Compatibility of *Atheta coriaria* with other biological control agents and reduced-risk insecticides used in greenhouse floriculture integrated pest management programs for fungus gnats

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Abstract—Fungus gnats (FG) (Diptera: Sciaridae: *Bradysia* spp.) are economically important pests of greenhouse flowers. Larvae feed on root tissue and transmit a variety of phytopathogens. *Atheta coriaria* (Kraatz) (Coleoptera: Staphylinidae) is a new biological control agent (BCA) for FG. To support its successful use by the greenhouse industry, its compatibility with current integrated pest management (IPM) programs used in floriculture was assessed. This included investigations of prey preference, possible detrimental interactions with other soil-dwelling BCAs, and the toxicity to *A. coriaria* of registered and novel insecticides. *Atheta coriaria* showed little preference among eggs of different pest species or between pest eggs and eggs of the intraguild predator *Hypoaspis aculeifer* (Canestrini) (Acari: Mesostigmata: Laelapidae). It preferred FG 1st-instar larvae to larvae and pupae of other soil-dwelling pests. The entomopathogenic nematode *Steinernema feltiae* (Filipjev) (Rhabditida: Steinernematidae) was compatible with *A. coriaria*, but *H. aculeifer* mites fed on *A. coriaria* larvae. Insect growth regulators with limited contact activity (e.g., diflubenzuron) were compatible with adult *A. coriaria* and had minimal effects on larvae compared with other insecticides. *Atheta coriaria* can be incorporated into an IPM program for FG if harsh insecticides are avoided, but interactions with predatory mites, as well as its effectiveness against other greenhouse pests when FG are present, require further investigation.

Résumé—Les sciarides (FG) (Diptera : Sciaridae : *Bradysia* spp.) sont des ravageurs d'importance économique des fleurs de serre. Les larves se nourrissent de tissus radiculaires et transmettent une variété de pathogènes. *Atheta coriaria* (Kraatz) (Coleoptera : Staphylinidae) est un nouvel agent de lutte biologique (BCA) contre les FG. Afin de favoriser l'utilisation efficace de cet agent par l'industrie de la culture en serres, nous évaluons sa compatibilité avec les programmes courants de lutte intégrée (IPM) en vigueur en floriculture. Cette évaluation comprend des études de préférence de proies, d'interactions potentiellement nuisibles avec d'autres BCA vivant dans le sol et de toxicité des insecticides enregistrés et nouveaux pour *A. coriaria*. *Atheta coriaria* montre peu de préférence pour les oeufs des différentes espèces de ravageurs et ne distingue pas entre les oeufs des ravageurs et ceux du prédateur de même guild *Hypoaspis aculeifer* (Canestrini) (Acari : Mesostigmata : Laelapidae). Il préfère les larves de premier stade de FG.

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aux larves et aux nymphes des autres ravageurs habitant le sol. Le nématode entomopathogène *Steinernema feltiae* (Filipjev) (Rhabditida : Steinernematidae) est compatible avec *A. coriaria*, mais les acariens *H. aculeifer* se nourrissent des larves d'*A. coriaria*. Les régulateurs de croissance d'insectes avec peu d'activité de contact (*par ex.*, le diflubenzuron) sont compatibles avec les adultes d'*A. coriaria* et ont un effet minimal sur les larves par comparaison aux autres insecticides. *Atheta coriaria* peut être intégré à un programme IPM pour les FC, si on évite les insecticides durs; il faut cependant étudier plus à fond ses interactions avec les acariens prédateurs, ainsi que son efficacité vis-à-vis des autres ravageurs des serres lorsqu'il y a des FC.

[Traduit par la Rédaction]

Introduction

Fungus gnats (FG) (Diptera: Sciaridae: *Bradysia* spp.), Western flower thrips (WFT), *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), and shore flies (SF), *Scatella stagnalis* Fallen (Diptera: Ephydriidae), are major pests of greenhouse flowers. FG larvae, ubiquitous in greenhouse crop production, feed on plant roots, reducing root mass and plant size (Harris *et al.* 1996). More significantly, FG transmit crown and root rot diseases, including those caused by *Botrytis*, *Fusarium*, *Pythium*, *Phoma*, and (or) *Verticillium* spp. (Kalb and Miller 1986; Farvin *et al.* 1988; Gillespie and Menzies 1993; Jarvis *et al.* 1993). WFT are difficult and expensive to control because of cryptic life stages (Seaton *et al.* 1997) and their resistance to many insecticides (Broadbent and Pree 1997). WFT injure hosts by feeding and vectoring diseases such as the *Tomato spotted-wilt virus* and *Impatiens necrotic spot virus* (Moyer and Daub 1994). SF, the least damaging of the three insects, can occur in high numbers in greenhouses and deposit large amounts of frass on foliage, making plants unappealing to consumers. Although they do not directly damage plant material, SF can disseminate *Pythium* spores (Goldberg and Stanghellini 1990). In the case of each of the above pests, at least one life stage lives in the soil.

Atheta coriaria (Kraatz) (Coleoptera: Staphylinidae) is a biological control agent (BCA) available in Canada primarily for FG control, but it also can be used to control WFT and SF. One adult *A. coriaria* can consume as many as 154 FG eggs, 134 SF eggs, or 95 WFT 2nd-instar larvae in 24 h (Carney *et al.* 2002). However, because it has been commercially available only since 2002, its suitability for integrated pest management (IPM) in floriculture production has not been fully assessed.

Determining possible detrimental interactions before releasing a BCA is essential if efficacy and cost-effectiveness of biocontrol are to be

achieved. The specific objectives of this study were to (i) determine prey preference of *A. coriaria* between FG and soil-dwelling stages of SF and WFT, since determining species-specific preferences of a predator is important in understanding pest population dynamics (Santos 1991; Clements and Harmsen 1992, 1993); (ii) investigate the possibility of intraguild predation (Rosensheim *et al.* 1995) between *A. coriaria* and other soil-dwelling BCAs commonly used for FG control, including the entomopathogenic nematode *Steinernema feltiae* (Filipjev) (Rhabditida: Steinernematidae) and the predatory mites *Stratiolaelaps scimitus* (Womersley) (Mesostigmata: Laelapidae) (often mistaken for *Hypoaspis miles* (Berlese) by biological control producers in North America (Walter and Campbell 2003)) and *Hypoaspis aculeifer* (Canestrini) (Mesostigmata: Laelapidae); and (iii) assess *A. coriaria* compatibility with several currently registered and novel insecticides.

Materials and methods

Prey preference of *A. coriaria*

Rearing

Atheta coriaria colonies were started from adult beetles donated by Biobest Canada Ltd. (Leamington, Ontario) and Koppert Canada Ltd. (Scarborough, Ontario). Colonies were reared as described by Carney *et al.* (2002), using peat moss as the rearing substrate and commercial trout food (Martin Mills Inc., Elmira, Ontario) as food.

FG and SF were collected from a local greenhouse. The latter were identified as *S. stagnalis* by Dr. Matthias Buck of the Insect Systematics Laboratory at the University of Guelph. The FG were identified as *Bradysia* spp., but as sciarids are a taxonomically difficult group, identification to species was not attempted. However, it is likely that they were *Bradysia impatiens* Johannsen, as it is the more common

of the two Nearctic species (the other being *Bradysia coprophila* (Linter)) associated with greenhouse flowers (Harris *et al.* 1995). Type specimens have been deposited in the National Insect Collection at Agriculture and Agri-Food Canada (AAFC) in Ottawa.

FG were reared in Plexiglas® cages filled with moistened commercial potting mix (Premier Pro-Mix® 'BX', Premier Tech Ltd., Rivière-du-Loup, Quebec) and fed approximately 1 g of ground alfalfa meal and two potato slices every 7 d. SF were reared in cages containing hydroponic fibre blocks (Pargro® rock wool, Plant Products Co. Ltd., Brampton, Ontario) covered with a mixture of greenhouse-collected algae. The blocks were maintained in approximately 3 cm of a phosphorus-rich nutrient solution. Colonies were kept in a growth chamber at $20 \pm 1^\circ\text{C}$, 60%–90% RH, and constant light.

To obtain specific life stages, FG or SF adults were chilled to inactivity by placing them in a freezer at -4°C for <1 min and then added to 60 mm $\times$ 15 mm petri dishes containing 3% Bacto-agar with 1% streptomycin. Eggs laid on agar were collected with a small camel's-hair paintbrush and either used directly in experiments or placed in clean, 60 mm $\times$ 15 mm, agar-filled petri dishes to rear to eclosion.

WFT 2nd-instar larvae were obtained from the Greenhouse and Processing Crops Research Centre, AAFC, Harrow, Ontario, and were reared to the pupal stage in 9 cm ventilated petri dishes containing kidney bean (*Phaseolus vulgaris* L.; Fabaceae) leaves kept at $25 \pm 1^\circ\text{C}$ and 60%–90% RH.

Paired-choice tests

Tests were conducted in 9 cm petri dishes containing moistened Whatman No. 3 filter paper for egg assay or filled to a depth of approximately 5 mm with 3% Bacto-agar for larval and pupal assays. *Atheta coriaria* adults were fed *Ephestia kuehniella* (Keller) (Lepidoptera: Pyralidae) eggs (Beneficial Insectary, Oakrun, California) for 6–8 h prior to experiments, as satiated predators are thought to be more selective in their choice of prey (Bilde and Toft 1994). Prey preference between species was determined by paired-choice tests, using the following combinations: FG eggs vs. SF eggs, FG 1st-instar larvae vs. SF 1st-instar larvae, and FG 1st-instar larvae vs. WFT pupae. For the egg trials, ten 1 cm diameter circles were indented

around the perimeter of the filter paper (Miller and Williams 1983). One FG and one SF egg were placed in each circle, and one adult *A. coriaria* was added to each dish. For trials between other life stages, 10 larvae or pupae of each species were arranged randomly on the agar. Egg and larval trials were replicated 13–18 times. The trial with WFT pupae was replicated 7 times because of limited WFT availability. All petri dishes were sealed with Parafilm® (Pechiney Plastic Manufacturing, Menasha, Wisconsin) and held in the dark at $20 \pm 1^\circ\text{C}$ and 90% RH. Amount of prey consumed was evaluated after 24 h. A paired *t* test was conducted to determine significant ($\alpha = 0.05$) differences in prey consumption using the PROC UNIVARIATE procedure in SAS v. 8.1 (SAS Institute Inc. 2001).

Intraguild predation

Compatibility with *S. feltiae*

In laboratory bioassays, three concentrations of *S. feltiae* infective juveniles (IJs) were tested on adult *A. coriaria*: 25 IJs/cm², 50 IJs/cm², and 100 IJs/cm². Larvae were treated with 12.5 IJs/cm², 25 IJs/cm², and 50 IJs/cm². Nematode concentrations were prepared from commercially available nematodes (Entonem®, Koppert Canada Ltd.) using the method described by Glazer and Lewis (2000).

The assay arena for adult *A. coriaria* was a 5 cm petri dish (10 adults/dish) lined with Whatman No. 1 filter paper and premoistened with 200 μL of deionized water. Each nematode treatment (10 replicates/treatment) was transferred to an individual petri dish in 100 μL of deionized water using a micropipette. Deionized water (100 μL /petri dish) was used as a control. To prevent cannibalism, 3rd-instar larvae were tested in 16-well plates (CD International Inc., Pitman, New Jersey) (1 larva/well; 10 wells/plate = 1 replicate) lined with 1.5 cm Whatman No. 1 filter paper. Nematode treatments were transferred to each well in 50 μL of water, with 50 μL /well of deionized water as a control. Only four replicates per treatment were used in the larval experiments because of limited availability of 3rd-instar larvae.

All treatments were kept in the dark at $25 \pm 1^\circ\text{C}$ and were sealed in plastic bags to prevent desiccation. Mortality was recorded after 48 h. Insect cadavers were then transferred individually to clean 5 cm petri dishes lined with Whatman No. 1 filter paper that was moistened with

500 µL of sterilized water to prevent contamination of cadavers with bacterial or fungal pathogens. The cadavers were incubated for 5–7 d at 25 ± 1 °C, after which they were dissected and examined for adult nematodes or nematode progeny to confirm that death was caused by *S. feltiae* infection. The experiment was repeated twice. Nematode viability was determined on each treatment date by confirming mobility under a dissecting microscope.

A combined variance analysis for each experiment was conducted, since there was no significant interaction between treatments and trial dates (Bowley 1999). Significant differences were detected using Tukey's multiple means comparison.

In growth room tests, 10 cm diameter plastic plant pots (10 replicates/treatment) were filled with 40 g of dry commercial potting mix (Premier Pro-Mix® 'BX') moistened with 100 mL of deionized water. Concentrations of 25 IJs/cm², 50 IJs/cm² (recommended rate — Koppert Canada Ltd.), and 100 IJs/cm² were delivered in 5 mL of deionized water to individual pots. Nematode treatments were watered in with 55 mL of deionized water, and approximately 20–30 min later, twenty 3rd-instar larvae were added to each pot along with excess *E. kuehniella* eggs. Deionized water (60 mL) was used as a control. Each pot had a cylindrical Plexiglas cage, with holes covered with fine screening for ventilation, fitted tightly on top to prevent escapes. The bottom of each pot was also screened to prevent beetle escapes through the drainage holes. Treatments were randomized in a growth room that simulated greenhouse conditions (24 ± 1 °C, 65%–95% RH, 16L:8D photoperiod). As dead larvae were extremely difficult to locate in the soil, pots were incubated for 12 d to determine adult *A. coriaria* emergence. For data analysis, percent emergence was converted to percent mortality using the following formula (Powell and Webster 2004):

$$[1 - (\text{no. of beetles surviving} / \text{no. of beetles at start})] \times 100$$

Data were corrected for nonemergence (= 20%) in the controls using Abbott's formula (Abbott 1925). An ANOVA with Tukey's multiple means comparison was used to determine significant ($\alpha = 0.05$) differences between treatments.

Compatibility with predatory mites in no-choice bioassays

In tests using *A. coriaria* as prey, we used a bioassay method modified from Wright and Chambers (1994). The assay arena consisted of a 20 mL snap-top vial filled to approximately 1 cm below the rim with a mixture of plaster of Paris (Burma Latex Co., Toronto, Ontario) and activated charcoal (Sigma-Aldrich Co., St. Louis, Missouri) (7:1) to maintain RH. A small amount of ground trout food was added as a food source for the *A. coriaria* larvae. Ten 1st instars, seven 2nd instars, or five 3rd instars of *A. coriaria* larvae were placed in individual vials. Ten to fifteen replicates per *A. coriaria* life stage were used, depending on larval availability. *Atheta coriaria* eggs were not tested because of insufficient numbers. One starved (i.e., for 6 h prior to the experiment) female *S. scimitus* (Koppert Canada Ltd.) was placed in each vial with the *A. coriaria* larvae. As *A. coriaria* larvae can be cannibalistic, vials containing larvae of each stage at the same densities as above, but without a mite, were used as controls (five replicates per stage). Vials were sealed in plastic bags to prevent desiccation and placed in an incubator at 20 ± 1 °C. After 24 h, the number of *A. coriaria* larvae consumed by *S. scimitus* was counted. Mean number of *A. coriaria* larvae of each instar cannibalized in the controls was used as a correction factor. Mean corrected number of prey consumed and standard errors were determined. The trial was repeated with *H. aculeifer*, with 9–15 replicates per *A. coriaria* stage.

The same methods just described were used to observe *H. aculeifer* as prey. One starved adult *A. coriaria* was added to a vial containing twenty *H. aculeifer* eggs, fifteen 3- to 6-day-old nymphs, fifteen 7- to 10-day-old nymphs, or ten adult mites. *Hypoaspis aculeifer* eggs were obtained by placing one female on a sweet pepper (*Capsicum* sp.; Solanaceae) leaf placed on agar in a petri dish with frozen *E. kuehniella* eggs as food, kept at 24 ± 1 °C and approximately 50% RH. Nymphs of specific ages were obtained by collecting *H. aculeifer* eggs over a 3 d period and incubating them at 21 ± 1 °C and approximately 50% RH until they hatched and reached the desired age. Nine to twelve replications per *H. aculeifer* stage were used.

Prey preference of *A. coriaria* between pest and intraguild prey

Methods and statistics used are the same as those described earlier. Paired-choice combinations were (i) FG eggs vs. *H. aculeifer* eggs and (ii) SF eggs vs. *H. aculeifer* eggs.

Insecticide compatibility

Insecticides

Technical-grade insecticides (>95% pure) available for use in direct-contact bioassays included the insect growth regulators cyromazine, diflubenzuron, and novaluron, the chloronicotinyl imidacloprid, and the carbamate bendiocarb. Formulated insecticides used in growth room bioassays and suitable as soil drenches were Citation 75WP® (cyromazine; Syngenta Crop Protection Canada, Guelph, Ontario), Dimilin 25WP® (diflubenzuron; Crompton Co/Cie, Middlebury, Connecticut), Intercept 60WP® (imidacloprid; Bayer CropScience, Calgary, Alberta), and Trumpet 80WP® (bendiocarb; Bayer CropScience).

Direct-contact bioassays

Direct-contact assays were carried out using a Potter spray tower (Potter 1952) located at the Southern Crop Protection and Food Research Centre, AAFC, London, Ontario. Insecticides were dissolved in acetone–olive oil (19:1) for use against adult *A. coriaria*. Acetone alone was used as the solvent for the larval bioassay, as the acetone–olive oil mixture resulted in high mortality of control larvae. The solvent was used as the control in each assay. Treatments were applied to adult and 3rd-instar *A. coriaria* as described by Harris *et al.* (1962). Adults were first chilled by placing them in a -20°C freezer for approximately 90 s. Each insecticide was tested at four concentrations: 0.0001%, 0.001%, 0.01%, and 0.1% (w/v) active ingredient. Four repetitions of 10 insects were tested at each concentration.

Following treatment, adults were placed in 5 cm petri dishes containing Whatman No. 1 filter paper moistened with 500 μL of water. Fresh food was given after 48 h, and 20 μL of water was added every 24 h. Larvae were placed individually in 2 cm diameter wells of bioassay trays with ventilated lids to prevent cannibalism. Each well was filled to within 0.5 cm from the top with a mixture of plaster of Paris and charcoal (see Intraguild predation). Trays were sealed in plastic bags to prevent

desiccation. Larvae were given an excess of frozen *E. kuehniella* eggs at 0 h but were not fed again, as all larvae had begun to pupate by 48 h.

Containers were randomized and held at $24 \pm 1^{\circ}\text{C}$ and 50% RH. Mortality was assessed at 24, 48, 72, and 96 h. Data were corrected for natural mortality (<8% in the adult bioassay on all days; $\leq 20\%$ in the 3rd-instar larval bioassay on all days) using Abbott's formula (Abbott 1925).

Growth room bioassays

Adult trial. Growth room bioassays were done as described for *S. feltiae* (see Intraguild predation). For insecticides applied as soil drenches (cyromazine, diflubenzuron, and imidacloprid), pots were treated with 80 mL of insecticide mixture at the recommended Canadian label rates (133 g/1000 L, 150 g/1000 L, and 133 g/1000 L of water, respectively). To simulate a soil-surface spray of bendiocarb (as per Canadian label directions), 5 mL of product at the recommended label rate (125 g/100 L of water) was distributed evenly over the soil surface. Water (75 mL) was added to each pot prior to addition of the bendiocarb to keep the amount of water in each of the treatments consistent. Deionized water (80 mL) was added to each of five control pots. Twenty adult *A. coriaria* were added to each pot with excess trout food (approximately 1 g). Each pot was caged and screened as described in Intraguild predation. Treatments were held at $25 \pm 1^{\circ}\text{C}$, 65%–95% RH, and 16L:8D photoperiod. The percentage of adult beetles surviving was determined after 96 h and converted to percent mortality (see Intraguild predation). Data were corrected for natural mortality (<5%) using Abbott's formula (Abbott 1925).

Larval trial. The method described above was used except twenty 3rd-instar or twenty 2nd-instar larvae were added to 10 cm diameter pots. Larvae were fed an excess of frozen *E. kuehniella* eggs every 48 h. Pots were incubated at $26 \pm 1^{\circ}\text{C}$ and 65%–95% RH. After 12 d, the pots containing 3rd instars were sieved to determine percent adult emergence. Pots containing 2nd instars were sieved after 14 d. Emergence was converted to corrected natural mortality using Abbott's formula (Abbott 1925), with 31% non-emergence observed in the 3rd-instar controls and 26% non-emergence observed in the 2nd-instar controls.

Table 1. Mean number ($\pm$ SE) of fungus gnats (FG) (*Bradysia* spp.), shore flies (SF) (*Scatella stagnalis*), and western flower thrips (WFT) (*Frankliniella occidentalis*) eaten by one satiated adult *Atheta coriaria* after 24 h in a paired-choice bioassay.

Prey species choice		Mean no. eaten		Statistics*
Prey 1	Prey 2	Prey 1	Prey 2	P, n
FG eggs	SF eggs	2.62 $\pm$ 0.61	1.69 $\pm$ 0.61	0.208, 13
FG 1st instars	SF 1st instars	4.22 $\pm$ 0.49	2.00 $\pm$ 0.49	<0.001, 18
FG 1st instars	WFT pupae	4.57 $\pm$ 0.61	2.57 $\pm$ 0.61	0.0064, 7

*Significant difference ($\alpha = 0.05$) determined using paired *t* tests.

For all insecticide trials, an ANOVA was conducted using the PROC GLM procedure in SAS v. 8.1 (SAS Institute Inc. 2001). Significant differences among treatments were determined with Tukey's multiple means comparison. Data from the direct-contact toxicity experiments were transformed using an arcsine square-root transformation prior to analysis to better meet the assumptions of variance (Bowley 1999). Insecticides were classified as nontoxic (<25% mortality), slightly toxic (25%–50% mortality), moderately toxic (50%–75% mortality), or toxic (>75% mortality) based on the International Organization for Biological Control classification for insecticide toxicity (Pietranonio and Benedict 1999).

Results

Prey preference of *A. coriaria*

There was no significant difference between the number of FG eggs and the number of SF eggs eaten by *A. coriaria*. However, significantly more ($P < 0.05$) FG 1st-instar larvae were eaten compared with either SF larvae or WFT pupae (Table 1).

Intraguild predation

Compatibility with *S. feltiae*

In laboratory bioassays with adult *A. coriaria*, there were no significant differences among any of the nematode treatments and the control (Fig. 1A), nor was evidence of nematode infection found in any of the adult cadavers. In the larval trials, mortality in all nematode treatments was higher than that in the control. The highest mortality (26.9%), seen in the 50 IJs/cm² treatment (Fig. 1B), was significantly different from the control. However, only 40%, 39%, and 60% of the mortality of 3rd instars in the 12.5 IJs/cm², 25 IJs/cm², and 50

IJs/cm² treatments, respectively, was confirmed to be due to nematode infection upon dissection (Fig. 1B). IJs and a limited number of pre-adult (4th instars) and adult nematodes (both males and females) were found.

In the growth room bioassays, when nematode treatments were corrected for non-emergence observed in the controls, twice the rate recommended by Koppert Canada Ltd. (100 IJs/cm²) caused significantly more mortality (25.4%) of 3rd-instar *A. coriaria* than the lowest rate (25 IJs/cm²; 12.8%) (Fig. 2).

Compatibility with predatory mites in no-choice bioassays

Stratiolaelaps scimitus and *H. aculeifer* attacked all larval stages of *A. coriaria* but consumed more 1st than 2nd or 3rd instars (Table 2). *Atheta coriaria* adults consumed all 20 *H. aculeifer* eggs provided in each replicate and almost all of the 2- to 5-day-old nymphs. Fewer 7- to 10-day-old nymphs and a negligible number of adults were consumed.

Prey preference of *A. coriaria* between pest and intraguild prey

The number of *H. aculeifer* eggs eaten by *A. coriaria* did not significantly differ from the number of FG eggs eaten but was significantly higher than the number of SF eggs eaten ($P = 0.015$) (Table 3).

Insecticide compatibility

Direct contact bioassays

All three insect growth regulators (IGRs) were considered nontoxic to adult *A. coriaria* after 96 h (Fig. 3A) and were significantly less toxic than 0.01% and 0.1% bendiocarb and 0.001%, 0.01%, and 0.1% imidacloprid. The two highest concentrations of bendiocarb and imidacloprid (0.01% and 0.1%) were toxic to adult *A. coriaria*.

Fig. 1. Average corrected percent mortality, with standard errors, of (A) adult and (B) 3rd-instar *Atheta coriaria* 48 h after exposure to *Steinernema feltiae* infective juveniles (IJs). Average percentage of total mortality due to confirmed nematode infection is shown in Fig. 1B. Columns with different letters (total mortality) or symbols (total confirmed infections) are significantly different (Tukey's, $\alpha = 0.05$).

The mortality caused by the IGRs to 3rd-instar *A. coriaria* was not significantly different from that caused by imidacloprid and bendiocarb at concentrations of 0.0001% to 0.01% after 96 h (Fig. 3B). At 0.1%, novaluron and diflubenzuron were not significantly different from imidacloprid or bendiocarb (Fig. 3B); all were considered toxic, causing >75% mortality. Cyromazine was not significantly different from novaluron or diflubenzuron at this concentration but was significantly less toxic than imidacloprid and bendiocarb and was considered moderately toxic.

Growth room bioassays

Cyromazine and diflubenzuron caused significantly less mortality of adult *A. coriaria* than bendiocarb or imidacloprid (Fig. 4A), which

Fig. 2. Average corrected percent mortality, with standard errors, of 3rd-instar *Atheta coriaria* (corrected for non-emergence of adult *A. coriaria* in control treatments) when exposed to one-half (25 infective juveniles (IJs)/cm²), one (50 IJs/cm²), and two (100 IJs/cm²) times the recommended rate of *Steinernema feltiae*. Columns with different letters are significantly different (Tukey's, $\alpha = 0.05$).

caused >90% mortality. In the emergence tests with both 2nd- and 3rd-instar *A. coriaria*, diflubenzuron was nontoxic and significantly different from the other treatments (Figs. 4B and 4C). Cyromazine resulted in 65% mortality to the 3rd instars, making it moderately toxic, but was still significantly less toxic than bendiocarb or imidacloprid (Fig. 4B). With 2nd instars, however, cyromazine caused 82% mortality (Fig. 4C) and was not significantly different from the other insecticides.

Discussion

Miller and Williams (1983) conducted prey preference trials with *A. coriaria* using eight species of nitidulid beetles and the house fly, *Musca domestica* L. (Diptera: Muscidae). Although preferences existed, they hypothesized that the wide range of hosts that *A. coriaria* fed on suggested that this biological control agent could easily switch from a preferred prey species to a nonpreferred species as prey populations fluctuated. In our experiments, *A. coriaria* consumed a substantial number of SF and WFT even though these were not the preferred prey. Therefore, *A. coriaria* could help control these pests when FG larvae are at low density.

The absence of significant preference between FG and SF eggs and even FG and *H. aculeifer* is in agreement with the generalist and opportunistic behaviour of *A. coriaria* (Carney *et al.* 2002). *Atheta coriaria*'s potential consumption of *Hypoaspis* spp. eggs could exceed the 20 eggs presented in this trial, as Carney *et al.*

Table 2. Mean number ($\pm$ SE) of prey eaten by one *Atheta coriaria*, *Stratiolaelaps scimitus*, or *Hypoaspis aculeifer* adult (starved for 6 h previously) in 24 h in a no-choice bioassay.

Predator species	Prey species						
	<i>A. cortaria</i>			<i>H. aculeifer</i>			
	1st-instar larvae	2nd-instar larvae	3rd-instar larvae	Eggs	2- to 5-day-old nymphs	7- to 10-day-old nymphs	Adults
<i>S. scimitus</i>	4.0±0.35	2.2±0.30	0.6±0.28	—	—	—	—
<i>H. aculeifer</i>	5.9±0.30	1.6±0.25	0.5±0.24	—	—	—	—
<i>A. cortaria</i>	—	—	—	20.0±0.88	14.0±0.79	6.1±0.84	1.6±0.98

(2002) showed that this predator can eat >150 *B. impatiens* eggs in 24 h.

The number of 1st-instar *A. coriaria* eaten by predatory mites in this experiment also is a concern. *Stratiolaelaps scimitus* is known to consume a similar number (approximately 4.0) of FG 2nd instars in 24 h (Wright and Chambers 1994). *Stratiolaelaps scimitus* is reported to consume only moving prey (Wright and Chambers 1994), but *H. aculeifer* readily eats eggs (Ragusa and Zedan 1988), which may exacerbate any potential impacts on *Atheta* populations.

This bidirectional intraguild predation (IGP) could negatively affect FG control. Previous greenhouse studies, however, have illustrated that a significant bidirectional IGP at the individual level may not be significant at the population level (Venzon et al. 2001).

The entomopathogenic nematode *S. feltiae* penetrated *A. coriaria* larvae, but low total mortality (<30%) in laboratory and growth room assays, and the even lower number of confirmed infections in the laboratory assay, showed that *A. coriaria* is a poor host. It appears that *S. feltiae* cannot reproduce in *A. coriaria*, as no progeny were seen in the 3rd-instar cadavers after 7 d. *Atheta coriaria* populations should not be significantly affected by *S. feltiae* applications in the greenhouse, especially since known preferred hosts (e.g., dipteran larvae) will be present in the media.

These trials also have illustrated the benefits of reduced-risk insecticides in IPM. Although toxic to larvae at high concentrations by direct contact, diflubenzuron was nontoxic (i.e., <25% mortality) to 2nd- and 3rd-instar *A. coriaria* when applied as formulated product. These results are similar to those reported by Gordon and Cornett (1986), who found no effect of formulated diflubenzuron on 1st-instar *Aleochara bilineata* Gyllenhal larvae (Staphylinidae: Aleocharinae). Diflubenzuron acts primarily as a stomach poison, resulting in limited toxicity to beneficials (Tomlin 2003). Its capacity to bind rapidly to soil particles and organic matter and to degrade quickly (LT₅₀ < 7 d) (Tomlin 2003) likely explains the differences seen in the direct-contact toxicity trials versus the growth room bioassays.

IPM programs must be efficacious, environmentally sound, and cost-effective. In Canada, the cost of a single application of either *A. coriaria* or an insecticide for FG control is comparable. However, some insecticides require repeated

Table 3. Mean number ($\pm$ SE) of fungus gnat (FG) (*Bradysia* spp.), shore fly (SF) (*Scatella stagnalis*), or *Hypoaspis aculeifer* eggs eaten by one adult (satiated) *Atheta coriaria* in 24 h in a paired-choice bioassay.

Prey species		Mean no. of prey eaten		Statistics*
Prey 1	Prey 2	Prey 1	Prey 2	P, n
FG eggs	<i>H. aculeifer</i> eggs	5.1 $\pm$ 0.77	4.8 $\pm$ 0.77	0.720, 17
SF eggs	<i>H. aculeifer</i> eggs	1.7 $\pm$ 0.72	3.1 $\pm$ 0.72	0.015, 15

*Significant difference ($\alpha = 0.05$) determined using paired *t* tests.

Fig. 3. Average corrected percent mortality of (A) adult ($R^2 = 0.900$) and (B) 3rd-instar ($R^2 = 0.808$) *Atheta coriaria* 96 h after exposure to technical-grade insecticides applied with a Potter spray tower (untransformed data shown). Columns with different letters are significantly different (Tukey's, $\alpha = 0.05$).

applications, can be phytotoxic, and can restrict reentry to the greenhouse. Currently, *A. coriaria* is slightly more expensive than the predatory mites tested or *S. feltiae*. However, it has been commercially available only since the fall of 2002, and cost may decrease as its use becomes more widespread and increased production leads to economies of scale.

Our data also suggest that *A. coriaria* may help to suppress WFT and SF. *Steinernema feltiae* control FG and have little impact on phorids (Jess and Bingham 2004). The predatory mites examined here target smaller FG larvae and bulb mites (*Rhizoglyphus robini* (Claparède)) (Astigmata: Acaridae) and have

Fig. 4. Average corrected percent mortality, with standard errors, of (A) adult ($R^2 = 0.973$), (B) 3rd-instar ($R^2 = 0.908$), and (C) 2nd-instar ($R^2 = 0.968$) *Atheta coriaria* following exposure to formulated insecticides applied to commercial potting mix in 10 cm plant pots at the recommended label rates. Columns with different letters are significantly different (Tukey's, $\alpha = 0.05$).

little impact on WFT pupae, collembola, phorids, and eggs of the pest moth *Duponchelia fovealis* (Zeller) (Jess and Bingham 2004; Biobest Biological Systems 2005; Koppert Biological Systems 2005). *Atheta coriaria* may prove to be the most cost-effective choice given its broad spectrum of activity.

Atheta coriaria could be incorporated effectively into a greenhouse floriculture IPM program for FG control. In a prophylactic approach, *S. feltiae* and *A. coriaria* could be applied together soon after potting, with a second combined application a few weeks later. However, if FG populations are abundant, slower-acting biological controls would not prevent economic damage and insecticides would be required. Currently, diflubenzuron would be the most appropriate insecticide to incorporate in the program because of its compatibility with *A. coriaria*, which could be safely introduced approximately 4–7 d after insecticide application to provide long-term FG control.

Our research has shown that *A. coriaria* has potential in an IPM program for FG; however, the data have also demonstrated that in dealing with a multiple pest/predator complex, a single pest management problem cannot be considered in isolation. In the case of *A. coriaria*, further research under commercial greenhouse conditions is needed to determine (i) effectiveness of *A. coriaria* for FG control when used alone or in combination with *S. feltiae*, (ii) potential to control SF and WFT in the presence of the preferred host, and (iii) interactions with beneficial predatory mites. Such studies are necessary to clarify the role of *A. coriaria* in a comprehensive IPM program for greenhouse floriculture.

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