Application of Molluscidal Nematodes to Slug Shelters: A Novel Approach to Economic Biological Control of Slugs

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INTRODUCTION

Slugs (Mollusca: Gastropoda) are serious pests in nurseries, home gardens, landscapes, greenhouses, and field crops, especially those under conservation tillage in North and Central America, Europe, and Asia (Arias and Crowell, 1963; South, 1992; DeAngelis, 1993; Hammond et al., 1999). In North America, the majority of damage to field crops occurs in the spring when large numbers of eggs hatch. Juvenile slugs cause significant defoliation leading to loss of crop vigor, and sometimes to a loss of stand. Damage in other settings, including the home landscape, occurs throughout the summer from feeding by juvenile and adult slugs. Deroceras reticulatum (Müller), commonly known as the gray garden slug, is the most damaging slug in field crops, nurseries, and home gardens (Hammond et al., 1999). Three other slug species, Deroceras laeve (Müller), Arion fasciatus (Nielsson), and Arion subfuscus (Draparnaud), have been reported in field crops and home gardens (Byers et al., 1989; Hammond et al., 1996), but none are as damaging as D. reticulatum. Slugs also pose a threat to wildlife and humans as they serve as intermediate hosts to many nematode parasites of vertebrates (South, 1992).

Although many cultural techniques have been suggested, such as increased tillage, varying planting dates, and row cleaners, none offer adequate control. The efficiency of most nonchemical control measures for the homeowner is questionable and usually inex-
volves hand picking or collecting slugs on a daily basis. The only therapeutic measure in field and horticultural crops and in the home landscape is the use of molluscicide baits (Hammond et al., 1996). All baits currently used in the United States, with only a few minor exceptions, contain metaldehyde. These molluscicide baits offer acceptable control when applied appropriately, although they are often rendered ineffective under wet and humid conditions that also favor slug activity (South, 1992). Also there are concerns about accidental poisoning to pets, birds, and wildlife.

Phasmarhabditis hermaphrodita (Schneider) (Rhabditida: Rhabditidae), a bacterial-feeding nematode, is a lethal parasite of pest slugs in the families Arionidae, Limacidae, and Milacidae (Gastropoda: Stylommatophora) (Wilson et al., 1993a). Infective juveniles (IJ s) of P. hermaphrodita enter the shell cavity beneath the phora (Wilson et al., 1993b, 1995). The nematodes are mass-produced in vitro with the bacterium, Moraxella osloensis (Bøvre & Henrik sen) as a food source using liquid fermentation technology (Wilson et al., 1993b, 1995). The nematodes are formulated as wettable powders and can be applied using most conventional pesticide application equipment (Glen and Wilson, 1997). Although efficacy of the molluscicidal nematodes has been demonstrated in field crops, a major factor limiting their large-scale use is the cost of application (Glen and Wilson, 1997). The high cost is mainly due to the inefficient mass production of this rather large species (mean IJ length 1097 μm and width 26.6 μm; Hooper et al., 1999), the lack of ambient storage stability, and a high application rate. Glen and Wilson (1997) concluded that under suitable soil moisture conditions, a minimum of 3 x 10^7 IJ s/ha is required to provide reliable protection of crops from slug damage under European conditions. Therefore, improved application techniques requiring fewer nematodes are needed. One option that has been proposed is to target nematode applications directly to the slug feeding sites. Hass et al. (1999a,b) reported that partial treatment of soil around all plants to be protected from slug damage is a potentially valuable method of reducing the overall nematode dose. However, the log time to 50% reduction in slug damage was related to the area treated and dose applied, thus compromising crop protection at least during initial stages.

A novel approach to reduce nematode dosage rate would be to target slug shelters for treatment as opposed to feeding sites and/or overall application. Slugs are nocturnal foragers and manifest a well-developed "homing behavior" (Taylor, 1902–1907), possessing an ability to relocate artificial shelters from distances more than a meter away (Rollo and Wellington, 1981). For example, Ariolimax columbianus (Gould) established a home site by excavating a depression in the soil and then foraged over an area extending at least 4.5 m from this home (Ingram and Adolph, 1943). Slugs relocate homes or shelters via mucous trails and the trail-following behavior is a widespread phenomenon among gastropods (Wells and Buckley, 1972). Shelters provide wet and humid conditions favorable for slug activity and mating, and protection against environmental extremes including sunlight, heat, and drying. As slugs may spend most of the day and significant part of the night in shelters, we hypothesized that application of molluscicidal nematodes only to slug shelters will be as effective as treating the entire area and be more economical. Therefore, the specific objectives of this study were to (i) evaluate differences in slug mortality between the overall application and treatment of only artificial slug shelters, (ii) determine the speed of slug mortality and plant damage reduction by the nematodes applied as an overall spray and only to slug shelters, and (iii) evaluate potential of nematode establishment in slug shelters to provide long-term control. All experiments were conducted in a newly developed bioassay arena with D. reticulatum and Impatiens or Hosta plants in a greenhouse. The most commonly used molluscicide, metaldehyde, was included in all experiments as a comparison.

**MATERIALS AND METHODS**

**Slugs and Nematodes**

D. reticulatum slugs were collected from agricultural fields, urban landscapes, and commercial nurseries in Ohio and stored at 5°C for no more than 1 month. Prior to the experiments, the slugs were removed from the cold storage and held in 9-cm-diameter petri dishes for 10 days at room temperature to determine the presence of any naturally occurring nematode infection. Slugs were fed on pieces of carrots and/or cabbage. The dead slugs were removed daily and examined for the presence of nematodes. The slugs that survived this incubation period were used in all experiments.

Phasmarhabditis hermaphrodita, DMG 0001 strain (NEMASLUG), was provided by MicroBio Ltd. (Cambridge, UK). The nematodes formulated in vermiculite were stored at 5°C for no more than 1 month prior to the application.

**Experimental Arena and Design**

All experiments were conducted in a greenhouse from October to January using 90 x 68 (maximum lengths) x 36-cm-deep black plastic animal-feeding tubs with a surface area of 0.48 m². Slug barriers, constructed from a copper cloth (0.03 cm wire diameter, McMaster-Carr Supply Company, Elmhurst, IL),
were mounted all around the tubs projecting about 4 cm above the tubs. The tubs were lined with a 5-cm-deep layer of concrete pebbles to prevent water stagnation. The concrete pebbles were covered with a black cloth liner and the tubs were filled with muck soil, up to a height of about 15 cm. Muck soil is a Linwood series soil, characterized as a loamy, mixed, euic mesic, terric, haplosaprist, pH 5.6, and a bulk density of 0.63 g/cm³. On a dry weight basis, the muck soil was 43.6% organic matter and 38% ash. It was collected from the Op horizon (top 25 cm) at the Muck Crops Branch in Celeryville, Ohio. Four plants, either Impatiens or Hosta, were planted in each tub and watered daily with a hose. Twelve slugs were introduced into each tub (3/plant) immediately after the application of nematodes or chemical molluscicide. The slugs were placed directly on the plants using a plastic spatula. The nematodes were mixed in water and their viability and total numbers determined by taking ten 100-μl sub-samples. The required nematode suspension was sprinkled uniformly on the surface of muck soil to be treated using a plastic bottle containing five holes in the center of the lid. The molluscicide granules were sprinkled on the soil by hand. There were six treatments in all experiments arranged in a complete randomized design, replicated four times. They were: (1) untreated control; (2) metaldehyde (2,4,6,8-tetramethyl-1,3,5,7-tetraoxacyclooctane) (Deadline MPs) applied at 1.13 g a.i./m² (i.e., 0.534 g/tub), (3) nematodes at 0.3 × 10⁶ IJs/m² (i.e., 144,000 IJs/tub) applied as overall spray; (4) nematodes at 0.6 × 10⁶ IJs/m² (i.e., 288,000 IJs/tub) applied as overall spray; (5) nematodes at 0.3 × 10⁶ IJs/m² applied only under a roofing shingle (area = 0.093 m²) (i.e., 27,000 IJs/tub); and (6) nematodes at 0.6 × 10⁶ IJs/m² applied only under a roofing shingle (i.e., 54,000 IJs/tub).

A 30 × 30-cm roofing shingle was placed in the center of each tub immediately after applying the treatments in all experiments except experiment 1 in which in the case of the first four treatments, shingles were not placed until 8 days after treatment application (see below). Air temperature and humidity in the greenhouse were recorded constantly using a hygrometer. Soil temperature at 5 cm depth was recorded using a probe once daily.

Experiment 1: Impatiens

In this experiment, the effect of different treatments on survival of slugs was determined in the presence of Impatiens. Nonsterilized muck soil was used. Four 6-week-old Impatiens plants were transplanted in each tub. Three slugs were introduced per plant (12/tub) 4 days after transplanting. A roofing shingle was placed as a slug shelter in the center of each tub that received treatment 5 or 6. It was noted that the slugs preferred to aggregate underneath the shingles during the day, thus using the shingle as a shelter. Shingles also allowed an easy detection of slugs. Therefore, shingles were placed in all the tubs 8 days after applying treatments. The numbers of surviving slugs in each tub, both under the shingles and outside, were counted on Day 10 and every 2 days thereafter until Day 18.

Due to the use of nonsterilized muck soil, stray corn seedlings started to emerge within a few days after applying treatments. Slugs appeared to prefer young corn seedlings over the mature Impatiens. Therefore, all the corn seedlings that emerged were removed once daily. Damage to Impatiens was still not significant and was therefore not quantified.

Experiment 2: Hosta

The same treatments were evaluated in this experiment with the following improvements in the overall protocol. Hosta (var. Platinum tiara) was used as a host plant because it suffers heavy slug damage in the nurseries and landscapes. The muck soil was sterilized at 121°C for 2 h to prevent germination of unwanted plants and to kill potential slug pathogens. Also roofing shingles were placed in all tubs immediately after applying the treatments. The numbers of leaves on each plant were counted immediately after making the treatments. Data on the numbers of surviving slugs, numbers of leaves showing slug damage, and percentage of leaf area consumed were recorded periodically starting 3 days after treatment. Leaf area consumption was quantified to the nearest 5%.

Experiment 3: Hosta

To evaluate whether the nematodes will provide continued control of invading slugs, the above experiment was continued beyond 17 days after treatment. The damaged plants were replaced with healthy Hosta plants. Additional slugs were introduced to bring the total number of slugs to 12 in each tub. No nematode or chemical treatment was applied. The numbers of leaves on each plant were counted immediately after adding the slugs. Data on the numbers of surviving slugs, numbers of leaves showing slug damage, and the proportion of each leaf damaged were recorded periodically starting 2 days after treatment as described above.

Statistical Analyses

Slug mortality data were analyzed using MLP3.08 (Ross, 1987). The time to 50 and 95% mortality (LT₅₀ and LT₉₅) was estimated using MLP, standard errors and 95% fiducial limits were obtained, and t tests were used to test for differences. Statistica 5.5 (Statsoft, 1999) was used to analyze the leaf damage data. Repeated-measures analysis was used to examine the change in number of leaves and leaf area damaged
overall application were the most effective treatments and these two treatments did not differ significantly (F = 0.003; df = 1,18; P > 0.90). On Day 12, the low nematode rate (i.e., recommended dose) applied as an overall treatment also became as effective as the metaldehyde and the high nematode rate applied as an overall spray. At this time, the high rate of nematodes applied only under the shingles was as effective as the low rate of nematodes applied as an overall treatment. At this time, the higher rate of nematodes applied only under the shingles was as effective as metaldehyde treatment and this trend continued for the rest of the experiment period. Typical signs of nematode infestation, including the raised mantle, were seen on several slugs in all the nematode treatments. Mean daily soil temperature and maximum and minimum air temperatures are presented in Fig. 1B.

Experiment 2: Hosta

Slug mortality. For the first 5 days after treatment, metaldehyde was the only treatment that caused significant reduction in slug survival (Fig. 2A). However, on Day 9, the high rate of nematodes applied as an overall treatment also reduced slug survival significantly as compared to the untreated control (F = 39.4; df = 1,18; P < 0.001) and became as effective as metaldehyde by Day 11. All treatments significantly reduced slug survival as compared with the untreated control by Day 11 (F = 45; df = 1,18; P < 0.001), and this trend continued until the end of the experiment. On Day 13, the high nematode rate applied only under the shingles was as effective as the metaldehyde treatment (P > 0.05). All nematode treatments were as effective as metaldehyde on Days 15 and 17. The LT₉₅ (i.e., time to 50% mortality) for the metaldehyde treatment was significantly lower (t = 4.48; df = 18; P < 0.001) than all the other treatments (Table 1). Also the LT₅₀ for the high rate of nematodes applied as an overall treatment was significantly (t = 2.32, df = 18; P < 0.05) lower than all the other nematode treatments. The LT₉₅ data showed no significant differences (P > 0.05) between metaldehyde and control and between metaldehyde and any of the nematode treatments (P > 0.05). There was no significant difference in the LT₉₅ between the shelter and the overall application at either low or high nematode rates.

Number of leaves damaged. All the treatments significantly reduced (F = 15.9, df = 1,18; P < 0.001) the numbers of Hosta leaves damaged by slugs as compared with the untreated control starting from Day 3 and the effect continued until the end of the experiment (Fig. 2B). Metaldehyde was the most effective treatment until Day 5. By Day 9, all treatments, except the lower nematode rate applied only under the shingles, were as effective as metaldehyde in reducing the numbers of leaves damaged (F = 1.80; df = 1,18; P >

**RESULTS**

Experiment 1: Impatiens

All the treatments, except the low nematode rate applied only under the shingles, caused significant reduction relative to the control (F = 2.65, df = 1,18; P > 0.10) in slug survival throughout the experiment (Fig. 1A). On the 10th day after application, metaldehyde and the high rate of nematodes applied as an overall application were the most effective treatments and these two treatments did not differ significantly (F = 0.003; df = 1,18; P > 0.90). On Day 12, the low nematode rate (i.e., recommended dose) applied as an overall treatment also became as effective as the metaldehyde and the high nematode rate applied as an overall spray. At this time, the high rate of nematodes applied only under the shingles was as effective as the low rate of nematodes applied as an overall treatment. At this time, the higher rate of nematodes applied only under the shingles was as effective as metaldehyde treatment and this trend continued for the rest of the experiment period. Typical signs of nematode infestation, including the raised mantle, were seen on several slugs in all the nematode treatments. Mean daily soil temperature and maximum and minimum air temperatures are presented in Fig. 1B.

Experiment 2: Hosta

Slug mortality. For the first 5 days after treatment, metaldehyde was the only treatment that caused significant reduction in slug survival (Fig. 2A). However, on Day 9, the high rate of nematodes applied as an overall treatment also reduced slug survival significantly as compared to the untreated control (F = 39.4; df = 1,18; P < 0.001) and became as effective as metaldehyde by Day 11. All treatments significantly reduced slug survival as compared with the untreated control by Day 11 (F = 45; df = 1,18; P < 0.001), and this trend continued until the end of the experiment. On Day 13, the high nematode rate applied only under the shingles was as effective as the metaldehyde treatment (P > 0.05). All nematode treatments were as effective as metaldehyde on Days 15 and 17. The LT₉₅ (i.e., time to 50% mortality) for the metaldehyde treatment was significantly lower (t = 4.48; df = 18; P < 0.001) than all the other treatments (Table 1). Also the LT₅₀ for the high rate of nematodes applied as an overall treatment was significantly (t = 2.32, df = 18; P < 0.05) lower than all the other nematode treatments. The LT₉₅ data showed no significant differences (P > 0.05) between metaldehyde and control and between metaldehyde and any of the nematode treatments (P > 0.05). There was no significant difference in the LT₉₅ between the shelter and the overall application at either low or high nematode rates.

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**FIG. 1.** (A) Mean (±SE) number of surviving Deroceras reticulatum (Experiment 1) in the untreated control (●); metaldehyde (□), overall Phasmarhabditis hermaphrodita application at low (3 × 10⁹ IJ s/ha) rate (▲), overall P. hermaphrodita application at high (6 × 10⁹ IJ s/ha) rate (○), P. hermaphrodita applied only to slug shelter at low (3 × 10⁹ IJ s/ha) rate (■), P. hermaphrodita applied only to slug shelter at high (6 × 10⁹ IJ s/ha) rate (●). Nonsterilized muck soil and four Impatients plants were used in each tub. Twelve adult slugs were placed directly on plants (3/plant) immediately after the application of nematodes. Shelters were placed only in the last two treatments in the beginning of the experiment and only after 8 days in all the other treatments. (B) Mean maximum (●) and minimum (○) air temperature in the greenhouse and mean soil temperature (▲) in the bioassay arena during Experiment 1.

through time. Hypotheses regarding the relative amounts of damage obtained with different treatments either on a single date or through time were tested using contrasts.
There were no differences among any of the treatments except for the control at 13 days after treatment. At the end of the experiment, over 97% of the leaves showed slug feeding damage in the untreated control as compared to only 38% in the metaldehyde, 39 and 41.5% in the high and low nematode treatments applied as overall applications, respectively, and 54 and 65% in the high and low nematode treatments applied as shelter applications, respectively.

Leaf area eaten. All treatments caused significant reduction in the leaf area consumed by the slugs from Day 5 onward ($F_{5,47} = 47.1; \text{df} = 1,18; P < 0.001$) (Fig. 2C). Metaldehyde was significantly more effective than the nematode treatments on Days 3 and 5 ($F_{5,47} = 6.0; \text{df} = 1,18; P < 0.05$) but was not different for the rest of the experimental period ($F = 0.30; \text{df} = 1,18; P > 0.05$). By Day 17, slugs consumed over 75% of the total leaf area in the untreated controls as compared to only 10.7 and 15% in the high and low nematode treatments applied as overall applications, respectively, 18% in the metaldehyde treatment, and 23 and 24.5% in the high and low nematode treatments applied as shelter applications. The two nematode treatments applied to shelters were marginally less effective than the two nematode treatments applied as overall application ($F = 3.2; \text{df} = 1,18; P < 0.10$) at the same rate. Mean daily soil temperature and maximum and minimum air temperatures are given in Fig. 3.

Experiment 3: Hosta

Slug mortality. When new slugs were introduced into the tubs from Experiment 2, the nematodes were extremely effective at killing the reintroduced slugs (Fig. 4A). Slug survival was highest in the metaldehyde treatment indicating no residual activity. In contrast, all the nematode treatments caused significantly greater reduction in slug survival by Day 7 than metaldehyde ($F = 82.3; \text{df} = 1,18; P < 0.001$), and the effect reaching 96-100% mortality by Day 14. The LT$_{50}$ ($t = 10.9; \text{df} = 18; P < 0.001$) and LT$_{95}$ ($t = 29.9; \text{df} = 18; P < 0.001$) showed that the metaldehyde treatment was significantly less effective than all treatments except for the control at 13 days after treatment. At the end of the experiment, over 97% of the leaves showed slug feeding damage in the untreated control as compared to only 38% in the metaldehyde, 39 and 41.5% in the high and low nematode treatments applied as overall applications, respectively, and 54 and 65% in the high and low nematode treatments applied as shelter applications, respectively.

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and shelter applications ($F = 2.3; df = 1.18; P > 0.15$), but no differences in the method of application for the same rate ($F = 0.04; df = 1.18; P > 0.80$).

Mean daily soil temperature and maximum and minimum air temperatures are presented in Fig. 3.

**DISCUSSION**

Conventional wisdom suggests that uniform coverage should be the ultimate goal of a pesticide application. However, Hislop (1987) indicated that there is no

![FIG. 3. Mean maximum (○) and minimum (○) air temperature in the greenhouse and mean soil temperature (▼) in the bioassay arena during Experiments 2 and 3. Arrow indicates the beginning of Experiment 3.](image)

![FIG. 4. Mean (±SE) number of surviving Deroceras reticulatum (A), percentage of leaves damaged (B), and percentage of leaf area eaten (C) by the reintroduced slugs (Experiment 3) in the untreated control (●), metaldehyde (○), overall Phasmarhabditis hermaphrodita application at low (3 x 10^9 IJs/ha) rate (▲), overall P. hermaphrodita application at high (6 x 10^9 IJs/ha) rate (▼), P. hermaphrodita applied only to slug shelter at low (3 x 10^9 IJs/ha) rate ( ■ ), P. hermaphrodita applied only to slug shelter at high (6 x 10^9 IJs/ha) rate ( ▼ ). Sterilized muck soil and four Hosta plants were used in each tub. Twelve adult slugs were placed directly on plants (3/plant). Shelters were placed in all treatments at the time nematode applications were first made.](image)
reliable correlation in the field between good coverage and biological result. Therefore, continued reliance on traditional paradigms has prevented potential breakthroughs in utilizing new pest control agents. The most interesting aspect of the present investigation is the remarkable performance of relatively low numbers of nematodes when applied directly to the slug shelters. Application of only 54,000 IJs under a roofing shingle (used as a slug shelter) provided as good or better slug control and feeding damage reduction than the overall application of 144,000 IJs to the entire 0.48 m² area. This represents a reduction of 63% in the numbers of nematodes required to treat the same area (i.e., $1.1 \times 10^9$ IJs/ha vs. $3.0 \times 10^9$ IJs/ha). Once optimized, the slug-shelter nematode application approach should prove economical in floriculture, horticulture, and agriculture.

The slug shelters most likely enhanced biological control by molluscicidal nematodes by providing protection against environmental extremes. Nematode survival, activity, and reproduction may have been improved under the shelters due to the provision of hosts and more conducive environment including high humidity, favorable soil moisture, and protection from direct sunlight. In our study, relatively small numbers of nematodes applied under the roofing shingles provided equal control to the recommended rate of nematodes applied to the entire surface of the exposed soil. The higher efficacy of nematodes applied under the shingles in Experiment 3 that evaluated longer term control provides further evidence of greater nematode persistence/recycling under the shingles. Therefore, the use of slug shelter for nematode application may prove quite effective.

We observed that _P. hermaphrodita_ recycled in the infected slugs in the greenhouse, and our results suggest potential for the use of this nematode for long-term slug control. Emergence of new generation infective juveniles from infected slugs was observed in all nematode treatments. The additional presence of recycled nematodes provided more rapid control of the reinfesting slugs than the initial control provided by the inundatively applied nematodes. In contrast, the activity of the metaldehyde diminished rapidly, and no suppression of the reinfesting slugs was observed after 17 days of application of the chemical. We propose that recycling may be an important characteristic of _P. hermaphrodita_, making it an extremely attractive inoculative release agent. This may be due to the relatively slow speed of slug mortality following nematode infection, allowing infected slugs to move back to the shelters/homing sites that are also more conducive for nematode reproduction, development, and persistence. Further, our recent studies (Tan and Grewal, 2001) suggest that _P. hermaphrodita_ infective juveniles can initiate and complete their life cycle on slug feces and dead slugs, indicating potential survival of the nematodes in the environment in the absence of the host.

This shelter application strategy would prove extremely useful in protecting young plants that suffer the most slug damage in floriculture, horticulture, and agriculture. The soil surface is more exposed when the plants are young, rendering applications less effective due to the inactivation of nematodes by environmental extremes. Slug shelters can be easily constructed from a range of materials including mulches, agricultural wastes, wood pieces, roofing shingles, tiles, or cardboard. The efficacy of the slug shelter approach may be further enhanced by combining nematodes with feeding attractants if needed. This study also suggests that the mature and/or larger plants may be protected from slug damage by treatment with relatively small numbers of nematodes only underneath the plants as opposed to an overall application to the entire area. The larger plants may serve as effective shelters as the slugs usually take refuge in the shaded areas.

There are two potential areas of concern in targeting “artificial” slug shelters for application of molluscicidal nematodes. First, in established home and other landscapes, there may be many areas that may serve as homing sites for slugs. In such situations, the application of nematodes directly to the natural homing sites

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**TABLE 2**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>LT$_{50}$</th>
<th>SE</th>
<th>95% FL</th>
<th>LT$_{95}$</th>
<th>SE</th>
<th>95% FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>11.3</td>
<td>0.6</td>
<td>10.187–12.702</td>
<td>22.3</td>
<td>2.0</td>
<td>19.195–27.715</td>
</tr>
<tr>
<td>Metaldehyde</td>
<td>15.2</td>
<td>1.2</td>
<td>13.501–18.702</td>
<td>26.9</td>
<td>3.2</td>
<td>22.267–37.033</td>
</tr>
<tr>
<td>Overall low</td>
<td>7.8</td>
<td>0.3</td>
<td>7.127–8.361</td>
<td>13.2</td>
<td>0.7</td>
<td>12.137–14.875</td>
</tr>
<tr>
<td>Overall high</td>
<td>7.1</td>
<td>0.3</td>
<td>6.625–7.623</td>
<td>10.8</td>
<td>0.5</td>
<td>10.007–11.918</td>
</tr>
<tr>
<td>Shelter low</td>
<td>7.1</td>
<td>0.3</td>
<td>6.608–7.624</td>
<td>10.9</td>
<td>0.5</td>
<td>10.099–12.051</td>
</tr>
<tr>
<td>Shelter high</td>
<td>7.1</td>
<td>0.3</td>
<td>6.051–7.181</td>
<td>11.1</td>
<td>0.5</td>
<td>10.235–12.448</td>
</tr>
</tbody>
</table>

Note. SE, standard error; FL, fiducial limits.
may prove more economical than the overall application to the entire area. Also, efficacy of feeding attractants may be tested to attract the slugs to artificial shelters as opposed to the natural shelters. Another potential concern is the possibility that the slugs may avoid nematode-treated areas as has been observed in a previous study (Wilson et al., 1999). We did not find any evidence of such behavioral avoidance of the artificial slug shelters in the present investigation. This may be due to the lower nematode dosage rate used in the present investigation than in the previous study. Wilson et al. (1999) reported that the tendency of D. reticulatum and A. ater to avoid nematode-treated areas depended upon nematode concentration and it only occurred at concentrations above 38 L j/s/cm². As our results indicate that the nematode application rate may be further reduced in the shelter approach, the slug-evasive behavior may not be important. Further research in this area is clearly warranted.

The bioassay developed during this investigation offers several advantages over the existing bioassay methods. The new bioassay is simple and provides an effective means of determining the effect of mollusicides on slug mortality and reduction in feeding damage. The mounted copper cloth serves as an effective barrier against slug escape. The size of the arena lends itself to the studies on slug foraging and homing behavior. Also, the use of simple slug shelters (roofing shingles) allows easy monitoring of slug populations as the slugs take refuge under the shelters during the day. This eliminates the need for time-consuming slug monitoring techniques involving flooding and/or sifting the soil (Wilson and Gaugler, 2000). Further, the animal feeding tubes used in this bioassay are relatively cheap and readily available and can be stacked when not in use.

This is the first study demonstrating the potential of P. hermaphrodita for slug control in North America. The nematodes have performed fairly well in Europe where the soil temperatures typically remain close to 10°C when the slugs are active under field conditions (Glen and Wilson, 1997). The air temperature in our greenhouse fluctuated considerably and ranged between 14 and 31.5°C and the soil temperature varied between 14 and 19°C. Excellent performance of P. hermaphrodita under these warmer conditions indicate its potential utility in the U.S. greenhouse industry and agriculture.

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REFERENCES


