Rove Beetle (Coleoptera: Staphylinidae) Predation on *Bradysia* sp. nr. *coprophila* (Diptera: Sciaridae)[1]

E.A. Echegaray, R.A. Cloyd[2], and J.R. Nechols

Department of Entomology, Kansas State University, Manhattan, Kansas 66506 USA

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Abstract Rove beetles (Coleoptera: Staphylinidae) are important predators of arthropods in soil habitats. However, minimal information is available on their effectiveness, including *Dalotia* (formerly *Atheta*) *coriaria* (Kraatz), which is a reported biological control agent of fungus gnats (*Bradysia* spp.) in greenhouses. In this study, predation by *D. coriaria* on *Bradysia* sp. nr. *coprophila*, was investigated in small containers (473 ml) in the laboratory using different numbers and ratios of predators and prey. In tests with 1–5 rove beetle adults and 10–40 fungus gnat larvae, predation was greatest at each prey density when four rove beetle adults were released, and lowest at three of four prey densities when five adult rove beetles were released. Per capita prey consumption was greatest when only one rove beetle was present, and predation efficiency decreased as predator numbers increased. This inverse relationship was strongest at the highest prey density (40 fungus gnat larvae). Thus, while using four rove beetle adults in conjunction with 10–40 fungus gnat larvae increased overall effectiveness (number of prey consumed), increasing the number of predators negatively affected predation efficiency. When predator and prey numbers were increased, the level of predation also increased, but only at the highest predator–prey ratio (1:5). At lower predator–prey ratios (1:10 and 1:20), adjusting numbers of predators and prey had no effect on predation. Based on our results, when used appropriately, *D. coriaria* may be a viable augmentative biological control agent of fungus gnats in greenhouse production systems.

Key Words biological control, prey consumption, predator–prey ratio, predation efficiency, predation efficacy

Studies of predator efficacy and efficiency are important in selecting suitable biological control agents for pest management (Farhadi et al. 2011) and for determining numbers to release in augmentative biological control programs. In greenhouse environments, natural enemies should respond rapidly to an increase in prey density, have high dispersal capacity, and survive at low prey densities (Albajes and Alomar 1999). However, in many cases, assessments to determine potential effectiveness of natural enemies, and the most efficient way to release them, have not been investigated before decisions to commercially produce and release biological control agents are made (Van Driesche and Heinz 2004). Because of low pest tolerance and the capacity of most greenhouse pests to increase their populations quickly, it is particularly important to understand how many natural enemies to release in order to achieve rapid pest suppression.

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[2]Corresponding author (email: rcloyd@ksu.edu).

Therefore, experiments involving predator–prey (or parasitoid–host) ratios are common (Chen et al. 2012, Gaudchau 1982, Gilkeson and Hill 1987, Opit et al. 2004).

This study focused on the rove beetle, *Dalotia* (formerly *Atheta*) *coriaria* (Kraatz), as a potential biological control agent of the fungus gnat, *Bradysia* sp. nr. *coprophila* (Lintner). *Dalotia coriaria* is a small predacious staphylinid beetle about 3–4 mm long and dark brown in color (Miller and Williams 1983). Adults are mobile and are capable of flying long distances, although they tend to spend most of their life span in growing media (Helyer et al. 2003). Both adults and larvae may feed on various life stages of certain insect pests, including fungus gnats, shore flies, and thrips (Helyer et al. 2003).

Fungus gnats are a serious pest in greenhouses worldwide (Dennis 1978, Hamlen and Mead 1979). Therefore, it would be useful to expand the number of augmentative biological control agents for which release information is available. Currently, the entomopathogenic nematode *Steinernema feltiae* Filipjev is widely used to suppress fungus gnat populations in soil/growing medium (Gouge and Hague 1995, Jagdale et al. 2004) and the predatory mite, *Stratiolaelaps scimitus* (Wormersley), formerly *Hypoaspis miles* (Berlese), is also available for commercial use (Walter and Campbell 2003, Wright and Chambers 1994). In addition, the hunter fly, *Coenosia attenuata* (Stein), has been shown to prey on fungus gnat larvae (Ugine et al. 2010). Among the other rove beetles that serve as predators (Devi et al. 2003, Padmavathi et al. 2008, Read 1962), the role and impact of *D. coriaria* is comparatively less well known. Therefore, our specific objectives were to ascertain how varying the number of predators relative to prey affected prey consumption by *D. coriaria* adults as well as predation efficiency. An initial experiment was conducted to test whether *D. coriaria* feeding status (degree of satiation) and fungus gnat larval instar affected prey consumption. The results obtained in this study contribute to providing a more comprehensive assessment of the effectiveness of *D. coriaria* as a biological control agent.

Materials and Methods

To assess the effect of predator feeding status and prey instar on prey consumption, a no-choice experiment was conducted in petri dishes (see details below). Experiments associated with predation efficiency and efficacy were conducted in 473-ml deli squat containers (Fabri-Kal Corp., Kalamazoo, MI) using Sunshine LC1 Professional Growing Mix growing medium (Sun Gro Horticulture, Inc., Bellevue, WA) as a substrate consisting of Canadian sphagnum peat moss (73–83%), perlite, and dolomitic lime. All experiments were conducted at temperatures between 22 and 24°C, 40–60% relative humidity (HOBO data loggers: Onset, MicroDaq, Contoocook, NH), and in total darkness. The procedures for rearing rove beetle colonies were the same as those described in Birken and Cloyd (2007).

Effect of prey instar and predator feeding status on prey consumption. To determine whether fungus gnat larval instar and predator feeding status affects prey consumption by *D. coriaria*, a 2-by-2 factorial experiment was conducted with instar (second- or third-instar fungus gnat larvae) as one factor and predator feeding

status (24-h starved or unstarved rove beetle adults) as the other factor. This resulted in four treatment combinations, which were replicated 10 times within 2 d. Second-instar (6–7 d old) and third-instar (8–9 d old) fungus gnat larvae were obtained based on the following procedure. A total of 10 fungus gnat larvae were collected from a fungus gnat–inoculated Sunshine LC1 Professional Growing Mix growing medium sample using a 150-mm disposable flint glass nonsterile Pasteur pipet (Fisher Scientific®, Pittsburgh, PA) and then placed into a 50 × 15-mm glass petri dish filled with 10–15 ml of water. Subsequently, 1.6 ml of water was poured into the 100 × 15-mm glass petri dish using a 10-ml-capacity plastic graduated cylinder. The bottom of the petri dish was lined with 90-mm-diameter filter paper (Whatman Int. Ltd., Maidstone, U.K.). Larvae were collected individually using the Pasteur pipet, transferred to the glass petri dish, and counted. Afterward, 2.0–2.2 ml of water was added to the petri dish. A single rove beetle (male or female) adult (<24 h old) was placed into the petri dish, and the number of fungus gnat larvae consumed was determined after 24 h by counting the number of head capsules, which served as a visual assessment of larvae consumed, and live fungus gnat larvae (larvae not consumed) in the petri dish for each treatment combination (starved and nonstarved rove beetle with second-instar fungus gnat larvae, and starved and nonstarved rove beetle with third-instar fungus gnat larvae) under a dissecting microscope. The number of head capsules and fungus gnat larvae was recorded.

Predation efficacy and per capita prey consumption by rove beetle adults at different prey densities, and predator:prey ratios. Based on the outcome of the feeding status and prey larval instar experiment in which there was no difference in consumption of fungus gnat larval instars (no-choice test) or effect of starvation on predators (see Results), a mixture of second- and third-instar larvae and unstarved rove beetles were used to assess prey consumption at different predator and prey (fungus gnat larvae) densities. Two series of experiments were conducted independently of one another. In each, one to five adult rove beetles and four densities of fungus gnat larvae (10, 20, 30, and 40) were included. In one series of experiments, all four fungus gnat densities were compared with each adult rove beetle number (1, 2, 3, 4, or 5), which was done independently in time. Predation was assessed based on the number of fungus gnat adults that emerged. In the other series of experiments, one to five rove beetle adults were compared at each of the four prey densities, with each prey density tested separately in time. Here, the degree of predation was measured as the number of prey consumed. Most of the treatments had 10 replications (one predator treatment for one experiment had only eight replications), and half of the replications were done on each of two consecutive days. Thus, time (Day 1 or Day 2) was evaluated as a block effect. In all experiments, replications and treatments were spatially arranged in a completely randomized design. To determine if predator efficiency was influenced by the number of predators competing for prey, the total number of prey consumed (or total number of fungus gnat adults that emerged) was divided by the number of predators in a given treatment. Thus, predation could be assessed on a per capita basis to evaluate efficiency. To compare predation within and among predator–prey ratios, ratios were determined for the various combinations of predators and prey that were tested across the experiments, resulting in three predator:prey ratios—1:5, 1:10, and 1:20.

For the experiments described above, the substrate was prepared based on the following procedure. A 6.0-L plastic container (Rubbermaid Home Products, Wooster, OH) was filled with Sunshine LC1 Growing Mix growing medium and then heated for 10 min at full power (1,200-W output) in a microwave. After cooling, 300 ml of growing medium were measured using a 600-ml beaker and placed into a 473-ml deli squat container, which is very similar in volume to a 10.1-cm container used in greenhouse production. Ventilation was provided by a modified lid with insect screening. Subsequently, 70 ml of water and approximately 3 g of raw oatmeal (The Quaker Oats Company, Chicago, IL) was added to the growing medium, and then thoroughly mixed using a spatula. Deli squat containers were labeled accordingly and maintained in an environmental growth chamber (CONVIRON® Controlled Environments Inc., Pembina, ND) at a temperature of 25 ± 2°C and total darkness for 48 h prior to being artificially infested with fungus gnat larvae.

Fungus gnat adults were collected from an established laboratory colony in 33.27-ml plastic vials using an aspirator before being placed into a 739-ml Rubbermaid container, which served as an oviposition chamber. The oviposition chamber consisted of a 100 × 15-mm glass petri dish lined with 90-mm filter paper, approximately 20 ml of moistened growing medium, and 1–2 g of raw oatmeal. The oviposition chamber was placed into the environmental growth chamber for 6–7 d in order to obtain a sufficient number of same-aged fungus gnat larvae.

A fungus gnat–infested growing medium sample (approximately 10 g) was placed into a 50 × 15-mm glass petri dish using a spatula, and water was added to loosen the growing medium. A total of 10, 20, 30, and 40 fungus gnat larvae were collected using a 150-mm disposable flint glass nonsterile Pasteur pipet, and then placed into a 50 × 15-mm glass petri dish filled with 8–10 ml of water. Larvae were counted and then the entire contents were poured into the deli squat container with 300 ml of growing medium. After all the deli squat containers were infested with fungus gnat larvae, they were placed in the environmental growth chamber for 24 h prior to introducing rove beetle adults.

One to five rove beetle adults (different ages and sexes) were collected from the main colony into 33.27-ml plastic vials using an aspirator, and then placed into the deli squat containers. Rove beetle adults from the main colony were maintained at a temperature of 24 ± 2°C, 50–60% relative humidity, and 12:12 (L:D) hour photoperiod 48 h after releasing the rove beetles. After releasing rove beetle adults into the deli squat containers with growing medium, all the containers were maintained under ambient laboratory conditions (22 ± 2°C; 40–60% relative humidity, and total darkness). Moisture was provided by placing each deli squat container into a 14-cm-diameter dish filled with 60 ml of water. Small holes, which had been perforated in the base of the containers, allowed the water to migrate up, via capillary action, and moisten the growing medium. After 10 d, yellow sticky card sections (2.5 × 2.5 cm in area) were glued to the inside of the deli squat container lids. After 7 d, data were collected by counting the number of fungus gnat adults captured on the yellow sticky cards.

Statistical analysis. Data from all three experiments were analyzed using a statistical analysis software program SAS Systems for Windows, version 9.2 (SAS Institute 2002). Data for the experiment that assessed prey consumption using starved and unstarved rove beetles on second- and third-instar fungus gnat larvae

were subjected to a general linear model (GLM) 2-by-2 factorial design analysis of variance (ANOVA) using the PROC GLM procedure, with the number of second- and third-instar fungus gnat larvae consumed as the dependent variable and fungus gnat larval instar and rove beetle feeding status (starved or nonstarved) as the main effects. Significance was determined for the two variables and the two-way interaction. Data associated with the predator–prey ratios (percent fungus gnat adults recovered) and per capita prey consumption at different fungus gnat larval densities were transformed using an arcsine transformation to normalize the data prior to analysis. Then, data affiliated with the number of fungus gnat adults recovered, per capita prey consumption, and prey consumption at different predator and prey densities with common or different ratios were subjected to ANOVA using the PROC ANOVA procedure (SAS Institute 2002). There was no significant block (time) effect for any of the experiments ($P > 0.05$). Therefore, data were pooled for both experimental days before performing mean separation tests. Significant differences among the means were determined using a Tukey's mean separation test with a significance level of $P \leq 0.05$. The data were expressed as percentages in order to correct for the differences in the actual numbers between the various predator:prey ratios.

Results

Effect of prey instar and predator feeding status on prey consumption. There were no significant effects on prey consumption associated with fungus gnat larval instars ($F = 1.42$; df = 1; $P < 0.24$), adult rove beetle feeding status ($F = 3.25$; df = 1; $P = 0.08$), or with the two-way interaction between feeding status and larval instar ($F = 0.23$; df = 1; $P = 0.63$). The number of second- and third-instar fungus gnat larvae consumed by individual rove beetles (starved and nonstarved combined) was 6.3 ± 0.5 and 7.1 ± 0.5 (mean ± SEM), respectively, which did not differ statistically ($F = 1.36$; df = 1, 39; $P = 0.25$). In addition, there were no significant differences ($F = 4.03$; df = 1, 39; $P = 0.05$) in prey consumption between starved (7.5 ± 0.6) and nonstarved (6.2 ± 0.4) rove beetles when pooled over prey larval instars.

Predation efficacy and per capita prey consumption by rove beetle adults at different prey densities, and predator:prey ratios. Results from the experiments in which both rove beetle and fungus gnat numbers varied are presented in Tables 1 through 3. There was a significant difference associated with the different rove beetle numbers (1–5) and initial fungus gnat larval numbers (10, 20, 30, and 40) (one rove beetle adult [$F = 33.86$; df = 3, 39; $P \leq 0.0001$], two rove beetle adults [$F = 67.76$; df = 3, 39; $P \leq 0.0001$], three rove beetle adults [$F = 32.16$; df = 3, 39; $P \leq 0.0001$], four rove beetle adults [$F = 22.28$; df = 3, 39; $P \leq 0.0001$], and five rove beetle adults [$F = 71.59$; df = 3, 39; $P \leq 0.0001$]) as shown in Table 1. Predictably, the number of fungus gnat adults recovered was directly related to the number of fungus gnat larvae exposed to rove beetle adults (Table 1). However, the reduction in fungus gnat adults varied with the number of rove beetles released. At all fungus gnat larval densities, the greatest reduction in fungus gnat adult numbers was observed when four rove beetle adults were released, and efficacy diminished as rove beetle numbers decreased (Fig. 1). However, fungus gnat numbers were

Table 1. Number of fungus gnat, *Bradysia* sp. nr. *coprophila*, adults recovered (mean ± SEM) after infesting the growing medium (Sunshine LC1 Professional Growing Mix; Sun Gro Horticulture, Inc., Bellevue, WA) with 10, 20, 30, or 40 fungus gnat larvae and releasing 1, 2, 3, 4, or 5 rove beetle, *Dalotia coriaria*, adults; *n* = number of replications.

Initial Number of Fungus Gnat Larvae	Number of Rove Beetle Adults per 473-ml Deli Squat Container				
	1 (*n* = 10)	2 (*n* = 10)	3 (*n* = 10)	4 (*n* = 8)	5 (*n* = 10)
10	6.4 ± 0.6 c*	5.9 ± 0.4 c*	5.7 ± 0.4 b*	4.9 ± 0.5 b*	9.4 ± 0.6 c*
20	13.2 ± 1.2 b	11.0 ± 1.3 b	9.0 ± 1.1 b	7.5 ± 1.1 b	9.8 ± 1.0 c
30	18.4 ± 1.3 a	20.7 ± 1.1 a	16.8 ± 1.2 a	13.8 ± 1.8 a	22.7 ± 1.2 b
40	21.6 ± 1.3 a	21.6 ± 0.7 a	18.8 ± 1.5 a	17.6 ± 1.0 a	28.1 ± 1.5 a

* Means followed by the same letter within a column are not significantly different ($P \geq 0.05$) as determined by a Tukey's means separation test.

the highest at all prey densities when five rove beetle adults were released (Table 1).

Over the range of fungus gnat densities tested (10–40 per container), the per capita consumption of fungus gnat larvae by rove beetle adults decreased as the number of predators increased (Table 2). Thus, predation efficiency was generally significantly higher when one rove beetle was released than when multiple predators were present. In most cases, predation was significantly the lowest when

Table 2. Per capita number of fungus gnat, *Bradysia* sp. nr. *coprophila*, larvae consumed (mean ± SEM) when different numbers of the rove beetle, *Dalotia coriaria*, adults were released into 473-ml deli squat containers with 10, 20, 30, or 40 fungus gnat larvae. There were 10 replications per treatment.

Number of Rove Beetle Adults per 473-ml Deli Squat Container	Initial Number of Fungus Gnat Larvae			
	10	20	30	40
1	3.6 ± 0.6 a*	7.0 ± 1.1 a*	11.6 ± 1.3 a*	18.4 ± 1.3 a*
2	2.1 ± 0.2 b	4.5 ± 0.6 ab	4.7 ± 0.5 b	9.2 ± 0.4 b
3	1.4 ± 0.1 b	3.7 ± 0.4 ab	4.4 ± 0.4 b	7.1 ± 0.5 bc
4	1.3 ± 0.1 b	3.1 ± 0.3 b	4.1 ± 0.5 b	5.6 ± 0.3 c
5	0.2 ± 0.1 c	2.0 ± 0.2 b	1.5 ± 0.2 c	2.4 ± 0.3 d

* Means followed by the same letter within a column are not significantly different ($P \geq 0.05$) as determined by a Tukey's means separation test.

Table 3. Percent fungus gnat, *Bradysia* sp. nr. *coprophila*, adults recovered after infesting the growing medium with fungus gnat larvae and releasing rove beetle, *Dalotia coriaria*, adults at different predator and prey densities and predator:prey ratios of 1:5, 1:10, and 1:20; *n* = number of replications.

Number of Predators	*n*	Number of Prey	Predator:Prey Ratio	Percent Fungus Gnat Adults Recovered
2	10	10	1:5	59.0 ± 3.8 a*
4	8	20	1:5	37.5 ± 5.5 b
1	10	10	1:10	64.0 ± 5.6 a*
2	10	20	1:10	55.0 ± 6.3 a
3	10	30	1:10	56.8 ± 3.8 a
4	8	40	1:10	44.1 ± 2.6 a
1	10	20	1:20	65.0 ± 5.4 a*
2	10	40	1:20	54.0 ± 1.8 a

* Means followed by the same letter within a predator:prey ratio (1:5, 1:10, and 1:20) are not significantly different ($P \geq 0.05$) as determined by a Tukey's means separation test.

five rove beetle adults were present (Table 2). Per capita prey consumption was also influenced by prey density. For any given number of rove beetles released, the number of prey consumed per predator generally increased with increasing prey density (Table 2). However, the rate of increase differed depending on the number of predators competing for prey. The density-dependent increase in predation was greatest when only one predator was present, and density-dependent increases in prey consumption was progressively more gradual as the number of predators increased (Fig. 2).

When the percentages of fungus gnat adults recovered were compared for different numbers of predators and prey at the same predator:prey ratio, there was a significant difference at the 1:5 ratio ($F = 10.90$; df = 1, 17; $P = 0.0045$) but not at 1:10 ($F = 2.34$; df = 3, 37; $P = 0.0911$) or 1:20 ($F = 3.18$; df = 1, 19; $P = 0.0913$) (Table 3). However, as prey numbers increased there was a general trend for less predation at all predator–prey ratios (Table 3). Comparisons between predator:prey ratios (based on pooling all data within the predator:prey ratios) showed that the number of fungus gnat adults recovered was significantly greater ($F = 32.21$; df = 2, 53; $P \leq 0.0001$) at the 1:20 predator:prey ratio than at 1:10 or 1:5.

Discussion

In this study, rove beetle adults consumed fungus gnat second- and third-instar larvae equally, and the number of larvae consumed by starved rove beetles did not differ significantly from nonstarved rove beetles. These results suggest that predation on fungus gnat populations by *D. coriaria* adults may be similar

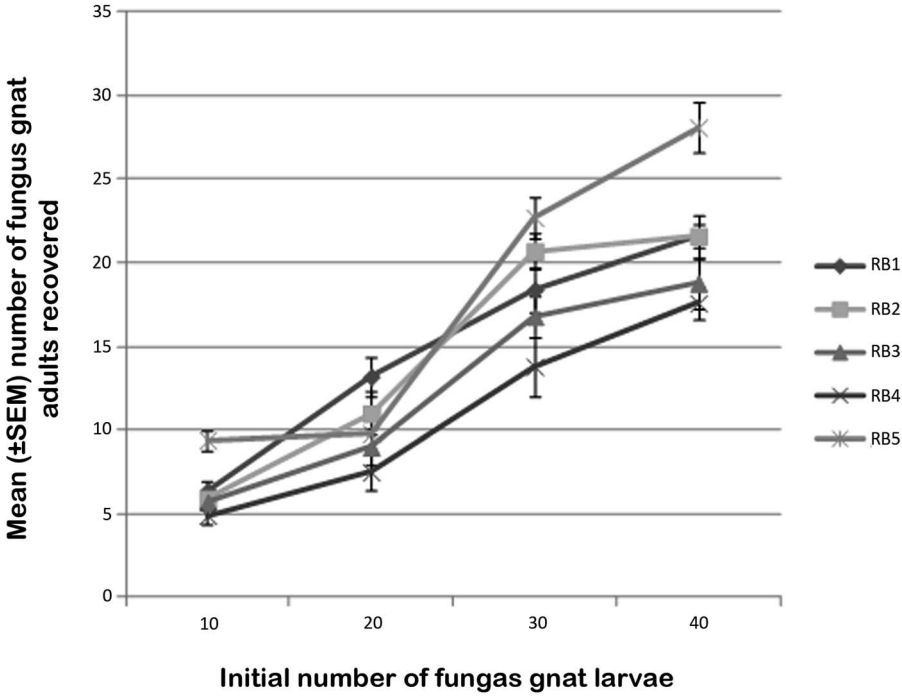

Fig. 1. Mean number (± SEM) of fungus gnat, *Bradysia* sp. nr. *coprophila*, adults recovered associated with increasing numbers of the rove beetle (RB), *Dalotia coriaria*, adults (RB1–RB5) and fungus gnat larvae (10–40). Vertical lines represent the standard error of the means.

regardless of the fungus gnat instar larvae encountered or the feeding status of the rove beetle. However, because rove beetles were starved for only 24 h in the present study, it is possible that a longer period of starvation may have resulted in a different level of predation. Also, because we did not give predators a choice of fungus gnat instars, we cannot state conclusively whether rove beetles would exhibit equal rates of prey consumption in situations where they encounter different fungus gnat larval instars.

Predation efficiency (as defined by per capita prey consumption) tended to decrease as predator numbers increased, and there was a reduction in efficiency for all treatments above one rove beetle (Fig. 2). This trend was evident for all prey densities tested. Predation efficiency was consistently the lowest when five rove beetles were released. A decrease in predation efficiency as the number of adult rove beetles released increased may have been due to mutual interference. Mutual interference is a common phenomenon affiliated with low prey availability or high predator density (Hassell et al. 1976). For the rove beetle, *Paederus fuscipes* (Curtis), mutual interference was demonstrated at high densities when predators fed on eggs of the rice leafroller, *Cnaphalocrocis medinalis* (Guenée) (Shen and Pang 1989).

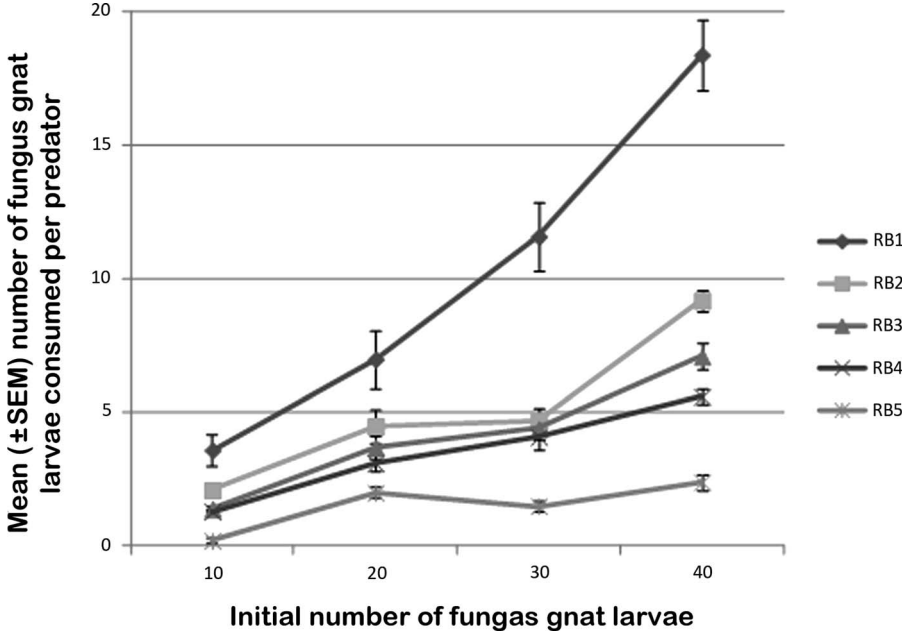

Fig. 2. Per capita prey consumption associated with increasing numbers of the rove beetle, *Dalotia coriaria*, adults (RB1–RB5) and fungus gnat, *Bradysia* sp. nr. *coprophila*, larvae (10–40). Vertical lines represent the standard error of the means.

In contrast to our findings associated with predation efficiency, total prey consumption by *D. coriaria* increased as the number of adult rove beetles released increased, reaching a maximum at four rove beetles. However, when five rove beetles were released, the lowest total prey consumption was observed, as indicated by the highest mean number of fungus gnat adults at the end of the experiment (Table 1). The decline in total predation could be related to interference competition as well as other factors, including shortened life spans of adult predators, lack of sufficient moisture in the containers (which could have an impact on rove beetle survival, therefore reducing the number of predators in the containers), and/or cannibalism. In fact, cannibalism among adult *D. coriaria* is common under laboratory conditions when crowding occurs (Miller and Williams 1983). A study by Cloyd and Chiasson (2007), which evaluated predation of fungus gnat larvae by *D. coriaria* adults under similar temperature and container conditions as in the current study, showed that when five rove beetle adults were released into a container with a density of 20 fungus gnat larvae, the mean emergence of fungus gnat adults was 15 and 16 for second- and third-instar larvae, respectively. This was higher than the mean emergence (approximately 10 fungus gnats) we observed in our study using the same number of rove beetle adults and a mixture of second- and third-instar fungus gnat larvae. The reason for these differences may be associated with the growing medium used. For example, Cloyd and Chiasson

(2007) used Universal SB300 Mix (SunGro Horticulture, Pine Bluff, AZ) that contains pine bark compost, Canadian sphagnum peat, horticultural vermiculite, and perlite; whereas in our study we used Sunshine LC1 Professional Growing Mix, which contains Canadian sphagnum peat moss and perlite. Growing medium could either directly affect fungus gnat larval survival (Lindquist et al. 1985) or influence rove beetle efficacy. This suggests that possible direct and indirect effects of growing medium require further investigation.

After releasing a single rove beetle adult, there was a positive density-dependent response in prey consumption that did not diminish at the highest fungus gnat larval density tested. Our data fit the Type I functional response as described by Holling (1959). Miller and Williams (1982) also reported a Type I functional response for *D. coriaria* to a different prey species (eggs of *Stelidota germinate* Say). As per Holling (1959), this predicts that higher fungus gnat larval densities are consumed by rove beetle adults until the predation curve associated with prey (fungus gnat larvae) consumption reaches a plateau (saturation level). However, for most insect predators, a Type II functional response is typical where the rate of prey consumption declines gradually over time. Therefore, in our study and that of Miller and Williams (1982), it is possible that the maximum number of prey exposed was not high enough to reach a saturation level. This may be relevant in adjusting release rates of rove beetles because fungus gnat larval densities higher than what we tested commonly occur in some greenhouse situations.

When predation was compared according to predator:prey ratio (Table 3), the percentage of fungus gnat adults recovered was statistically higher at the 1:10 and 1:20 ratios than at the 1:5 ratio, suggesting that predators were unable to consume many of the prey before they had completed larval development at the two lower ratios. Selecting the appropriate predator:prey ratio is key to achieving successful augmentative biological control. However, for *D. coriaria*, as with other predators, the ratio that provides effective suppression may vary depending on several factors, including the search area/volume, initial pest density, and pest population growth potential. With respect to the search environment, our study was conducted in relatively small containers (similar to 10.1 cm), which are typical for propagating many greenhouse-grown plants. Thus, recommending a 1:5 rove beetle:fungus gnat release ratio may be suitable for producers who are using small containers. However, adjusting the predator release rate would be needed, with an increased proportion of predators as container size increased.

Pest density can also impact the efficacy of a given predator:prey ratio. For example, when the predatory mite, *Phytoseiulus persimilis* Athias-Henriot, was released at a 1:10 ratio, which typically provides adequate suppression of twospotted spider mite (*Tetranychus urticae* Koch) populations, floral damage to potted *Impatiens walleriana* Hook. f. plants were greater when the initial pest population was larger (Alatawi et al. 2007). It was concluded that the capacity for aesthetic damage before biological control could occur was greater when the initial pest density was higher. Similarly, our study with fungus gnats showed that, at a fixed predator:prey ratio, the level of biological control differed depending on the number of prey. However, in contrast to the findings of Alatawi et al. (2007) where plant damage was used as an indicator of the effectiveness of predator:prey ratio, we observed a statistically greater suppression of fungus gnats by rove beetles when prey were more abundant, but only at the 1:5 ratio

(Table 3). In fact, at all three predator:prey ratios, there was a trend for fewer fungus gnat adults emerging when pest numbers were higher. In all treatments, because more predators were released when there was more prey (rove beetle numbers ranged from one to four in the comparisons), we associate the higher levels of prey suppression with there being more rove beetle adults foraging for prey in the relatively small containers. This conclusion is consistent with the data in Table 1 and Fig. 1, which showed a general decrease in fungus gnat adult emergence as the number of rove beetles released increased up to four predators. Regardless of predator:prey ratio or the numbers of predator and prey evaluated, predation never exceeded 50%. A thorough examination of the growing medium showed that fungus gnat larvae were able to avoid predation by hiding inside potato, *Solanum tuberosum* L., granules soon after infestation (Echegaray 2012), which may partly explain the low predation rates.

Our experiment was a short-term assessment that did not include pest reproductive potential. However, because more fungus gnat progeny are produced within a generation than rove beetles, it is possible that a higher predator:prey ratio may be required for longer-term suppression of fungus gnat populations. But prey consumption by rove beetles intensifies as fungus gnat larval populations increase (Echegaray 2012), which could offset pest population growth and mitigate crop losses. However, predator release rates cannot be determined until relationships between predators and pest population growth, and pest populations on crop loss resulting in economic thresholds have been established. Therefore, further research under greenhouse conditions is warranted. Although a certain level of plant damage may occur when using rove beetles as the only management strategy, overall, rove beetle adults may be useful in suppressing fungus gnat populations, and may subsequently reduce the need for insecticide applications. This is the first study to estimate the predation efficiency and efficacy of *D. coriaria* against *B.* sp. nr. *coprophila* under conditions similar to those under greenhouse production systems. Therefore, this study has quantitatively shown that the rove beetle is, in fact, a viable biological control agent that when used appropriately can suppress fungus gnat populations.

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