition, the estimated mean probability of western flower thrips captured on YSC was higher for 2 times the predator–prey ratio than 3 and 4 times the predator–prey ratio. Furthermore, there was a significantly higher estimated mean probability of western flower thrips adults captured on the YSC in the 15.2-cm than in the 11.5-cm containers.

Exposure time of prey to a predator can influence predation efficacy. The exposure time of western flower thrips prepupae to rove beetle adults is longer (about 1 d) than for the pupae (Zhang et al. 2007). However, the results from our study indicate that predation efficacy of rove beetle adults on western flower thrips prepupae was not significantly different from that of the pupae despite development taking a day longer. Therefore, exposure time associated with the two western flower thrips pupal stages may not affect the predation efficacy of rove beetle adults.

Initial pest density may influence predation efficacy at a given predator–prey ratio (Echegaray et al. 2015; Herrick and Cloyd 2018). For instance, when *D. coriaria* adults were released at a 1:5 (*D. coriaria* adults:fungus gnat larvae) predator–prey ratio to suppress fungus gnat, *Bradysia* sp. nr. *coprophila* (Lintner) (Diptera: Sciaridae), larval populations, percent fungus gnat adults captured on YSC decreased significantly from 59% to 37.5% as the initial number of fungus gnat larvae increased from 10 to 20 (Echegaray et al. 2015). In our study, the estimated mean probability of western flower thrips adults captured on YSC decreased for 2 and 3 times the predator–prey ratio, but there was no difference between 3 and 4 times.

←

combinations of three predator–prey ratios (1:5, 1:10, and 1:15) and 2, 3, and 4 times the predator–prey ratios: 1:5 (3A), 1:10 (3B), and 1:15 (3C) in Experiment 2. Estimated means followed by different letters within the same predator–prey ratio and times the predator–prey ratio indicate significant differences (Bonferroni's adjusted $P < 0.05$).

Searchable area may affect the predation efficacy of *D. coriaria* on soil-dwelling prey, such as fungus gnat larvae (Echegaray et al. 2015; Herrick and Cloyd 2017). Herrick and Cloyd (2017) proposed that predation of *D. coriaria* adults on fungus gnat larvae may be negatively affected by a greater searchable area associated with the 15.2-cm containers (1,834.82 cm^3 with 2.0 L of growing medium) used in the greenhouse experiment compared to the smaller searchable area associated with 473-mL deli containers (616.14 cm^3 with 0.3 L of growing medium) used in the laboratory experiment. In general, our study showed that predation efficacy of rove beetle adults on western flower thrips prepupae in the 15.2-cm containers was lower than in the 11.5-cm containers, especially at the 1:15 predator–prey ratio. This may be associated with more western flower thrips prepupae available for rove beetles at the 1:15 predator–prey ratio compared to 1:5 and 1:10.

The ability to determine an appropriate predator–prey ratio based on predation efficacy may enhance the success of an augmentative biological control program (Amoah et al. 2016; Cheng et al. 2012; Echegaray et al. 2015; Gaudchau 1982; Hamlen and Lindquist 1981; Opit et al. 2004). For example, Cheng et al. (2012) found that the predator, *Mallada basalis* (Walker) (Neuroptera: Chrysopidae), suppressed populations of *Tetranychus kanzawai* (Kishida) (Acari: Tetranychidae) and *Panonychus citri* (McGregor) (Acari: Tetranychidae) on papaya (*Carica papaya* L.), at a predator–prey ratio of 1:15 or greater. Moreover, effective suppression was achieved at a predator–prey ratio of 1:10 when using the predatory mite, *Phytoseiulus persimilis* (Athias-Henriot) (Acari: Phytoseiidae), against the twospotted spider mite, *Tetranychus urticae* (Koch) (Acari: Tetranychidae), on lima bean (*Phaseolus lunatus* L.) plants (Amoah et al. 2016). In greenhouse experiments, Herrick and Cloyd (2018) reported that, although there were no significant differences in predator–prey ratios (rove beetle adults:fungus gnat larvae = 1:4, 1:2, and 1:1.3), 10 rove beetle adults provided sufficient regulation of fungus gnat larval populations regardless of fungus gnat larval numbers.

In our study, predation efficacy at the 1:15 predator–prey ratio was significantly higher than at 1:5 but not significantly different from 1:10. It is possible that mutual interference (competition that occurs when access to resources is negatively affected by the presence of other individuals within a species or population [Delong and Vasseur 2011]) may have occurred at the 1:5 predator–prey ratio but not at the 1:10 or 1:15. Compared to the 1:10 and 1:15 ratios, there were less prey available for each rove beetle adult at the 1:5 ratio, and competition may have been greater among rove beetle adults. However, fewer rove beetle adults need to be released at the 1:15 predator–prey ratio compared to 1:10, which may result in a cost savings to greenhouse producers. Therefore, the 1:15 predator–prey ratio requires the release of fewer rove beetle adults to suppress/reduce western flower thrips adult populations.

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