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Research

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Evaluation of reflective mulch and insect exclusion coverings for allium leafminer (Diptera: Agromyzidae) management in allium crops

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Allium leafminer (*Phytomyza gymnostoma* Loew) is a recent invasive pest in the United States causing serious economic loss in organic allium crops. Organic management of *P. gymnostoma* is currently limited to foliar applications of spinosad, but this strategy is not always sufficient under high infestations. Nonchemical management tools used either alone or in combination with spinosad are needed to improve *P. gymnostoma* management. Reflective mulch alone or combined with spinosad as well as insect exclusion coverings were evaluated for managing *P. gymnostoma* in allium crops in New York from 2018 to 2021. Reflective mulch alone reduced the numbers of oviposition marks by 16% and densities of larvae plus pupae by 40% compared with those in standard plastic mulch. Reflective mulch combined with 1 spinosad application reduced *P. gymnostoma* densities to levels lower than those in reflective mulch alone, but 2 spinosad applications were required to provide an acceptable control level. Combining with reflective mulch, row covers, and insect netting reduced *P. gymnostoma* densities by 76% compared with those without physical barriers, and the level of control was comparable to that provided by 2 spinosad applications. *Phytomyza gymnostoma* densities in allium crops grown under row covers deployed throughout the entire period when flies were active tended to be lower than those protected during shorter periods (80% reduction). Future management of *P. gymnostoma* in allium crops should consider either combining reflective mulch with 2 foliar spinosad applications or deploying insect exclusion coverings. The advantages and challenges of using these management strategies are discussed.

Key words: Phytomyza gymnostoma, cultural practice, organic vegetable production, invasive pest

Allium leafminer, *Phytomyza gymnostoma* Loew (Diptera: Agromyzidae), is an invasive pest native to Europe and was first detected in the United States in 2015 (Barringer et al. 2018). *Phytomyza gymnostoma* has spread to nearby states on the East coast since its invasion and is established as far north as New York and Massachusetts and as far south as Virginia. Hosts of *P. gymnostoma* are limited to those in the *Allium* genus including leek, onion, garlic, scallion, chives, shallot, as well as ornamental and wild species (Barringer et al. 2018, Lingbeek et al. 2021, CABI 2022). Crop damage can be caused by all *P. gymnostoma* life stages. Females puncture leaves (usually the upper portion) with their ovipositors generating a series of linear white marks; these aesthetic blemishes on scallions and chives can make them unmarketable. Both male and female adults feed on plant exudates produced by the oviposition punctures. Females infrequently lay eggs during this process as only 4% of the oviposition marks contain eggs (Lai et al. 2023). Larvae feed (mine) inside the leaves, which in severe cases can lead to leaf distortion and wilting. The most significant damage occurs when late instars feed and pupate at the base of plants, which typically increases rot-causing pathogen infections in bulbs. In addition, the presence of larvae and pupae at the base of the plant contaminates crops like leek, onion, and garlic, reducing their marketability (Coman and Rosca 2011a, 2011b, Laznik et al. 2012, Barringer et al. 2018, CABI 2022).

In North America, *P. gymnostoma* has 2 generations per year (Barringer et al. 2018). The spring generation emerges after 350°C

Table 1. Information regarding field trials designed to evaluate various management practices for allium leafminer, *P. gymnostoma*, in New York.

Study[a]	Trial	Year	Season	Crop	Cultivar[b]	Seeding in transplant trays	Transplanting in the field	Harvest	Treatments
I	1	2018	Fall	Leek	Megaton	27 April	7 June	8 November	White/reflective mulch
	2	2018	Fall	Scallion	White Spear	27 June	8 August	8 November	White/reflective mulch
	3	2019	Spring	Garlic	Spanish Roja	NA	25 October 2018	24 June	Black/reflective mulch
II	4	2019	Spring	Scallion	Nabechan	12 March	11 April	17 June	Black/reflective mulch × spinosad
III	5	2019	Fall	Leek	Megaton	15 April	25 June	30 October	White/reflective mulch × spinosad
IV	6	2020	Fall	Leek	Megaton	26 March	16 June	10 November	Row cover/insect netting/spinosad
	7	2021	Fall	Leek	Lancelot	26 March	10 June	3 November	Row cover/insect netting/spinosad

[a]I: Standard and Reflective Mulch Trials; II: Standard and Reflective Mulch with a Single Spinosad Application Trial; III: Standard and Reflective Mulch with Multiple Spinosad Applications Trial; IV: Physical Barrier Types and Duration of Protection Trials.
[b]Seed producer: Megaton Leek—Stokes Seeds, Holland, MI, USA; White Spear and Nabechan Scallion—Johnny's Selected Seeds, Winslow, ME, USA; Spanish Roja Garlic—Burpee Seeds and Plants, Philadelphia, PA, USA; Lancelot Leek—Bejo Seeds Inc., Oceano, CA, USA.

days (threshold of 1°C from January 1), which typically ranges from mid-March to late-April (Lingbeek et al. 2021). Active through May and early June, *P. gymnostoma* aestivates in the pupal stage during the summer months until the fall generation emerges in September with activity extending through November. *Phytomyza gymnostoma* overwinters in the pupal stage at the base of plants or in surrounding soil (Lingbeek et al. 2021).

Phytomyza gymnostoma can be successfully managed using insecticides, especially cyantraniliprole (IRAC group 28), dinotefuran (IRAC group 4A), and spinetoram (IRAC group 5) (Nault et al. 2020). Generally, 2 applications timed after the first week of initial *P. gymnostoma* detection is sufficient to manage *P. gymnostoma* (Nault et al. 2022). For organic production, spinosad (IRAC group 5) is the best product to manage *P. gymnostoma*, but it does not provide acceptable control when infestations are high (Nault et al. 2020, 2022). Because effective chemical options are limited for organic growers, non-chemical management strategies for *P. gymnostoma* should be identified.

Plastic mulch, especially those with reflective properties, can improve insect pest management by repelling the pest or affecting the pest's ability to locate its host (Bégin et al. 2001, Vincent et al. 2003, Díaz and Fereres 2007). Reflective mulch reduced the number of mines caused by American serpentine leafminer, *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae), in tomato (*Solanum lycopersicum* L.) and squash (*Cucurbita* spp.) (Wolfenbarger and Moore 1968), but failed to repel vegetable leafminer, *Liriomyza munda* Frick, in snap bean (*Phaseolus vulgaris*) (Webb and Smith 1973). Plastic mulch is commonly used in organic allium crop production. The black plastic mulch is usually used in the spring to increase soil temperature, while the white plastic mulch is used in summer/fall crops to decrease soil temperature. However, the effects of standard mulch types and reflective mulch on *P. gymnostoma* in allium crops have not been evaluated.

Protecting crops from insect pests using physical barriers like floating row covers and netting has been suggested for managing *P. gymnostoma* (Kahrer 1999, Bégin et al. 2001, Coman and Rosca 2011a, Durlin et al. 2015, Lingbeek et al. 2021). Vegetable leafminer, *Liriomyza sativae* Blanchard, was completely excluded by row covers in cantaloupe/honeydew melon (*Cucumis melo* L.), while other leafminer (*Liriomyza* sp.) densities in tomato were significantly reduced using row covers (Natwick and Laemmlen 1993, Orozco-Santos et al. 1995, Gogo et al. 2014). Physical barriers have not been evaluated for *P. gymnostoma* management in allium crops.

The purpose of this study was to identify cultural practices that would reduce damage to allium crops caused by *P. gymnostoma*. The first objective evaluated the effect of reflective mulch on infestation levels and damage. We hypothesized that the number of oviposition marks and larval and pupal densities would be lower in reflective mulch than in standard types of plastic mulch (white and black). The second objective assessed the performance of reflective mulch and spinosad applications for reducing infestation levels. We hypothesized that reflective mulch plus spinosad would reduce *P. gymnostoma* infestation levels more than if either tactic were used alone. The third objective evaluated the impact of physical barriers (row cover and insect exclusion netting) and the duration of their deployment on larval and pupal densities when reflective mulch was used. We hypothesized that physical barriers (regardless of type) installed in the field when *P. gymnostoma* flies were first detected and maintained throughout the season would provide the best protection against *P. gymnostoma* compared with alternative periods of physical barrier deployment. Moreover, we hypothesized that physical barriers would provide comparable levels of *P. gymnostoma* control as that provided by foliar applications of spinosad.

Materials and Methods

Seven field trials were conducted at the Hudson Valley Farm Hub (41°54′55.6″N 74°04′57.8″W) and on a commercial farm (41°55′47.6″N 74°03′58.8″W) both near Hurley, New York from 2018 to 2021 to evaluate reflective mulch and its integration with spinosad and physical barriers for *P. gymnostoma* management. Details of these trials including year, season, crop, cultivar, time of seeding in the greenhouse, transplanting in the field, and harvest as well as treatments are presented in Table 1. Leek and scallion plants were propagated by planting seeds in multicell plug flats with 3–4 seeds per cell. Seedlings were maintained in a greenhouse at the Hudson Valley Farm Hub and maintained under standard growing conditions before transplanting in the field. Seed garlic was saved from the previous harvest at the Hudson Valley Farm Hub and planted directly in the field. Trials were conducted in a sequence of 4 studies (described in the next section; see details in Table 1). All trials included plots that had 2 rows per bed, 15 cm (6 inches) between plants in a row, and plastic mulch with drip irrigation. Plot beds were spaced 2 m apart. For all 7 trials, treatments were arranged in randomized complete block designs with 4 replications.

Experimental Designs and Data Collection

Standard and *Reflective Mulch Trials.*

Reflective mulch was evaluated for management of *P. gymnostoma* on scallion and leek in the fall and garlic in the spring (trials 1–3 in Table 1). Reflective mulch (Silver Plastic; SIL424; 0.025 mm [1 mil] thickness; Rain-Flo Irrigation, East Earl, PA, USA) was compared with white (White on Black; WH424; 0.025 mm [1 mil] thickness; Rain-Flo Irrigation, East Earl, PA, USA) or black (Black Embossed; BLK424; 0.025 mm [1 mil] thickness; Rain-Flo Irrigation, East Earl, PA, USA) standard mulch types in the fall and spring trials, respectively. Each plot was 6.1 m (20 ft) long with a 1.5 m (5 ft) buffer zone between plots. Trials 1 and 2 targeted the fall generation of *P. gymnostoma*, while trial 3 targeted the spring generation.

Oviposition marks were counted on 20 randomly selected plants in each plot weekly after the initial observation of marks in trials 1 and 2. However, only the sampling date with the most overall oviposition marks was used to compare the effect of mulch type. At the end of the season, 10–25 plants per plot were harvested in all 3 trials (trials 1–3). Plants were taken to the laboratory where plants were carefully dissected, and the numbers of *P. gymnostoma* larvae and pupae per plant were recorded. A number of plants sampled depended on the condition of the crop in the trial and the availability of labor time to process the samples in a timely manner.

Standard and *Reflective Mulch with a Single Spinosad Application Trial.*

The effectiveness of combining a single foliar application of spinosad with reflective mulch for *P. gymnostoma* management was evaluated in trial 4 in the spring of 2019 (Table 1). Plots were 3 m (10 ft) long with a 1.5 m (5 ft) buffer zone between plots. Treatments included black mulch, black mulch with 1 spinosad application, reflective mulch, and reflective mulch with 1 spinosad application.

Following the recommendations by Nault et al. (2020), spinosad (Entrust SC; Corteva Agriscience, Indianapolis, IN, USA) was applied 3.5 weeks after the initial observation of *P. gymnostoma* oviposition marks in the trial on 10 May at a rate of 0.1 kg a.i. per ha and co-applied with potassium salts of fatty acids at 1.5% (V/V) (M-Pede; Gowen Company, Yuma, AZ, USA) to improve the performance of spinosad. Applications were made using a CO_2-pressurized, backpack sprayer that delivered 367 L/ha at 276 kPa (40 psi) using a boom equipped with 2 twin turbojet nozzles (TTJ60-11003VS) spaced 0.4 m (17.5 inches) apart that covered the width of the bed (0.8 m; 32 inches). To assess performance of the treatments, 20 plants per plot were dissected, and numbers of *P. gymnostoma* larvae and pupae per plant were recorded.

Standard and *Reflective Mulch with Multiple Spinosad Applications Trial.*

The effectiveness of combining either 1 or 2 foliar applications of spinosad with reflective mulch for *P. gymnostoma* management was evaluated in trial 5 in fall 2019 (Table 1). Plots were 4.6 m (15 ft) long with a 1.5 m (5 ft) buffer zone between plots. Treatments included white mulch, white mulch with 1 spinosad application, white mulch with 2 spinosad applications, reflective mulch, reflective mulch with 1 spinosad application, and reflective mulch with 2 spinosad applications. For treatments with 1 spinosad application, the application was made 3 weeks after the initial observation of *P. gymnostoma* oviposition marks in the trial on 27 September. For treatments with 2 spinosad applications, applications were made 2 and 4 weeks after the initial observation of oviposition marks, on 20 September and 4 October, respectively. Spinosad applications and data collection followed the same procedure as described in the *Standard and Reflective Mulch with a Single Spinosad Application Trial.*

Physical Barrier Type and Duration of Protection Trials

The effectiveness of row covers and exclusion netting for *P. gymnostoma* management were evaluated in trials 6 and 7 in fall 2020 and 2021, respectively (Table 1). In addition, the effect of the period that these physical barriers were deployed on their effectiveness against *P. gymnostoma* was evaluated. Reflective mulch was used across treatments. Plots were 3 m (10 ft) long with a 0.9 m (3 ft) buffer zone between plots.

The row covers (DeWitt Floating Row Cover, 18.6 g per m^2 [0.55 oz per square-yard], Nolt's Produce Supplies, LLC, Leola, PA, USA) and insect exclusion netting (ProtekNet 25 g 0.35 mm × 0.35 mm, Dubois Agrinovation, Saint-Remi, QC, Canada) were used in this study. Treatments included row cover, row cover supported by metal hoops, row cover with hoops but installed late, row cover with hoops but removed early, insect exclusion netting, and insect exclusion netting with hoops. Two applications of spinosad and a nontreated control were included in the experiment. Altogether, there were 8 treatments (Table 2).

In both years, treatments of row cover and insect netting either with or without hoops were installed within the first several days of

Table 2. Dates of physical barrier installation, removal, and spinosad applications in the Physical Barrier Type and Duration Trials designed to manage allium leafminer, *P. gymnostoma*, in New York.

	Fall 2020		Fall 2021	
Treatments/dates	Installation	Removal	Installation	Removal
Row cover	8 September	10 November	7 September	3 November
Row cover w/hoops	8 September	10 November	7 September	3 November
Row cover w/hoops—late cover	25 September	10 November	20 September	3 November
Row cover w/hoops—early removal	8 September	14 October	7 September	5 October
Insect netting	8 September	10 November	7 September	3 November
Insect netting w/hoops	8 September	10 November	7 September	3 November
	Application 1	**Application 2**	**Application 1**	**Application 2**
Spinosad *2	25 September	8 October	15 September	29 September
Nontreated control	-	-	-	-
First oviposition mark observed	8 September		3 September	

Note. Leeks were grown on reflective mulch across treatments.

the initial observation of *P. gymnostoma* oviposition, and they were kept there until harvest. Because growers may not always install row covers in a timely manner, we included a "row cover with hoops—late cover" treatment in which row covers were installed 2 weeks after the initial *P. gymnostoma* flight and then kept until harvest. On the other hand, growers may wish to remove row covers early to harvest their crop, so we included a "row cover with hoops—early removal" treatment in which row covers were installed before the *P. gymnostoma* flight, but then removed after only 4–5 weeks. On the other hand, spinosad (same formulation, rate, and application details as described previously) applications were made 2 and 4 weeks after the initial observation of *P. gymnostoma* oviposition marks. Dates of installation and removal of physical barriers and spinosad applications are listed in Table 2. In both trials 6 and 7, 20 plants per plot were dissected and numbers of *P. gymnostoma* larvae and pupae per plant were recorded.

Statistical Analyses

The numbers of *P. gymnostoma* oviposition marks on the sampling date with the most overall marks (trials 1 and 2 in *Standard and Reflective Mulch Trials* only) and the number of *P. gymnostoma* per plant (larvae, pupae, and larvae plus pupae) at harvest were the response variables to compare management practices. Raw data were averaged across samples from a plot. All statistical analyses were conducted in SAS (SAS Studio version 3.81; Enterprise edition 2022; SAS Institute Inc., Cary, NC, USA).

For the *Standard and Reflective Mulch Trials*, data were pooled across trials 1–3 to enhance the statistical power after confirming the trial/crop type factor was not significant as a fixed factor in preliminary analyses. A number of oviposition marks was analyzed by a *t*-test using the PROC TTEST procedure (SAS Institute 2013). *Phytomyza gymnostoma* count data were analyzed using generalized linear mixed models with the Poisson distribution and the log link function under the PROC GLIMMIX procedure (SAS Institute 2013); type of plastic mulch was a fixed factor, while trial and replication were random factors.

For the *Standard and Reflective Mulch with a Single Spinosad Application Trial* and the *Standard and Reflective Mulch with Multiple Spinosad Applications Trial*, *P. gymnostoma* count data were analyzed using generalized linear mixed models under the PROC GLIMMIX procedure (SAS Institute 2013); treatment was the fixed factor, and replication was the random factor. The Gaussian distribution and the identity link function were used when the normality assumption was met; otherwise, the Poisson or the negative binomial distribution was used with the log link function.

For the *Physical Barrier Type and Duration of Protection Trials*, data were pooled from the leek trials in fall 2020 and 2021 after confirming the insignificance of the year factor in preliminary analyses. *Phytomyza gymnostoma* count data were subjected to a square-root transformation (i.e., $\sqrt{x+3/8}$) to remedy large variances in several treatments and zero-inflated count data. Square-root transformed data were analyzed using generalized linear mixed models under the PROC GLIMMIX procedure with the Gaussian distribution and the identity link function (SAS Institute 2013). Treatment was the fixed factor, while trial and replication were the random factors.

Least squares means (LS means) were used in post hoc comparisons of *P. gymnostoma* count data in all trials, and Tukey studentized range [honestly significant difference (HSD)] test was used for mean comparisons when the fixed factor was significant at $\alpha = 0.05$. In one case, the T grouping method was used for LS means separation of a number of larvae plus pupae in the *Standard and Reflective Mulch with a Single Spinosad Application Trial* because the Tukey HSD was too conservative to provide mean separation.

Results

Standard and Reflective Mulch Trials

Across trials 1 and 2, plants grown on reflective mulch had significantly fewer *P. gymnostoma* oviposition marks (16% reduction) than the standard white mulch ($t = 10.2$; $df = 15$; $P < 0.001$; Fig. 1). Across trials 1, 2, and 3, plants grown on reflective mulch had significantly lower numbers of *P. gymnostoma* larvae (46% reduction) and larvae plus pupae (36% reduction) than those grown on the standard mulch type (larvae: $F = 6.15$; $df = 1, 22$; $P = 0.021$; larvae and pupae: $F = 6.17$; $df = 1, 22$; $P = 0.021$; Fig. 2). Numbers of *P. gymnostoma* pupae only were not different between the reflective and standard mulch type ($P > 0.05$; Fig. 2).

Standard and Reflective Mulch with a Single Spinosad Application Trial

Phytomyza gymnostoma pressure was low in scallions in spring 2019 (trial 4). Scallions grown on reflective mulch with or without the spinosad application had significantly lower numbers of *P. gymnostoma* larvae plus pupae than scallions grown on standard black mulch, but were similar to those grown on black mulch with the spinosad application ($F = 3.75$; $df = 3, 12$; $P = 0.041$; Fig. 3). Similar results were observed for numbers of larvae alone, but treatment means were not statistically different ($P > 0.05$; Fig. 3). Numbers of pupae among treatment combinations of mulch types either with or without spinosad application were not different ($P > 0.05$; Fig. 3). Regardless of mulch type, the spinosad application did not significantly reduce numbers of *P. gymnostoma* (Fig. 3).

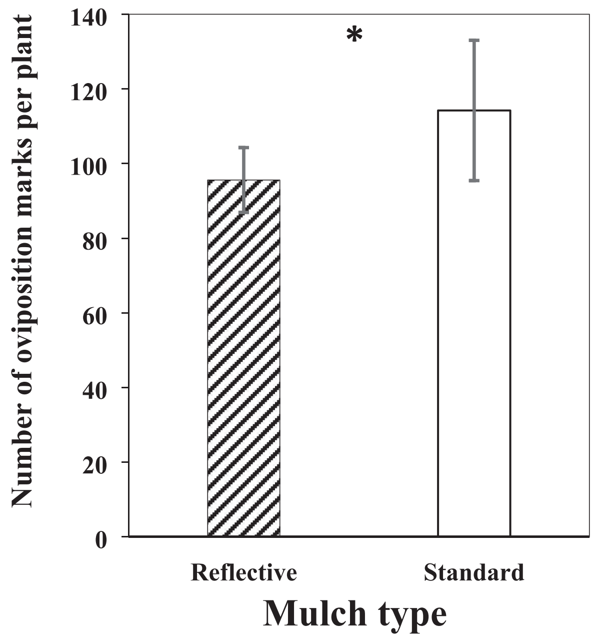

Fig. 1. Mean (±SE) number of *P. gymnostoma* oviposition marks per plant on the sampling date with the most overall number of marks between reflective and standard (white) mulch for fall plantings. Data were pooled from trial 1 (leek) and trial 2 (scallion) in fall 2018. Asterisk indicates a significant difference ($t = 10.2$, $df = 15$, $P < 0.001$). SE, standard error.

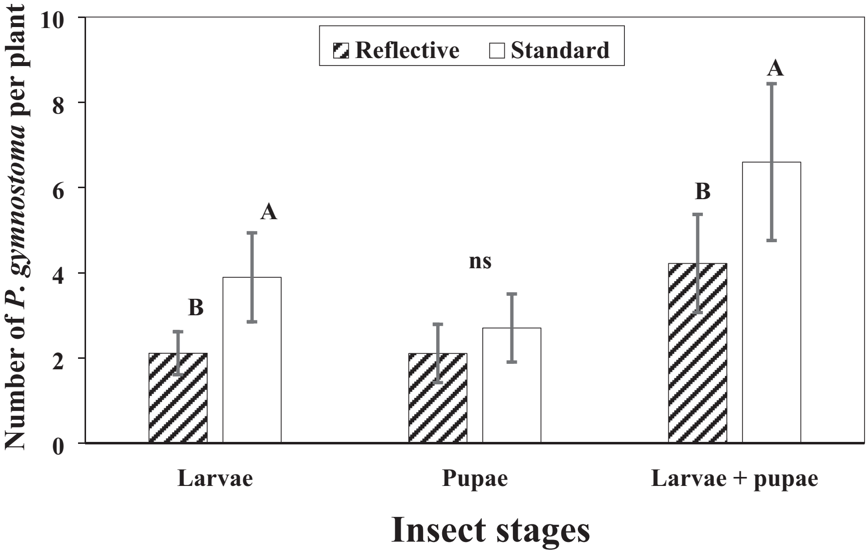

Fig. 2. Mean (±SE) number of *P. gymnostoma* larvae, pupae, and larvae plus pupae per plant at harvest. Data were pooled from trial 1 (leek in fall 2018), trial 2 (scallion in fall 2018), and trial 3 (garlic in spring 2019). White and black plastic mulch are considered as the standard mulch types in fall and spring plantings, respectively. Different letters within each insect stage indicate significant differences in least square means of number of *P. gymnostoma* between mulch types (Tukey-HSD; $P < 0.05$; $n = 4$); while "ns" indicates no significant differences ($P > 0.05$).

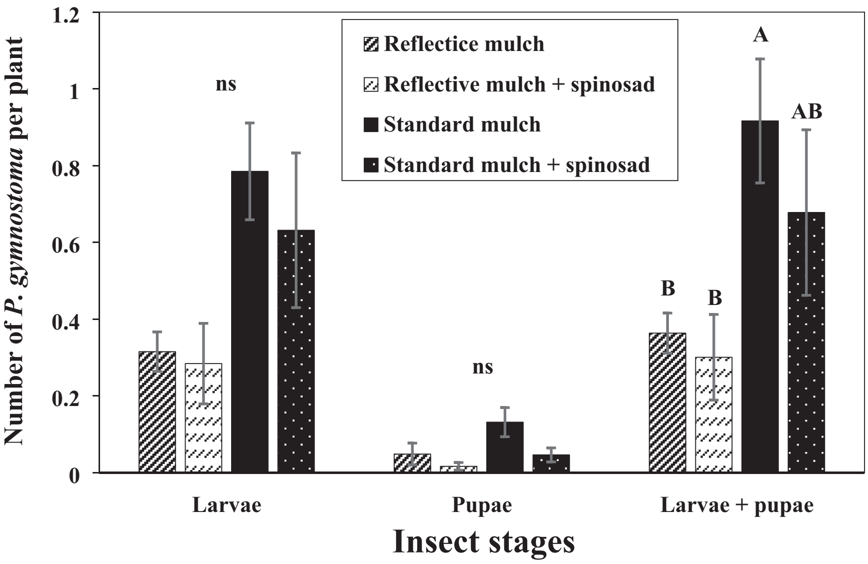

Fig. 3. Mean (±SE) number of *P. gymnostoma* larvae, pupae, and larvae plus pupae per plant at harvest in the scallion trial in spring 2019 (trial 4). Black plastic mulch was the standard mulch type. Different letters within each insect stage indicate significant differences in least-square means of number of *P. gymnostoma* among treatments of mulch and spinosad combinations (Tukey-HSD; $P < 0.05$; $n = 4$); while "ns" indicates no significant differences ($P > 0.05$).

Standard and Reflective Mulch with Multiple Spinosad Applications Trial

Phytomyza gymnostoma pressure was high in leek in the fall of 2019 (trail 5). Combinations of mulch type and spinosad applications affected densities of *P. gymnostoma* larvae ($F = 20.69$; $df = 5, 15$; $P < 0.001$), pupae ($F = 20.82$; $df = 5, 15$; $P < 0.001$), and larvae plus pupae ($F = 38.06$; $df = 5, 15$; $P < 0.001$) (Fig. 4). Numbers of *P. gymnostoma* in leeks grown on reflective mulch were not significantly different from those grown on the standard white mulch across all 3 *P. gymnostoma* variables, regardless of spinosad application (Fig. 4). One spinosad application significantly reduced numbers of *P. gymnostoma* across all 3 variables regardless of mulch type; the only exception was that larval densities in the reflective mulch treatment with or without 1 application were similar. Two spinosad applications further significantly reduced the numbers of larvae and larvae plus pupae compared with those in the single spinosad application, regardless of mulch type (Fig. 4). Pupal densities in treatments that had 2 spinosad applications were statistically similar to those that received one application (Fig. 4).

Physical Barrier Type and Duration of Protection Trials

Across trials 6 and 7, numbers of *P. gymnostoma* larvae, pupae, and larvae plus pupae per plant were significantly affected by the different treatments (larvae: $F = 5.78$; $df = 7, 49$; $P < 0.001$; pupae: $F = 17.82$; $df = 7, 49$; $P < 0.001$; and larvae plus pupae: $F = 8.93$, $df = 7, 49$; $P < 0.001$; Fig. 5). Numbers of larvae in the treatments with row cover, row cover with hoops, insect netting, and insect netting with hoops were significantly lower than those in the non-treated control, while the number of larvae in the row cover treatment was also lower than the number in the treatment with row cover with hoops removed early; the number of larvae in the spinosad treatment was not different from any other treatment (Fig. 5). Numbers of pupae in all treatments including the spinosad treatment were significantly lower than those in the non-treated control. In addition, the numbers of pupae in the row cover, row cover with hoops, and insect

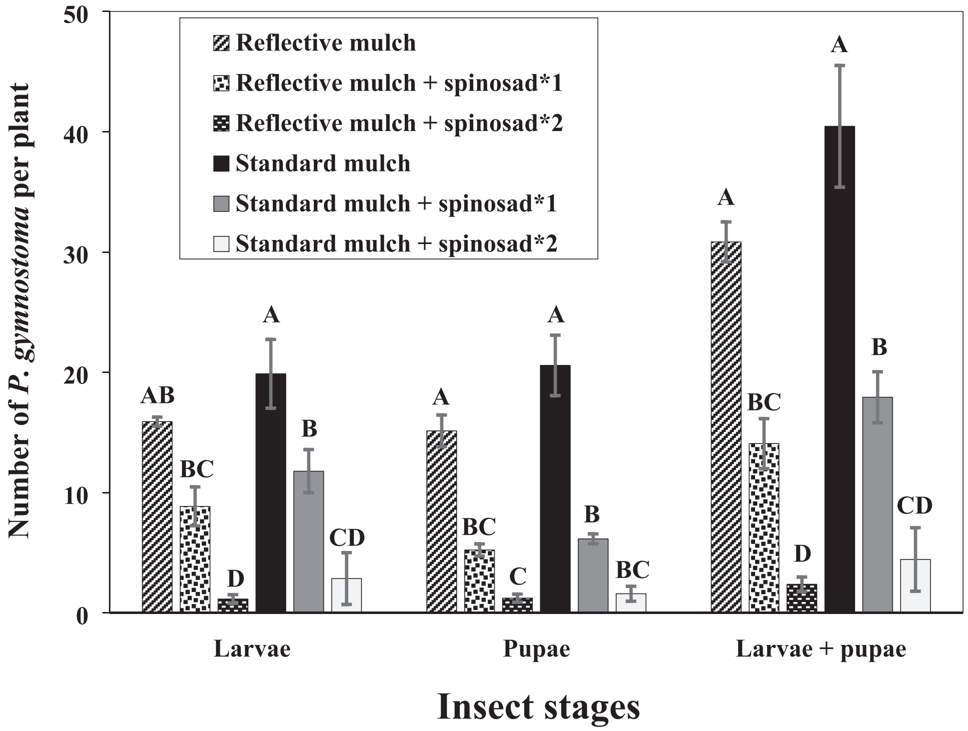

Fig. 4. Mean (±SE) number of *P. gymnostoma* larvae, pupae, and larvae plus pupae per plant in the leek trial in fall 2019 (trial 5). White plastic mulch was the standard mulch type. Different letters within each insect stage indicate significant differences in least square means of number of *P. gymnostoma* among treatments of mulch and spinosad combinations (Tukey-HSD; $P < 0.05$; $n = 4$).

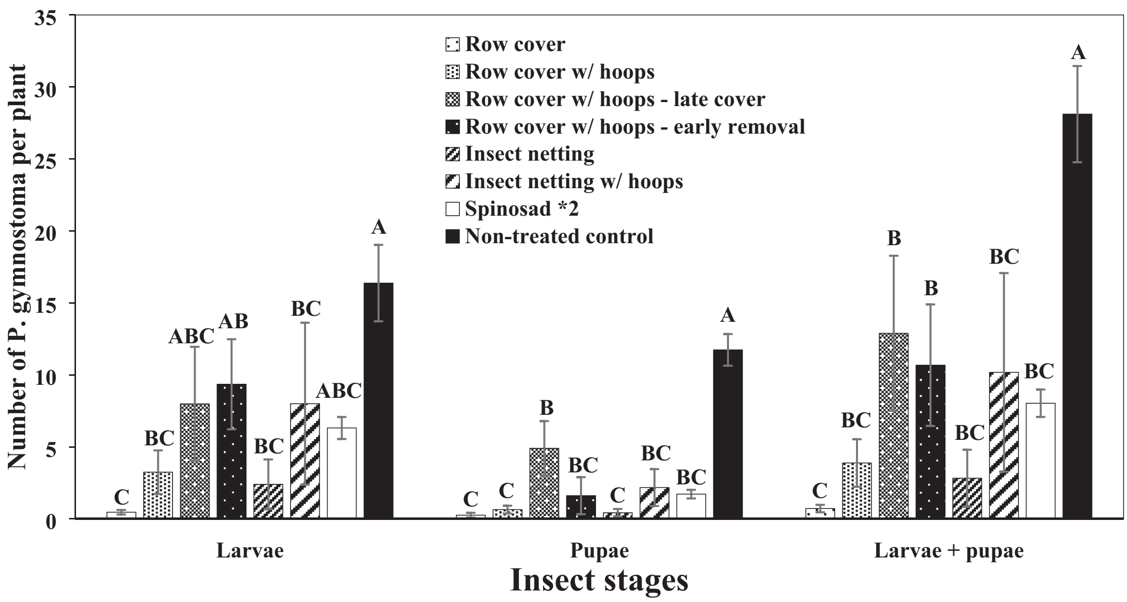

Fig. 5. Mean (±SE) number of *P. gymnostoma* larvae, pupae, and larvae plus pupae per plant across fall leek trials in 2020 and 2021 (trials 6 and 7). Different letters within each insect stage indicate significant differences in least-square means of square-root transformed number of *P. gymnostoma* among treatments (Tukey-HSD; $P < 0.05$; $n = 8$). Leeks were grown on reflective mulch across treatments including the negative control.

netting treatments were lower than those in the row cover with hoops installed during late treatment (Fig. 5). Numbers of larvae plus pupae in all treatments including the spinosad treatment were significantly lower than the number in the non-treated control, and the number of larvae plus pupae in the row cover treatment also was significantly lower than those in the treatments with row cover with hoops installed late or removed early (Fig. 5).

Discussion

Alternative management practices to insecticides for *P. gymnostoma* are highly desirable in organic allium crop production as the current strategy relies on foliar applications of spinosad (Nault et al. 2022). In the sequence of experiments conducted to evaluate the effectiveness of reflective mulch alone and in combination with spinosad and physical barriers for *P. gymnostoma* management, our study showed that reflective mulch combined with 2 spinosad applications and with physical barriers deployed during the entire period that *P. gymnostoma* flies were active reduced densities below grower economic thresholds of 2 and 4 *P. gymnostoma* larvae and/or pupae per scallion and leek, respectively.

Reflective mulch alone significantly reduced oviposition marks and densities of *P. gymnostoma* in allium crops like scallion, leek, and garlic when compared with standard black and white mulch types in 2 of 3 datasets. Reflective mulch on average decreased the total number of *P. gymnostoma* (larvae plus pupae) per plant by 40% (ranging from 22% to 60%) at harvest. The reduction in the numbers of oviposition marks and densities of *P. gymnostoma* in plants indicated that reflective mulch either repels or interferes with the ability of adult flies to find their host to feed and lay eggs. The high reflectance of ultraviolet light in aluminized films impairs an insect's ability to locate its host (Kring and Schuster 1992, Bégin et al. 2001), and this is likely true as well for *P. gymnostoma*.

Mulches have been used in agricultural systems for decades mainly to achieve soil temperature regulation, weed management, and water and soil conservation (Jabran 2019). Positive impacts on insect pest management could be another benefit of mulches (organic or inorganic) either by repelling insect pests, providing alternative inhabitancy for insect pests, or promoting activities of biological entities like natural enemies (Zehnder and Hough-Goldstein 1990, Lament 1993, Brust 1994, Vincent et al. 2003, Gill et al. 2010, Barche et al. 2015, Quintanilla-Tornel et al. 2016, Jabran 2019, Choudhary et al. 2021). In some cases, mulches could also increase vegetable crop yield and quality as well as shorten the growing season (Lament 1993, Barche et al. 2015, Choudhary et al. 2021). In organic allium crop production, mulches are commonly used for weed control and soil temperature regulation to improve plant growth, crop yield, and quality. In onion production specifically, reflective mulch increased onion growth and quality (Sarkar et al. 2019). Reflective mulch also has been evaluated for onion thrips, *Thrips tabaci* Lindeman, management in onion, although the effectiveness was variable (Till et al. 2004, Iglesias et al. 2021). Disadvantages of reflective mulch include its cost, installation, removal, and disposal (Schalk et al. 1979, Greer and Dole 2003, Vincent et al. 2003, Jabran 2019).

Phytomyza gymnostoma densities in scallions and leeks grown on reflective mulch were still higher than current tolerance thresholds (i.e., 2 and 4 *P. gymnostoma* per plant, respectively) in 2 of 3 datasets. Our findings indicated that although reflective mulch can reduce *P. gymnostoma* densities, reflective mulch alone likely will not provide sufficient reduction, especially under a moderate to high *P. gymnostoma* infestation. Therefore, integrating another management tactic with reflective mulch will be necessary. Our study showed that the reduction of *P. gymnostoma* larval and pupal densities using a combination of reflective mulch and a single spinosad application was greater than using reflective mulch alone, but not greater than a single spinosad application on standard mulch under high *P. gymnostoma* infestation (*Standard and Reflective Mulch with Multiple Spinosad Applications Trial*; trial 5). Regardless, *P. gymnostoma* densities in allium crops grown using a combination of reflective mulch and a single spinosad application were still higher than the level tolerated by growers, despite a 65% reduction in *P. gymnostoma* densities. Only reflective mulch combined with 2 spinosad applications provided a sufficient reduction in *P. gymnostoma* densities to a level that would be considered economical (below the grower tolerance threshold); in trial 3, this treatment provided a 94% reduction in *P. gymnostoma* densities. When *P. gymnostoma* pressure was moderate (>2 larvae plus pupae per plant) to high (>20 larvae plus pupae per plant), reflective mulch with 2 spinosad applications could provide sufficient management. In contrast, 2 spinosad applications with the standard mulch type were not good enough to reduce *P. gymnostoma* densities to an acceptable level when pressure was high, which is consistent with findings reported by Nault et al. (2022).

Physical barriers are tools that can serve as alternatives to insecticides for pest management. Physical control methods for insect pests were highly relied upon before the advent of modern insecticides and are recently being re-examined because of problems with insecticide resistance and environmental contamination as well as an increase in the popularity of organic farming (Boiteau and Vernon 2001). Our study demonstrated that both row covers and insect netting significantly reduced *P. gymnostoma* densities in leek. In addition, both types of insect exclusion coverings were as effective as 2 spinosad applications in reducing *P. gymnostoma* densities at harvest. Row covers provided the best *P. gymnostoma* control when they were deployed during the entire period that *P. gymnostoma* flies were active. Moreover, this strategy was better than using 2 applications of spinosad with reflective mulch and was the only treatment providing sufficient *P. gymnostoma* reduction to levels that met the economic tolerance level (i.e., 4 *P. gymnostoma* per leek) in this experiment (trials 6 and 7).

Insect exclusion coverings could also prevent infestations of sporadic insect pests of allium crops such as *L. trifolii* and saltmarsh caterpillar, *Estigmene acrea* (Drury); however, the coverings may not be effective enough to exclude thrips, especially *T. tabaci*. The beneficial effect of reflective mulch on *P. gymnostoma* management is likely diminished by the use of insect exclusion coverings. Therefore, insect exclusion coverings could be considered a standalone management strategy to replace foliar applications of spinosad.

There are limitations to using insect exclusion coverings. For example, weed and foliar disease control becomes challenging after the crop is covered. Installing row covers 2 weeks after the initial observation of *P. gymnostoma* oviposition marks or removing row covers a month before harvest would provide growers with more flexibility, while still providing a significant reduction of *P. gymnostoma* densities at harvest; however, *P. gymnostoma* densities were not lower than the grower tolerance threshold when not covered during the entire adult flight period. Using insect exclusion coverings with and without hoops resulted in similar effectiveness in reducing *P. gymnostoma* densities. Using coverings without hoops could cause plant distortion and damage to allium crops. In contrast, using coverings with hoops can reduce plant distortion from direct contact with the coverings, but will increase the amount of material needed to cover the same area. Overall, the economic and labor costs of implementing insect inclusion coverings can be an impediment to adoption by growers (Boiteau and Vernon 2001). Interfering with pollination is another common challenge of using insect exclusion coverings in crops that require pollination, but this is not an issue for the production of allium crops that are not grown for seed.

Using reflective mulch with spinosad applied at 2 and 4 weeks after the initial observation of *P. gymnostoma* oviposition marks should be an advancement over exclusively relying on spinosad applications. Alternatively, covering allium crops with physical barriers like row covers and insect netting during the period *P. gymnostoma* flies are active is an effective alternative to foliar applications of spinosad. Both are useful management practices that should not only benefit organic allium crop growers but also could be deployed in conventional allium crop production systems where appropriate.

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Author contributions

Pin-Chu Lai (Formal analysis [lead], Visualization [equal], Writing—original draft [lead], Writing—review & editing [equal]), Ethan Grundberg (Conceptualization [equal], Data curation [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Resources [equal], Visualization [equal], Writing—review & editing [equal]), Teresa Rusinek (Conceptualization [equal], Data curation [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Resources [equal], Visualization [equal], Writing—review & editing [equal]), and Brian Nault (Formal analysis [supporting], Supervision [lead], Visualization [supporting], Writing—review & editing [equal])

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