Predation of Western Flower Thrips (Thysanoptera: Thripidae) Pupal Populations by Rove Beetle, *Dalotia coriaria* (Kraatz) (Coleoptera: Staphylinidae), Adults[1]

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Abstract *Dalotia coriaria* Kraatz (Coleoptera: Staphylinidae) is a commercially available, soil-dwelling predator that preys upon a variety of insect pests that reside in soils or growing media. The impact of *D. coriaria* on the western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), however, is not well documented. Three laboratory experiments were conducted to assess predation efficacy of *D. coriaria* adults on western flower thrips pupal populations typically found in the soil or growing medium. Treatments included prepupae only, pupae only, and a prepupae-pupae combination (1:1). Six numbers (0, 1, 2, 3, 4, and 5) of beetle adults and four initial numbers (15, 20, 25, and 30) of thrips pupal populations were examined for each pupal stage treatment. For each pupal stage treatment, the estimated mean probability of thrips adults captured on yellow sticky cards decreased as the number of beetle adults released increased from one to three, but there was no significant effect after releasing additional beetles. Furthermore, there were no differences in response to the predator:prey ratio or initial prey number within each predator:prey ratio examined across the pupal populations examined in this study. These results (a) provide insight into the predatory behavior of *D. coriaria* adults on western flower thrips pupal populations, which may have practical implications for greenhouse production systems; and (b) indicate that, regardless of the initial numbers of western flower thrips prepupae and/or pupae in the growing medium, three *D. coriaria* adults per 15.2-cm container may be recommended for use of this predator against western flower thrips.

Key Words predation efficacy, predator:prey ratio, biological control

Western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is an important pest of horticultural crops worldwide (Cloyd 2009; Kirk 2002; Lewis 1997; Reitz 2009; Robb and Parrella 1995). Western flower thrips cause direct and indirect plant damage (Chisholm and Lewis 1984; Harrewijn et al. 1996; Hunter and Ullman 1989; Pappu et al. 2009), which has resulted in substantial economic losses (Goldbach and Peters 1994; Reitz and Funderburk 2012). Consequently, greenhouse producers routinely apply insecticides to suppress western flower thrips populations (Cloyd 2009; Kontsedalov et al. 1998; Loughner et al. 2005).

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However, due to the intensive selection pressure associated with insecticide applications, western flower thrips populations have developed resistance to insecticides from many different chemical classes (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, alternative plant protection strategies are warranted such as augmentative biological control that involves releasing or applying natural enemies (e.g., predators, parasitoids, or entomopathogenic fungi) to suppress pest populations (Parrella et al. 1992; van Lenteren and Woets 1988).

The predatory rove beetle, *Dalotia coriaria* (Kraatz) (Coleoptera: Staphylinidae), may be a viable biological control agent of western flower thrips (Carney et al. 2002) and is commercially available from most biological control suppliers (Jandricic et al. 2005; Warner and Getz 2008). The rove beetle has been reported to prey upon the soil-dwelling life stages of several greenhouse insect pests including prepupae and pupae of western flower thrips and the larvae of shore flies (*Scatella* spp.) and fungus gnats (*Bradysia* spp.) (Carney et al. 2002; Echegaray et al. 2015; Herrick and Cloyd 2017, 2018; Jandricic et al. 2006).

Studies associated with predator–prey interactions have been conducted in regard to functional and numerical responses (Patel and Zhang 2017; Rahman et al. 2012). In our study, we concentrated on evaluating the predation efficacy of a rove beetle (predator) on western flower thrips (prey) based on different predator and prey numbers. Predation efficacy determines the ability of a predator to suppress prey populations, which is important in selecting biological control agents (Farhadi et al. 2011) and in assessing the numbers of predators to release in augmentative biological control programs (Echegaray et al. 2015; Herrick and Cloyd 2017, 2018). Due to low pest tolerance and the capacity of most greenhouse insect and mite pests to increase populations rapidly, determining an appropriate predator:prey ratio to effectively suppress pest populations is important. Consequently, studies have evaluated predator:prey ratios associated with various predators and prey (Cheng et al. 2012; Echegaray et al. 2015; Gaudchau 1982; Gilkeson and Hill 1987; Herrick and Cloyd 2017, 2018; Opit et al. 2004,). Furthermore, different initial prey numbers at a given predator:prey ratio may also affect predation efficacy (Echegaray et al. 2015; Herrick and Cloyd 2017, 2018).

Successful suppression of western flower thrips populations using the rove beetle, *D. coriaria*, is contingent on evaluating predation efficacy based on different numbers of predator and prey as well as on determining an appropriate predator:prey ratio. However, the effect of *D. coriaria* on western flower thrips is not well understood. Therefore, the objectives of this study were to determine the effects of: (a) different absolute numbers of predator (rove beetle) and prey (western flower thrips), (b) different initial prey numbers, and (c) different predator:prey ratios (1:5, 1:10, and 1:15) on the predation efficacy of *D. coriaria*.

Materials and Methods

Insect colonies. A western flower thrips colony was maintained under laboratory conditions (20–24°C, 50–60% relative humidity, and constant light) in Glad® plastic containers (20.4 × 14.4 × 9.4 cm, length×width×height [L×W×H]) (The Glad Products Co., Oakland, CA, USA) with a round hole (9.5 cm diameter

[diam]) cut in the lid that was covered with No-Thrips insect screening (mesh size: 0.15 × 0.15 mm) (Greentek, Janesville, WI, USA). Green beans (*Phaseolus vulgaris* L.) were purchased from a local supermarket and soaked in soapy water (1.5 ml DAWN® Ultra dishwashing liquid [Procter & Gamble, Cincinnati, OH, USA] in a 9.4-L plastic container filled with tap water) for 20 min to remove any potential pesticide residues and then rinsed with tap water and allowed to dry. The green beans were provided as food and oviposition sites for adults and a food source for larvae. Green beans were changed every 2–3 d.

A rove beetle colony was maintained in 7.8-L plastic rectangular containers (34.8 × 24.7 × 12.4 cm, L×W×H) (Rubbermaid Home Products, Wooster, OH, USA) with growing medium under laboratory conditions of 20–24°C, 45–60% relative humidity, and constant darkness. Growing medium preparation was as follows: a 6.0-L plastic container (28.5 × 11.0 cm, diameter × height [D×H]) (Rubbermaid Home Products) was filled with Sunshine LC1 RSi Professional Growing Mix (SunGro Horticulture, Inc., Bellevue, WA, USA) growing medium composed 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 6.0-L 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 had cooled, 1.8 L of tap water was applied to the growing medium, which was then thoroughly mixed. About 3.0 L of the sterilized growing medium was placed into each 7.8-L plastic rectangular container. Approximately 15 g of dry oats (*Avena sativa* L.) (The Quaker Oats Co., Chicago, IL, USA) was placed, every 4–5 d, onto the growing medium surface in a line (lengthwise) within each 7.8-L plastic rectangular container. About 15 ml of tap water was sprayed, every 1–2 d, onto the oats using a 946-ml plastic spray bottle (Delta Industries, King of Prussia, PA, USA) 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).

Preparation of newly emerged rove beetle adults. Five third-instar rove beetles 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 three to four pieces of dry oats. A total of 20 Gladware containers with third-instar larvae were prepared and placed into an environmental growth chamber (Conviron® Controlled Environments Inc., Pembina, ND, USA) set at 21–27°C and constant darkness. There was no evidence of any cannibalism associated with the rove beetles (Y.L., pers. obs.). The sex ratio of rove beetle adults was 1:1 (female:male).

Rove beetle adults were observed 7 d later, with most adults eclosing after 11 d (Y.L., pers. obs.). Newly eclosed adults (1– 3 days old) were individually placed in 9-dram (33-ml) 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.

Experimental procedures. Three laboratory experiments were conducted to assess predation efficacy of rove beetles on three western flower thrips pupal populations, namely prepupae (Experiment 1), pupae (Experiment 2), and 1:1 prepupae:pupae combination (Experiment 3). This treatment structure allowed for evaluating the effects of predator:prey ratios (1:5, 1:10, and 1:15), accounting for

Table 1. Number of predators [rove beetle (RB), *Dalotia coriaria*, adults] and selected predator:prey ratios (1:5, 1:10, and 1:15) obtained by combining different predator numbers (1, 2, 3, 4, and 5) associated with rove beetle adults, and initial prey numbers (15, 20, 25, and 30) of western flower thrips (WFT), *Frankliniella occidentalis*, for all three experiments.

Number of Predators (Rove Beetle Adults)	Predator:Prey Ratios					
	1:5		1:10		1:15	
	RB	WFT	RB	WFT	RB	WFT
1	—	—	—	—	1	15
2	—	—	2	20	2	30
3	3	15	3	30	—	—
4	4	20	—	—	—	—
5	5	25	—	—	—	—

differences in initial prey number, on the predation efficacy of rove beetle adults (Table 1). Each experiment was set up as a randomized complete block design, with experimental round (day) as a blocking factor. Each experiment was completed in five experimental rounds, one per day. In each experiment, predation efficacy was evaluated using a two-way factorial treatment structure consisting of all combinations of six numbers (0, 1, 2, 3, 4, and 5) of newly eclosed rove beetle adults and four initial numbers (15, 20, 25, and 30) of one of the three western flower thrips pupal populations. By combining factor levels, this treatment structure further enabled evaluation of the effects of selected predator:prey ratios (1:5, 1:10, and 1:15) with increasing initial prey number on predation efficacy of rove beetles.

For each experiment, approximately 1.2 L of sterilized Sunshine LC1 RSi Professional Growing Mix growing medium was placed into each 15.2-cm-diameter plastic container (15.2 × 14.3 cm, D×H) (Dillen Products Inc, Middlefield, OH, USA). A section of green bean (5 cm in length) was placed on the growing medium surface beside the inside rim of each 15.2-cm container to provide a food source for western flower thrips adults that eclosed.

Prepupae and pupae were obtained from the laboratory colony using a moistened, soft-bristled brush. Fifteen, 20, 25, or 30 of one western flower thrips pupal population were randomly positioned on the growing medium surface. For the treatments involving uneven initial numbers (15 and 25) of western flower thrips prepupae-pupae combination, the numbers of prepupae and pupae were alternated on each day.

Prepupae and pupae are generally located at a depth of 1–5 mm in compost that is a freshly steam-sterilized mixture (50:50 by volume) of loam and medium grade sphagnum peat (Helyer et al. 1995). Furthermore, prepupae and pupae may be distributed throughout the growing medium via cracks and crevices present on the growing medium surface (Y.L., pers. obs.). Therefore, no additional growing medium was needed to cover the prepupae or pupae. One to two hours after western flower thrips prepupae or pupae were placed on the growing medium surface; one, two, three, four, or five newly eclosed rove beetle adults were released into each 15.2-cm container. Each container was covered with No-Thrips insect screening, hot-glued to the edge of the container, which provided ventilation and prevented western flower thrips adults from escaping upon eclosion. For each experimental round (day), a total of 24 containers (15.2 cm), one container per treatment combination, was prepared and maintained in the laboratory at 19–25°C, 50–60% relative humidity, and a 16:8 (light:dark) hour photoperiod.

Rove beetle adults primarily reside in the growing medium; however, they can fly and will disperse within a greenhouse away from the original release site (Helyer et al. 2003). Therefore, in order to prevent rove beetle adults from being captured on the yellow sticky cards prior to western flower thrips adult eclosion (Zhang et al. 2007), a yellow sticky card was affixed onto the inside center of the No-Thrips insect screening within each container 5 d after the experiment was initiated. Simultaneously, the 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 completion of the experiment. To maintain moisture, about 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.

The number of western flower thrips adults for each experiment and rove beetle adults for the last three experimental rounds of Experiment 3 captured on the yellow sticky cards were recorded 17 d following initiation of the experiment. The number of western flower thrips adults captured on the yellow sticky cards was used as an indirect assessment of predation efficacy which was, in turn, quantified by the binomial probability of western flower thrips adults captured on the yellow sticky cards (refer to statistical analysis).

To confirm rove beetle adult survival in the last three experimental rounds of Experiment 3, the growing medium from each 15.2-cm container was placed into a 9.4-L plastic rectangular container [40.2 × 26.4 × 12.8 cm, L×W×H) (Rubbermaid Home Products). About 0.8 L of tap water was added to each 9.4-L plastic rectangular container to saturate the growing medium, which resulted in rove beetle adults emerging from the growing medium (Y.L., pers. obs.). Then, approximately 15 g of oats were placed on the growing medium surface as a food source for the rove beetle adults. Each 9.4-L plastic rectangular container was covered using a modified lid with insect screening (mesh size: 0.2 × 0.8 mm) (Greentek). Rove beetle adults in each container were recorded 24 h after the growing medium was saturated. Rove beetle adults recovered after completing the experiment were based on adults captured on the yellow sticky cards and adults recovered from the growing medium.

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 yellow sticky cards out of the initial number of one western flower thrips pupal population in the container. A logit link function was used to estimate the probability of western flower thrips adults captured on the yellow sticky cards. The linear predictor included the fixed effects of number of rove beetle adults, initial number of one western flower thrips pupal population, and the two-way interaction. Random effects included the blocking effect of experimental round (day) and the effect of container as the unit of observation identified by the cross product of experimental round (day) and treatment combination. This was needed to account for an over-dispersion observed in preliminary analyses.

Over-dispersion was evaluated using the maximum likelihood–based fit statistic Pearson chi-squared/df when needed. The final statistical model used for inferences was fitted using residual pseudolikelihood. Degrees of freedom were approximated and estimated standard errors were adjusted using Kenward-Roger's procedure. Tukey-Kramer's or Bonferroni's adjustments were used to adjust pairwise comparisons to avoid inflation of type 1 error due to multiplicity. Tailored contrasts were used to compare selected treatment combinations representing the predator:prey ratios (1:5, 1:10, and 1:15) with different initial prey numbers. All statistical models were fitted using the PROC GLIMMIX procedure (SAS Institute 2012).

Results

Assessment of baseline conditions. When no rove beetle adults were released, the estimated mean (95% confidence interval [CI]) probability of western flower thrips adults captured on the yellow sticky cards was 99% (97.3%, 99.6%) (mean (95% CI) in Experiment 1, 96.1% (91.7%, 98.2%) in Experiment 2, and 97.6% (95%, 98.8%) in Experiment 3 (Fig. 1). The high recovery of western flower thrips adults in the absence of rove beetle adults demonstrates minimal natural mortality of western flower thrips prepupae or mortality caused by handling prevented prepupae and pupae from developing into adults. Moreover, descriptive statistics of rove beetle adults recovered at the end of the experiment confirm their general presence and survival during the experimental period (Table 2).

Effect of different absolute numbers of predator and prey on predation efficacy. No significant interactions were identified between the number of rove beetle adults released and the initial number of prepupae ($F = 1.36$; df = 15, 95.99; $P = 0.19$) in Experiment 1; pupae ($F = 1.00$; df = 15, 96; $P = 0.46$) in Experiment 2; or the prepupae-pupae combination ($F = 1.07$; df = 15, 96; $P = 0.39$) in Experiment 3 on the estimated mean probability of western flower thrips adults captured on the yellow sticky cards. Therefore, results are presented as marginal mean estimates for each of the treatment factors.

Experiment 1 (prepupae). The estimated mean probability of western flower thrips adults captured on the yellow sticky cards was negatively affected when increasing numbers of rove beetle adults were released ($F = 31.11$; df = 5, 96; $P < 0.0001$; Fig. 1A). Specifically, the estimated mean probability of western flower thrips adults captured on the yellow sticky cards decreased significantly when the number of rove beetle adults released increased from one to three, four, or five. However, when two rove beetle adults were released, results were not significantly different from any of the other release numbers. Furthermore, there was no evidence of any effect of initial number of western flower thrips prepupae ($F = 0.15$;

Table 2. Mean (minimum, maximum) number of rove beetle, *Dalotia coriaria*, adults recovered at the end of Experiment 3 associated with treatment combinations consisting of five numbers (1, 2, 3, 4, and 5) of rove beetle adults initially released and initial numbers (15, 20, 25, and 30) of western flower thrips, *Frankliniella occidentalis*, for the prepupae-pupae combination (1:1).

Numbers of Rove Beetle Adults Initially Released	Initial Numbers of Western Flower Thrips for the Prepupae-Pupae Combination (1:1)			
	15	20	25	30
1	1.0 (1, 1)	1.0 (1, 1)	1.0 (1, 1)	1.0 (1, 1)
2	0.7 (0, 1)	1.0 (0, 2)	1.7 (1, 2)	1.7 (1, 2)
3	1.7 (1, 2)	1.7 (1, 2)	1.7 (1, 2)	1.3 (1, 2)
4	1.7 (1, 2)	2.0 (1, 3)	1.7 (0, 3)	3.0 (3, 3)
5	2.7 (2, 3)	1.7 (1, 3)	2.7 (2, 4)	3.7 (2, 5)

df = 3, 96; $P = 0.93$) on the estimated mean probability of western flower thrips adults captured on the yellow sticky cards.

Experiment 2 (pupae). The estimated mean probability of western flower thrips adults captured on the yellow sticky cards was negatively affected by the number of rove beetle adults released ($F = 56.95$; df = 5, 96; $P < 0.0001$; Fig. 1B), but there was no evidence of any effect of initial number of western flower thrips pupae ($F = 1.21$; df = 3, 96; $P = 0.31$). The estimated mean probability of western flower thrips adults captured on the yellow sticky cards was significantly higher when releasing one compared to four rove beetle adults. However, there was no evidence that the estimated mean probability of western flower thrips adults captured on the yellow sticky cards differed after releasing one, two, three, and five rove beetle adults or after releasing two, three, four, and five rove beetle adults (Fig. 1B).

Experiment 3 (prepupae-pupae combination). The estimated mean probability of western flower thrips adults captured on the yellow sticky cards was negatively affected by the number of rove beetle adults released ($F = 41.45$; df = 5, 96; $P < 0.0001$; Fig. 1C). However, there was no evidence of any effect of initial number associated with the western flower thrips prepupae-pupae combination ($F = 1.30$; df = 3, 96; $P = 0.28$). The estimated mean probability of western flower thrips adults captured on the yellow sticky cards was significantly higher when releasing one compared to three, four, and five rove beetle adults. Nonetheless, there was no evidence that the estimated mean probability of western flower thrips adults captured on the yellow sticky cards differed when either one or two rove beetle adults were released, or among releasing three, four, and five rove beetle adults (Fig. 1C).

Effects of predator–prey ratios, accounting for different initial prey numbers, on predation efficacy. **Experiment 1 (prepupae).** At the 1:15 predator:prey ratio, the estimated mean probability of western flower thrips adults

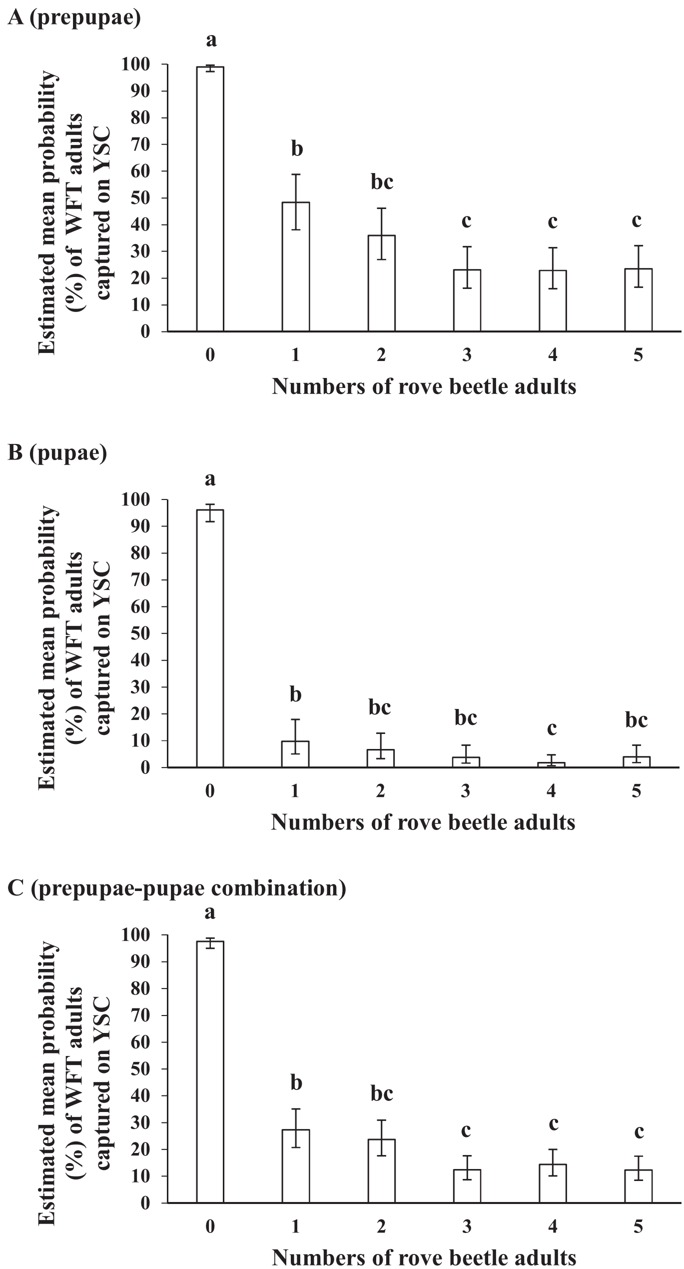

Fig. 1. Estimated mean probability (95% confidence intervals) of western flower thrips (WFT), *Frankliniella occidentalis*, adults captured on yellow sticky cards (YSC) when zero, one, two, three, four, and five rove beetle, *Dalotia coriaria*, adults were released in Experiment 1 [A (prepupae)], Experiment 2 [B (pupae)], and Experiment 3 [C (prepupae-pupae combination)].

Table 3. Predator:prey ratios, number of rove beetle (*Dalotia coriaria*) adults, number of western flower thrips (*Frankliniella occidentalis*) prepupae, and comparisons with the estimated mean probability (95% confidence intervals [CI]) of western flower thrips adults captured on yellow sticky cards for different initial prey numbers within each predator:prey ratio and among three predator:prey ratios (1:5, 1:10, and 1:15) in Experiment 1.

Predator: Prey Ratios	Number of Rove Beetle Adults	Number of Western Flower Thrips	Comparison Within Each Predator:Prey Ratio; Mean 95% CI, (%)*	Comparison Among Three Predator:Prey Ratios; Mean 95% CI, (%)**
1: 5	3	15	14.3 (6.6, 28.3) a	19.5 (12.9, 28.3) A
1: 5	4	20	26.2 (14.6, 42.3) a	
1: 5	5	25	19.3 (10.3, 33.2) a	
1: 10	2	20	35.3 (21.2, 52.6) a	30.2 (20.4, 42.2) AB
1: 10	3	30	25.5 (14.7, 40.6) a	
1: 15	1	15	68.7 (50.7, 82.4) b	51.2 (38.0, 64.1) B
1: 15	2	30	33.4 (20.4, 49.4) a	

* Estimated means followed by different lowercase letters within each predator:prey ratio are significantly different ($P < 0.05$).
** Estimated means followed by different uppercase letters among the three predator:prey ratios are significantly different ($P < 0.05$).

captured on the yellow sticky cards decreased significantly from 68.7% (50.7%, 82.4%) to 33.4% (20.4%, 49.4%) when the initial number of western flower thrips prepupae increased from 15 to 30. However, there was no evidence that the estimated mean probability of western flower thrips adults captured on the yellow sticky cards differed due to initial prey numbers within the 1:10 ($t = 1.00$, df $= 59.96$, $P = 0.32$) or 1:5 predator:prey ratio ($F = 0.97$; df $= 2, 93$; $P = 0.38$; Table 3).

After adjusting for the initial number of western flower thrips prepupae, the estimated mean probability of western flower thrips adults captured on the yellow sticky cards at the 1:5 predator:prey ratio (19.5% [12.9%, 28.3%]) was significantly lower than the 1:15 predator:prey ratio (51.2% [38%, 64.1%]). However, the estimate at the 1:10 predator:prey ratio (30.2% [20.4%, 42.2%]) was not significantly different from the other predator:prey ratios (1:5 and 1:15) (Table 3).

Experiment 2 (pupae). There was no evidence of any differences in the estimated mean probability of western flower thrips adults captured on the yellow

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Estimated means followed by different letters within each experiment indicate significant differences ($P < 0.05$) among different numbers of rove beetle adults released.

Table 4. Predator:prey ratios, number of rove beetle (*Dalotia coriaria*) adults, number of western flower thrips (*Frankliniella occidentalis*) pupae, and comparisons with the estimated mean probability (95% confidence intervals [CI]) of western flower thrips adults captured on yellow sticky cards for different initial prey numbers within each predator:prey ratio and among three predator:prey ratios (1:5, 1:10, and 1:15) in Experiment 2.

Predator: Prey Ratios	Number of Rove Beetle Adults	Number of Western Flower Thrips	Comparison Within Each Predator:Prey Ratio; Mean 95% CI, (%)*	Comparison Among Three Predator:Prey Ratios; Mean 95% CI, (%)**
1: 5	3	15	5.4 (1.4, 17.9) a	2.8 (1.0, 7.3) A
1: 5	4	20	0.9 (0.1, 7.6) a	
1: 5	5	25	4.4 (1.3, 13.7) a	
1: 10	2	20	7.8 (2.6, 21.3) a	6.7 (2.9, 14.8) A
1: 10	3	30	5.8 (1.9, 16.2) a	
1: 15	1	15	14.2 (5.0, 34.1) a	8.9 (3.9, 18.9) A
1: 15	2	30	5.4 (1.8, 15.4) a	

* Estimated means followed by different lowercase letters within each predator:prey ratio are significantly different ($P < 0.05$).

** Estimated means followed by different uppercase letters among the three predator:prey ratios are significantly different ($P < 0.05$).

sticky cards among the predator:prey ratios ($F = 2.15$; df = 2, 96; $P = 0.12$) or among different initial prey numbers within each predator:prey ratio (1:5 ratio: $F = 1.11$; df = 2, 96; $P = 0.33$; 1:10 ratio: $t = 0.42$, df = 70.29, $P = 0.68$; and 1:15 ratio: $t = 1.40$, df = 66.08, $P = 0.17$; Table 4).

Experiment 3 (prepupae-pupae combination). At the 1:10 predator:prey ratio, the estimated mean probability of western flower thrips adults captured on the yellow sticky cards decreased significantly from 38.7% (23.8%, 56.1%) to 7.5% (3.4%, 15.8%) when the initial number of western flower thrips prepupae-pupae combination increased from 20 to 30. However, there was no evidence of any significant differences due to initial prey number at the 1:5 ($F = 0.38$; df = 2, 86.43; $P = 0.69$) or 1:15 predator:prey ratio ($t = 1.72$, df = 68.51, $P = 0.091$). In addition, there was no evidence of any significant differences in the estimated mean probability of western flower thrips adults captured on the yellow sticky cards among the three predator:prey ratios ($F = 0.76$; df = 2, 77.63; $P = 0.47$; Table 5).

Discussion

In this study, we quantitatively and indirectly evaluated the predation efficacy of rove beetle adults on western flower thrips pupal populations (prepupae and pupae). Overall, for each pupal population, the estimated mean probability of

Table 5. Predator:prey ratios, number of rove beetle (*Dalotia coriaria*) adults, number of western flower thrips (*Frankliniella occidentalis*) associated with the pupal population (prepupae and pupae) combination (1:1), and comparisons with the estimated mean probability (95% confidence intervals [CI]) of western flower thrips adults captured on yellow sticky cards for different initial prey numbers within each predator:prey ratio and among three predator:prey ratios (1:5, 1:10, and 1:15) in Experiment 3.

Predator: Prey Ratios	Number of Rove Beetle Adults	Number of Western Flower Thrips	Comparison Within Each Predator:Prey Ratio; Mean 95% CI, (%)*	Comparison Among Three Predator:Prey Ratios; Mean 95% CI, (%)**
1: 5	3	15	16.2 (7.6, 31.1) a	16.8 (11.3, 24.1) A
1: 5	4	20	20.6 (10.9, 35.5) a	
1: 5	5	25	14.0 (7.0, 26.1) a	
1: 10	2	20	38.7 (23.8, 56.1) a	18.5 (11.6, 28.1) A
1: 10	3	30	7.5 (3.4, 15.8) b	
1: 15	1	15	32.5 (18.4, 50.7) a	23.5 (15.4, 34.2) A
1: 15	2	30	16.4 (8.7, 28.7) a	

* Estimated means followed by different lowercase letters within each predator:prey ratio are significantly different ($P < 0.05$).

** Estimated means followed by different uppercase letters among the three predator:prey ratios are significantly different ($P < 0.05$).

western flower thrips adults captured on the yellow sticky cards decreased as the number of rove beetle adults released increased from one to three; however, there was no effect after releasing additional rove beetle adults. Moreover, across the pupal populations evaluated in this study, there was no evidence of any differential effects associated with predator:prey ratios or initial prey number. Therefore, the results from this study provide insights into the potential predatory behavior of *D. coriaria* adults on the western flower thrips pupal populations which may have practical implications for successful implementation of biological control programs in greenhouse production systems. In addition, the pupal stages of western flower thrips are resistant to insecticides (Seaton et al. 1997). Therefore, *D. coriaria* may provide mortality on life stages that are difficult to manage with insecticides.

Selecting an appropriate predator:prey ratio 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, successful suppression has been achieved at ratios between 1:20 and 1:4 when using the predatory mite, *Phytoseiulus persimilis* (Athias-Henriot) (Acari: Phytoseiidae), against the twospotted spider mite, *Tetranychus urticae* (Koch) (Acari: Tetranychidae), on greenhouse ornamentals (Hamlen and Lindquist 1981). Moreover, Echegaray et al. (2015) recommended a 1:5 *D. coriaria* adult:fungus gnat, *Bradysia* sp. nr. *coprophila* (Lintner) (Diptera: Sciaridae), larvae release ratio for greenhouse producers after evaluating the predation efficacy of *D. coriaria* adults on fungus gnat larvae under laboratory conditions. 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, when predation efficacy was compared among predator:prey ratios in the experiments associated with pupae and the prepupae-pupae combination, the estimated mean probability of western flower thrips adults captured on the yellow sticky cards was not significantly different. As such, predation efficacy was not enhanced as the predator:prey ratio increased from 1:15 to 1:5. However, at the same initial prey number, fewer rove beetle adults need to be released at the predator:prey ratio of 1:15 compared to 1:10 and 1:5. Therefore, the 1:15 predator:prey ratio may be a practical recommendation for greenhouse producers when using *D. coriaria* adults against western flower thrips pupal populations in 15.2-cm containers.

Initial pest number may affect predation efficacy at a given predator:prey ratio (Echegaray et al. 2015). For instance, when the predatory mite *P. persimilis* was released at a ratio of 1:10 (*P. persimilis*: twospotted spider mite, *T. urticae*), flower damage to potted *Impatiens walleriana* Hook. f. plants was greater when the initial pest population was higher (Alatawi 2006). When *D. coriaria* adults were released at a 1:5 (*D. coriaria* adult:fungus gnat larvae) predator:prey ratio to suppress fungus gnat larval populations under laboratory conditions, the percent fungus gnat adults captured on the yellow sticky cards decreased significantly from 59% to 37.5% as the initial number of fungus gnat larvae increased from 10 to 20 (Echegaray et al. 2015). Similarly, our results with prepupae indicated that, at a 1:15 predator:prey ratio, the estimated mean probability of western flower thrips adults captured on the yellow sticky cards decreased significantly from 68.7% to 33.4% when the initial number of western flower thrips prepupae increased from 15 to 30. Furthermore, for the prepupae-pupae combination, the estimated mean probability of western flower thrips adults captured on the yellow sticky cards at a 1:10 predator:prey ratio decreased significantly from 38.7% at an initial number of 20 western flower thrips prepupae-pupae combination to 7.5% at an initial number of 30 western flower thrips prepupae-pupae combination. It is likely that searching time of rove beetle adults was reduced as prey number increased in the same searchable area.

This study is the first to evaluate predation of the rove beetle, *D. coriaria* on western flower thrips in 15.2-cm containers that are commonly used in greenhouse production systems (Reiley and Shry 2001). Previous studies associated with *D. coriaria* feeding on western flower thrips were conducted in either Petri dishes or relatively small containers (such as 5.5-cm-diameter cups). For instance, Carney et al. (2002) evaluated the potential predation (maximum number of prey consumed in 24 h) of *D. coriaria* on western flower thrips late second-instar larvae or pupae in Petri dishes under laboratory conditions. Moreover, Saito and Brownbridge (2016) assessed how integrating *D. coriaria* with entomopathogenic fungi or predatory mites would suppress populations of the soil-dwelling life stages (late second-instar larvae, prepupae, and pupae) of western flower thrips in 5.5-cm-diameter plastic cups (120 ml in volume). However, searchable area may affect the predation efficacy of *D. coriaria* on soil-dwelling prey (Echegaray et al. 2015; Herrick and Cloyd 2017, 2018). Therefore, this study was conducted in 15.2-cm containers (1,834.8 cm^3 with 1.2 L of growing medium) typically used to grow greenhouse horticultural plants (Reiley and Shry 2001). Consequently, the results of this study have practical value to greenhouse producers who want to use rove beetles in biological control programs against western flower thrips pupal populations. Furthermore, our findings indicate that, regardless of the initial number of western flower thrips prepupae, pupae, or prepupae-pupae combination in containers, three rove beetle adults per 15.2-cm container may be sufficient within the range of the initial prey number tested in this study.

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