Journal of Economic Entomology, 113(5), 2020, 2300–2309
doi: 10.1093/jee/toaa128
Advance Access Publication Date: 13 June 2020
Research

OXFORD

Managing Allium Leafminer (Diptera: Agromyzidae): An Emerging Pest of Allium Crops in North America

Brian A. Nault,[1,6] Lindsy E. Iglesias,[1] Riley S. Harding,[1] Ethan A. Grundberg,[2] Teresa Rusinek,[3] Tim E. Elkner,[4] Brandon J. Lingbeek,[5] and Shelby J. Fleischer[5]

[1]Department of Entomology, Cornell University, Cornell AgriTech, 15 Castle Creek Dr., Geneva, NY 14456, [2]Eastern New York Commercial Horticulture Program, Cornell Cooperative Extension, 18 Seward Avenue, Suite 300, Middletown, NY 10940, [3]Eastern New York Commercial Horticulture Program, Cornell Cooperative Extension, Hudson Valley Laboratory, 3357 Route 9W, Highland, NY 12528, [4]Southeast Agricultural Research & Extension Center, Pennsylvania State University Extension, 1446 Auction Road, Manheim, PA 17545, [5]Department of Entomology, Pennsylvania State University, 501 ASI Building, University Park, PA 16802, and [6]Corresponding author, e-mail: ban6@cornell.edu

Subject Editor: Joseph Munyaneza

Received 28 April 2020; Editorial decision 18 May 2020

Abstract

Allium leafminer, *Phytomyza gymnostoma* Loew, is the newest invasive pest of allium crops in North America. Larvae initially feed in the upper canopy before mining toward the base of the plant to pupate. Crop loss occurs when larvae destroy vascular tissue, facilitating infection by bacterial and fungal pathogens that cause rot. Contamination also occurs when larvae and pupae are present at harvest. In response to this invasion, efficacy of 14 insecticide active ingredients applied via foliar sprays, transplant treatments, and drip chemigation was evaluated for managing *P. gymnostoma*. Multiple field studies were conducted in onions, leeks, and scallions in Pennsylvania and New York, United States in 2018 and 2019. The highest and most consistent levels of *P. gymnostoma* control occurred using foliar applications of dinotefuran, cyantraniliprole and spinetoram (84–89% reduction in damage; 95% reduction in *P. gymnostoma* densities). Despite the success of dinotefuran and cyantraniliprole applied as foliar sprays, neither was effective in controlling *P. gymnostoma* when administered via drip chemigation. Other foliar-applied insecticides that significantly reduced densities of *P. gymnostoma* in one or two experiments included abamectin, acetamiprid, cyromazine, imidacloprid, lambda-cyhalothrin, methomyl, and spinosad. Active ingredients that never controlled *P. gymnostoma* included azadirachtin, kaolin clay, pyrethrin, and spirotetramat. Spinosad applied to bare-root and plug-tray transplants immediately before transplanting reduced *P. gymnostoma* damage in the field by >90%. Implications of using these insecticides and application strategies are discussed within the context of developing a sustainable IPM program.

Key words: *Phytomyza gymnostoma*, *Allium cepa*, *Allium porrum*, *Allium fistulosum*, invasive species

Allium leafminer, *Phytomyza gymnostoma* Loew, is an invasive pest in North America that was first detected in 2015 (Barringer et al. 2018). Originally from Europe, *P. gymnostoma* was first discovered in Pennsylvania, United States and has subsequently spread to Connecticut, Maryland, Massachusetts, New Jersey, and New York, United States (Iglesias and Nault 2020a). *Phytomyza gymnostoma* is a specialist that only infests wild and cultivated plants in the genus *Allium* (Barringer et al. 2018). In the northeastern United States, allium crops attacked by *P. gymnostoma* include chive (*A. schoenoparasum*), garlic (*A. sativum*), leek (*A. porrum*), onion (*A. cepa*), ramps (*A. tricoccum*), and scallion (*A. fistulosum*) (BAN & SJF personal observations). In Europe and North America, entire plantings of allium crops have become infested with *P. gymnostoma* (Coman and Rosca 2011b, Durlin et al. 2015), resulting in total crop loss. Consequently, *P. gymnostoma* is considered a significant pest of allium crops in Europe (Ðuric´ and Hrnčic´ 2014) and North America (Barringer et al. 2018).

Phytomyza gymnostoma has two generations per year in Europe and North America (Collins and Lole 2005, Coman and Rosca 2011b, Barringer et al. 2018). In the northeastern United States, the first generation is active in spring from March through June. First-generation adults emerge from overwintered pupae located within their former host or in nearby soil beginning in March through early May. Oviposition on crops occurs from March through May (~5 to 6 wk) and larvae complete several instars before pupating in June. After pupae spend a few months estivating, second-generation adults emerge in the fall during mid-September and October. Oviposition occurs during this period (~up to 8 wk) and larvae develop and complete pupation in November and December.

First-instar *P. gymnostoma* hatch from eggs laid inside leaf tissue, typically in the upper portion of the canopy. Larvae initially mine within leaf tissue, but eventually move downward towards the base of the plant where they pupate (Coman and Rosca 2011b). Feeding can cause extensive damage to plants, rendering the crop unmarketable. Moreover, feeding and mining destroy plant tissue and increases the vulnerability of the crop to infection by bacterial soft rot pathogens and fungal pathogens such as white rot, *Sclerotium cepivorum* (Coman and Rosca 2011a).

Pesticides can be extremely effective in managing invasive pests (McLaughlin and Dearden 2019). Insecticide use has been recommended as a strategy to manage *P. gymnostoma* in Europe (Agallou et al. 2004, Talotti et al. 2004). For example, in Italy, foliar applications of cyromazine, dimethoate, fenitrothion, imidacloprid, and spinosad effectively reduced densities of *P. gymnostoma* larvae and pupae per plant (Talotti et al. 2003, 2004). In Romania, foliar applications of abamectin, acetamiprid, cypermethrin + chlorpyrifos, imidacloprid + deltamethrin, novaluron, and spinosad provided high levels of *P. gymnostoma* protection in onion, garlic and leek (90–98% control) (Coman and Rosca 2011a). With the exception of spinosad, these insecticides are synthetic and cannot be used on organic farms, which tend to have the most damaging infestations (Zandigiacomo and Dalla Monta 2002, MacLeod 2007). In all studies, multiple foliar applications of insecticides were evaluated, but none were evaluated via drip chemigation or transplant treatment.

Drip chemigation can be highly effective for managing insect pests of vegetable crops (Ghidiu et al. 2012). Systemic insecticides belonging to the neonicotinoid and anthranilic diamide classes are especially efficacious for managing pests when delivered via drip chemigation. For example, imidacloprid and other neonicotinoids administered via drip chemigation have controlled aphids, cucumber beetles, and wireworms on various vegetable crops (Palumbo 1997, Kuhar and Speese 2002, Arrington et al. 2016). Diamide insecticides like chlorantraniliprole delivered via drip chemigation reduced damage by corn earworm, *Helicoverpa zea* Boddie, and American serpentine leafminer, *Liriomyza trifolii* (Burgess), in tomato, as well as *Liriomyza* spp. damage in romaine lettuce (Palumbo 2008, Schuster et al. 2009, Kuhar et al. 2010). Delivering neonicotinoid and anthranilic diamide insecticides via drip chemigation could be effective for managing *P. gymnostoma* in allium crops.

Treating vegetable seedlings propagated in greenhouses with insecticides before transplanting in the field is a commonly recommended practice for protecting crops against early-season pests (Reiners et al. 2020). For example, treating seedlings with imidacloprid prior to transplanting protected broccoli and cabbage from swede midge, *Contarinia nasturtii* (Hallett et al. 2009), tomatoes from whiteflies, *Bemisia* spp. (Stansly et al. 1998, Sun and Liu 2016) and melons from striped cucumber beetle, *Acalymma vittatum* (Fleischer et al. 1998). Treating cabbage seedlings grown in soil-filled trays with chlorantraniliprole prior to transplanting provided protection against cabbage looper, *Trichoplusia ni* (Hübner) (Cameron et al. 2015). Treating bean plants grown in soil-filled pots with spinosad reduced densities of pea leafminer larvae, *L. huidobrensis* Blanchard (Weintraub and Mujica 2006). Coating young onion plants in spinosad immediately before transplanting them in the field provided excellent protection against onion maggot, *Delia antiqua* Meigen (Iglesias and Nault 2020b). Treating young allium crop plants before transplanting also could be an effective strategy for managing *P. gymnostoma*.

The purpose of this study was to identify insecticide active ingredients and delivery systems for effectively managing infestations of *P. gymnostoma* on various allium crops in the northeastern United States. A total of 14 active ingredients were evaluated; ten conventional products and four Organic Materials Review Institute (OMRI)-listed products, which are permitted for use in organic production. Products were selected based on either their previous success in managing *P. gymnostoma* in Europe or because they are known to manage other agromyzid leafminers in allium crops. Dinotefuran and cyantraniliprole were evaluated as drip-chemigation treatments, whereas spinosad was evaluated as a transplant treatment. We hypothesized that all products evaluated, regardless of their mode of delivery, would provide control of *P. gymnostoma*. Our results also are anticipated for use in updating pesticide labels. *Phytomyza gymnostoma* could be added to the list of pests for bulb vegetable crops group (Crop group 3) that are controlled by effective products, and delivery of the product could be expanded to include drip chemigation, transplant treatment, or both.

Materials and Methods

Field experiments were conducted in Pennsylvania, United States and in New York, United States in 2018 and 2019. In Pennsylvania, the experiment was performed at the Southeast Agricultural Research and Extension Center (SEAREC), Landisville, PA (40°07′07.5″N 76°25′38.5″W). In New York, experiments were conducted on a commercial farm near Red Hook, NY (42°01′20.2″N 73°52′41.9″W). Insecticide active ingredients, product names, manufacturers, and rates evaluated in all experiments are shown in Table 1.

Experimental Designs and Insecticide Application Delivery Systems

Foliar Applications and Drip-Irrigation Treatments in Leek Experiment (A)

Leek seeds (cv. Tadorna) were planted in a greenhouse and maintained at SEAREC before being transplanted on 5 July. Each plot consisted of a single 7.6 m long row and plots were laterally separated from each other by 1.2 m and vertically separated within rows by 0.4 m. Planting density was one plant per 0.3 m. The experiment included eight treatments (six foliar-applied and two drip-chemigation administered) and an untreated control (Table 1). Treatments were arranged in a randomized complete block design and each treatment was replicated four times. Foliar-applied treatments were made on 26 September, 2 and 26 October, and 4 November, spanning the period flies were active and oviposition marks on leaves were evident. To improve coverage, conventional products were co-applied with phosphatidylcholine, methylacetic acid and alkyl polyoxyethylene ether (LI-700; Loveland Products Inc., Greeley, CO) at a rate of 0.25% v:v; OMRI-Listed products were co-applied with K salts of fatty acids (M-Pede; Gowan Company, Yuma, AZ) at a rate of 1.5% v:v. Drip-chemigation treatments were applied on 24 September and 4 and 24 October. More details about insecticide applications are described in the *Insecticide application methodologies* section. Weeds and foliar diseases were managed following typical herbicide and fungicide programs used in Pennsylvania (MACVPG 2020).

Foliar Applications and Transplant Treatment in Onion Experiment (B)

Onion seeds (cv. Highlander) were planted at Sunbelt Transplants Inc., Buckeye, AZ. After a few months, plants were removed and transported to New York as 'bare-root' plants. On 13 April 2018,

Table 1. Insecticides evaluated for managing *Phytomyza gymnostoma* in various allium crops in Pennsylvania and New York, United States in 2018 and 2019

Active ingredient[a]	Product name	Rate (a.i. kg/ha)	Company	Experiment[b]
Abamectin	Agri-Mek SC	0.02	Syngenta	B, C, D
Acetamiprid	Assail 30SG	0.17	United Phosphorus Inc.	B, C, D
Azadirachtin*	Aza-Direct	0.03	Gowan	A, B, C, D
Azadirachtin + pyrethrin*	Azera	0.04 + 0.05	Valent USA	A
Cyantraniliprole	Exirel	0.1	FMC	A, B, C, D
	Verimark	0.15	FMC	A
Cyromazine	Trigard	0.14	Syngenta	B, C, D
Dinotefuran	Scorpion 35SL	0.2	Gowan	A, B, C, D
	Scorpion 35SL	0.3	Gowan	A
Imidacloprid	Admire Pro	0.05	Bayer CropScience	B, C, D
Kaolin clay*	Surround WP	53.2	NovaSource	B
Lambda-cyhalothrin	Warrior II w/zeon technology	0.03	Syngenta	B, C, D
Methomyl	Lannate LV	1.01	DuPont Crop Protection	B, D
Pyrethrin*	PyGanic Specialty	0.06	Valent USA	A, B, C, D
Spinetoram	Radiant SC	0.07	Corteva Agriscience	A, B, C, D
Spinosad*	Entrust SC	0.12	Corteva Agriscience	B, C, D, E
Spirotetramat	Movento	0.09	Bayer CropScience	B

[a] Products followed by an (*) are listed by the Organic Materials Review Institute.

[b] Crop, season, year and location product was evaluated: (A) leek, *Allium porrum*, in fall 2018 in Pennsylvania, (B) bulb onion, *A. cepa*, in spring 2018 in New York, (C) leek, *A. porrum*, in fall 2018 in New York, (D) scallion, *A. fistulosum*, in fall 2018 in New York, and (E) scallion, *A. fistulosum*, in fall 2019 in New York.

these plants were transplanted in two-row plots, which were 3 m long and separated from each other by 0.5 m. Plot beds were spaced 1.5 m apart and separated within rows by 0.9 m of bare ground. Planting density was one plant per 0.3 m. There were 14 foliar-applied treatments plus an untreated control (Table 1); one row in each plot received spinosad (Entrust SC) as a transplant treatment and the other row did not receive a transplant treatment (n = 30 treatments total). The experiment was a split-plot with foliar-applied insecticide as the main-plot factor and transplant treatment with spinosad as the subplot factor arranged in a randomized complete block design and treatments replicated four times.

Foliar applications were made on 7, 14, 21, and 29 May. As mentioned earlier, this period spanned the time flies were active and oviposition marks on leaves were observed. To improve spray coverage, LI-700 at a rate of 0.25% v:v was co-applied with synthetic products; terpene polymers, mineral oil, alkyl amine ethoxylated or Pinolene (Nu Film P; Miller Chemical & Fertilizer, LLC, Hanover, PA) at a rate of 0.6 liter/ha was co-applied with OMRI-Listed products. The spinosad transplant treatment was made immediately before transplanting on 13 April. Additional details about how spinosad was administered is described in the *Insecticide application methodologies* section. Weeds and foliar diseases were managed following typical pesticide programs for New York (Reiners et al. 2020).

Foliar Applications in Leek Experiments (C)

In 2018, leek seeds (cv. Lancelot) were planted at Dixondale Farms, Carrizo Springs, TX. After a few months, bare-root plants were removed and transported to New York. On 14 June, plants were transplanted in two-row plots using the same plot size and arrangement as described in the 2018 bulb onion experiment (B). Planting density was one plant per 0.3 m. There were 11 foliar-applied treatments plus an untreated control (Table 1). Treatments were arranged in a randomized complete block design and each treatment was replicated four times. Foliar applications were made on 19 and 27 September and 4, 10, 18, and 25 October based on the same rationale described earlier. The same surfactants and rates used in the 2018 bulb onion experiment (B) were co-applied with insecticides in this experiment. Weed and disease management practices were followed for New York (Reiners et al. 2020).

In 2019, leek seeds (cv. Tadorna) were planted in an environmentally controlled greenhouse and maintained at SEAREC before being transplanted on 6 July. The same plot size, planting density, and arrangement were used as described in the 2018 foliar sprays and drip-irrigation treatment in leek experiment (A). However, the experiment only included spinosad (Entrust SC) at a rate of 0.4 liter/ha + M-Pede at a rate of 1% v:v and an untreated control. Treatments were arranged in a randomized complete block design and each treatment was replicated four times. Foliar applications were made on 25 September and 4, 11, and 21 October. More details about insecticide applications are described in the *Insecticide application methodologies* section. Weeds and foliar diseases were managed as described earlier for Pennsylvania (MACVPG 2020).

Foliar Applications in Scallion Experiment (D)

Scallion seeds (cv. Nabechan F1) were planted in 128-cell plug trays (Griffin Greenhouse Supplies, Inc., Auburn, NY) in an environmentally controlled greenhouse and maintained for 2 mo at MX Morningstar Farm, Hudson, NY. On 29 August 2018, plants were transplanted in two-row plots following the same plot size and arrangement, as described in the 2018 leek experiment (C). Planting density was six to nine plants per 0.3 m. There were 12 foliar-applied treatments plus an untreated control (Table 1). Treatments were arranged in a randomized complete block design and each treatment was replicated four times. Insecticides were co-applied with the same surfactants on the same dates as those described for the 2018 leek experiment (C). Weeds and foliar diseases were managed as described earlier for New York (Reiners et al. 2020).

Foliar Applications With Different Adjuvants in Scallion Experiment (E)

Scallions (cv. Nabechan F1) were obtained from MX Morningstar Farm, as described previously. Plants were transplanted on 29 August 2018 and 1 August 2019 in New York. Plots had the same dimensions, planting density and arrangement, as described in the

2018 scallion experiment (D). There were two foliar-applied treatments of spinosad (Entrust SC), one co-applied with Nu Film P and the other with M-Pede, plus an untreated control. Rates of spinosad, Nu Film P, and M-Pede were 0.6 liter/ha, 0.6 liter/ha, and 1.5% v:v, respectively. Treatments were arranged in a randomized complete block design and each treatment was replicated four times. In 2018, treatments were applied on the same dates as those described for the 2018 scallion experiment (D), while in 2019, treatments were applied on 18 and 24 September and 2, 8, 15, and 23 October. Weeds and foliar diseases were managed as described earlier for New York (Reiners et al. 2020).

Transplant Treatments in Scallion Experiment (F)

Scallions (cv. Nabechan F1) were obtained as described in the previous scallion experiments (D and E). Plants were transplanted on 29 August 2018 and 1 August 2019 in New York. In both trials, plots had two rows with the same dimensions, planting density and arrangement, as described in the 2018 and 2019 scallion experiments (D and E). In 2018, there was one transplant treatment type ('plug-tray drench') and an untreated control; in 2019, there were two transplant treatment types ('plug-tray drench' and 'bare-root dip') and an untreated control. To obtain bare-root transplants grown in plug trays, all soil attached to roots was removed. Spinosad (Entrust SC) was used in all experiments. In both years, treatments were arranged in a randomized complete block design and each treatment was replicated four times. Details about how spinosad was administered are described in the *Insecticide application methodologies* section. Weeds and foliar diseases were managed as described earlier for New York (Reiners et al. 2020).

Insecticide Application Methodologies

In Pennsylvania, foliar applications were made using a CO_2-pressurized, backpack sprayer (R & D Sprayers, Opelousas, LA) that delivered 140 liters/ha at 103 kPa through a single cone-tip nozzle (TeeJet TXA80015VK, Spraying Systems, Wheaton, IL) directed over the top of the row. Drip-chemigation applications were made by injecting the insecticide into the irrigation line using a custom-designed, multi-treatment injector. The system was only run long enough to make applications and flush the lines as soil moisture was adequate in the fall of 2018.

In New York, foliar applications were made using a CO_2-pressurized, backpack sprayer (R & D Sprayers) that delivered 421 liters/ha at 276 kPa using a boom equipped with four twin-flat fan nozzles (TeeJet-60 8003VS) that covered a 1.5 m swath of ground. Both plot rows were sprayed with one pass. Transplant treatments were administered differently to bare-root plants and plug-tray plants. However, in both cases, the rate of spinosad (Entrust SC) used was 7.09 g AI per 10,000 plants. Bare-root plants were partially submerged by hand in a solution containing Entrust SC and water for 30 sec, removed and allowed to dry, and then transplanted in the field. The amount of solution needed to treat 10,000 bare-root onion plants was 4.8 liters. Transplants grown in plug trays, which had holes in the bottom, were placed in similar-sized plastic trays that contained the Entrust SC and water solution. Plants were treated 24 h before transplanting in the field to allow sufficient time for the solution in the bottom tray to wick upwards into the soil and roots. A total of 4.6 liters of the solution was needed to treat 10,000 plug-tray plants.

Damage Assessments

Plants were destructively sampled at harvest to assess damage and record densities of *P. gymnostoma* larvae and pupae. A plant was considered damaged if it contained either a larva, pupa or both in the marketable portion of the crop. For leek and scallion, this included the below-ground portion of the plant and the above-ground portion up to the leaf axil. For onion, this included the bulb. Severity of damage was not measured in this study.

In Pennsylvania, on 4 December 2018 (Experiment A) and 11 November 2019 (Experiment C), 10 leek plants per plot were harvested and later assessed for damage and insect densities in the laboratory. In New York on 18 June 2018 (Experiment B), 20 onion plants were uniformly sampled throughout each plot and damage and insect densities were later assessed in the laboratory. Also, in New York on 7 November 2018 (Experiment C), 10 leek plants were harvested and assessed for damage and insect densities as described above. In New York, on 26 November 2018 (Experiment D and F) and 11 November 2019 (Experiment E and F), 50 and 30 scallion plants per plot, respectively, were uniformly harvested and inspected for damage and insects in the laboratory. Voucher specimens are housed in the Department of Entomology, Cornell University, Cornell AgriTech, Geneva, NY and in the Department of Entomology, Pennsylvania State University, University Park, PA.

Statistical Analyses

Percentages of damaged plants and densities of *P. gymnostoma* per plant were the response variables in all studies. In four studies that had the largest sample size, simple linear regression analysis was used to determine whether percent damaged plants and densities of *P. gymnostoma* per plant were positively correlated (PROC REG, SAS Institute 2016). Samples that had no *P. gymnostoma* were omitted from the analysis.

With the exception of the onion experiment (B), all data were analyzed using regression analysis for mixed models (PROC MIXED, SAS Institute 2016) in which insecticide treatment was a fixed main effect in the model and replication was a random factor. For the onion experiment (B), data also were analyzed using regression (PROC MIXED, SAS Institute 2016), but for a split-plot model that had foliar-applied insecticide as the main-plot factor, transplant treatment as a sub-plot factor (both fixed effects), and replication and replication × foliar-applied insecticide treatment as random factors.

Percentage data were transformed using a square root (x + 0.001) function to stabilize variance before analysis, whereas insect density data were transformed before analysis using a $\log_{10}(x + 1)$. Treatment means were compared using Tukey's Studentized Range (HSD) Test at $P < 0.05$ (SAS Institute 2016). Estimates of percent control relative to values in the untreated plots were made as (untreated control – treatment)/ untreated control × 100%.

Results

Damage by *P. gymnostoma* in untreated plots tended to be highest in leek (range: 55 to 100%), followed by scallion (range: 20 to 90%) and then onion (30%). Mean densities of *P. gymnostoma* per plant in untreated plots also tended to be highest in leek (range: 1.5–7.7) followed by scallion (range: 0.12–2.7) and bulb onion (0.43).

The percentage of damaged plants was positively correlated with densities of *P. gymnostoma* per plant. In leek in Pennsylvania in 2018 (Experiment A), the relationship was significant ($F = 104.2$; df = 1, 30; $P < 0.0001$; $y = 19.8 + 23.4x$; root mean square error (RMSE) = 11.0; $R^2 = 0.78$) (Fig. 1A). In bulb onion in New York in 2018 (Experiment B), the relationship was also significant ($F = 410.6$; df = 1, 56; $P < 0.0001$; $y = 3.8 + 56.4x$; RMSE = 5.4; $R^2 = 0.88$)

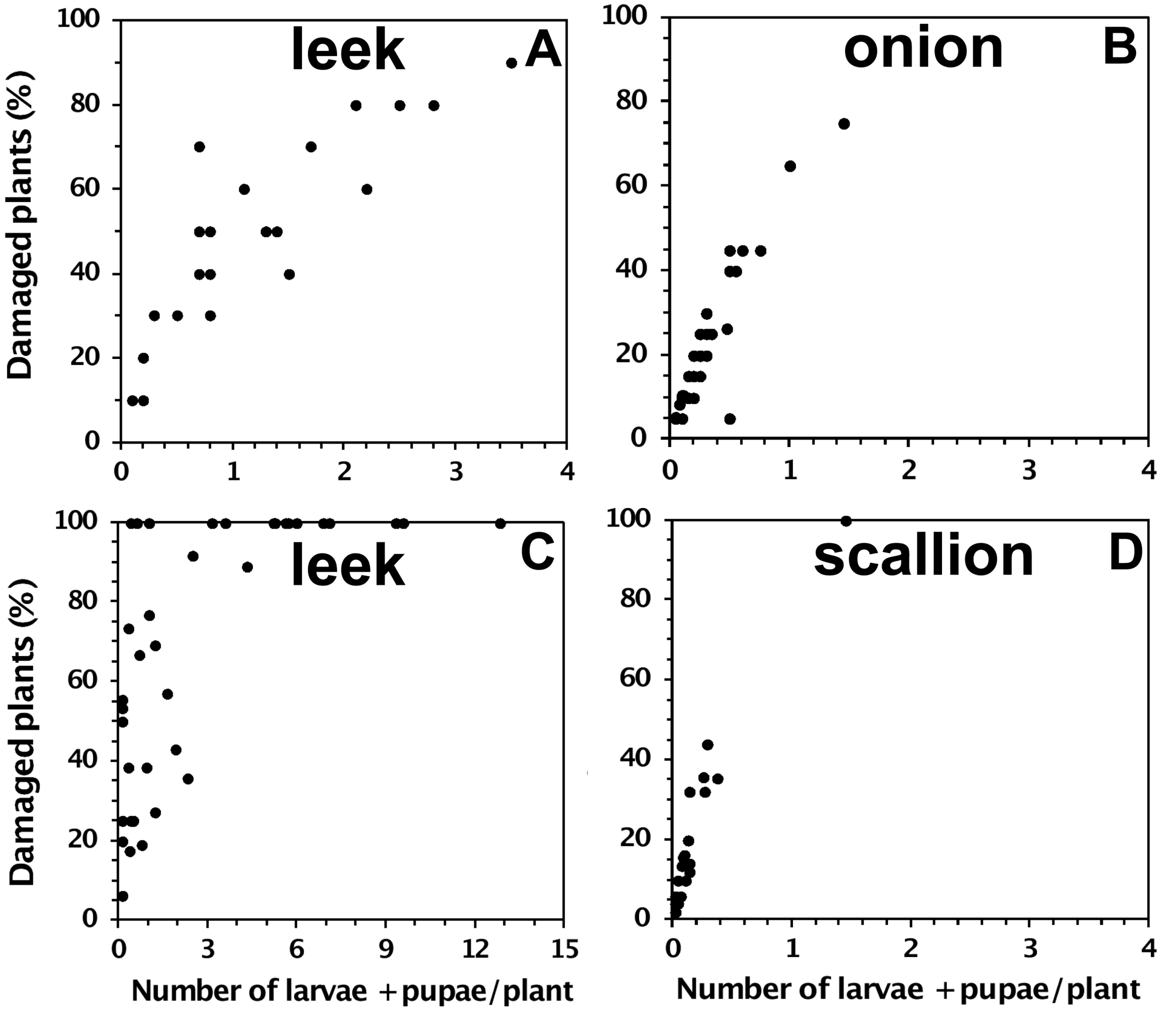

Fig. 1. Positive relationships between percentage of allium crop plants damaged by *Phytomyza gymnostoma* and densities of larvae + pupae per plant. Leek, *A. porrum*, in Pennsylvania in 2018 (Experiment A) (A); bulb onion, *A. cepa*, in New York in 2018 (Experiment B) (B); leek, *A. porrum*, in New York in 2018 (Experiment C) (C); and scallion, *A. fistulosum*, in New York in 2018 (Experiment D) (D).

(Fig. 1B). In leek in New York in 2018 (Experiment C), the relationship was positive ($F = 26.0$; df = 1, 36; $P < 0.0001$; $y = 49.7 + 6.6x$; RMSE = 25.1; $R^2 = 0.42$) (Fig. 1C). In scallions in New York in 2018 (Experiment D), the relationship was also positive, but not significant ($F = 3.8$; df = 1, 22; $P = 0.065$; $y = 17.0 + 58.3x$; RMSE = 41.9; $R^2 = 0.15$) (Fig. 1D).

Foliar Applications and Drip-Irrigation Treatment in Leek Experiment (A)

Percentages of leeks damaged by *P. gymnostoma* in plots treated with foliar applications of dinotefuran, spinetoram and cyantraniliprole were significantly lower than untreated controls ($F = 10.5$; df = 8, 24; $P < 0.0001$), and control was estimated to be 82% (Table 2). Similarly, densities of *P. gymnostoma* in plots treated with foliar applications of these three insecticides were significantly lower (87 to 93%) than those in the untreated control ($F = 21.0$; df = 8, 24; $P < 0.0001$) (Table 2). These three insecticides provided an equivalent level of *P. gymnostoma* control. In contrast, foliar applications of pyrethrin, azadirachtin, and azadirachtin + pyrethrin, as well as drip-chemigation treatments of cyantraniliprole and dinotefuran, failed to significantly reduce damage and densities of infested plants (Table 2).

Foliar Applications and Transplant Treatment in Onion Experiment (B)

Onions damaged by *P. gymnostoma* were affected by the foliar-applied insecticide treatment, the transplant treatment, and their interaction (interaction terms of $F = 2.6$; df = 14, 45; $P = 0.0084$ for percent damage, and $F = 4.6$; df = 14, 45; $P < 0.0001$ for insect densities). However, differences among subplot means, detailed in Supp. Table S1 (online only), generally followed the same patterns seen among main effects.

Among the foliar application main effects, damage in plots treated with spinetoram, methomyl, cyromazine, dinotefuran, and acetamiprid was significantly lower (86 to 93%) than damage in the untreated control ($F = 5.0$; df = 14, 42; $P < 0.0001$) (Table 3). Densities of *P. gymnostoma* in plots treated with these five insecticides plus cyantraniliprole also were significantly lower (88 to 96%) than those in the untreated control ($F = 5.4$; df = 14, 42; $P < 0.0001$) (Table 3). These six insecticides provided an equivalent level of *P. gymnostoma* control but did not provide significantly better control than levels provided by all other treatments, except pyrethrin (Table 3).

Percentages of onions damaged by *P. gymnostoma* that received the transplant treatment were significantly lower (88%) than the

Table 2. Mean (±SEM) percentage of leek plants, *Allium porrum,* damaged by *P. gymnostoma* as well as mean density (±SEM) of larvae + pupae per plant after four weekly foliar or three drip applications of various insecticides in fall 2018 in Pennsylvania

Active ingredient(s)[a]	Application method	Percentage of damaged plants[b,c]	Number of larvae + pupae per plant[b]
Untreated control	-	55 (7)a	1.5 (0.3)ab
Pyrethrin*	Foliar	83 (3)a	2.7 (0.3)a
Azadirachtin*	Foliar	50 (11)a	0.7 (0.2)bc
Azadirachtin + pyrethrin*	Foliar	43 (5)a	0.8 (0.2)b
Cyantraniliprole	Drip	40 (4)a	0.9 (0.2)b
Dinotefuran	Drip	35 (3)ab	0.7 (0.1)bc
Dinotefuran	Foliar	10 (4)bc	0.2 (0.1)cd
Spinetoram	Foliar	10 (4)bc	0.1 (0.04)cd
Cyantraniliprole	Foliar	10 (7)c	0.1 (0.1)d

[a] Active ingredients followed by an (*) are listed by the Organic Materials Review Institute.

[b] Means followed by the same letter within a column are not significantly different (Tukey HSD; $P > 0.05$; $n = 4$). Damage data and count data were transformed using a sqrt ($x + 0.001$) function and a log ($x + 1$) function before analysis, respectively; untransformed means are presented.

[c] A plant was considered damaged if it had ≥ 1 larva and/or ≥ 1 pupa.

Table 3. Mean (±SEM) percentage of bulb onion plants, *Allium cepa*, damaged by *Phytomyza gymnostoma* as well as those infested with larva + pupae after four weekly foliar applications of insecticides in spring 2018 in New York

Active ingredient[a]	Percentage of damaged plants[b,c]	Number of larva + pupae per plant[b]
Untreated control	18.8 (6.3)ab	0.26 (0.09)ab
Pyrethrin*	25.0 (10.5)a	0.41 (0.19)a
Azadirachtin*	13.3 (5.4)abc	0.20 (0.07)abc
Spirotetramat	12.3 (5.4)abc	0.15 (0.07)abc
Kaolin clay*	10.6 (5.5)abc	0.13 (0.07)bc
Spinosad*	8.8 (3.9)abc	0.09 (0.04)bc
Abamectin	4.4 (1.1)abc	0.04 (0.01)bc
Imidacloprid	4.4 (2.4)bc	0.06 (0.03)bc
Cyantraniliprole	3.2 (1.4)bc	0.03 (0.01)c
Lambda-cyhalothrin	3.8 (1.8)bc	0.04 (0.02)bc
Spinetoram	2.6 (1.4)c	0.03 (0.01)c
Methomyl	2.5 (2.5)c	0.03 (0.03)c
Cyromazine	2.5 (1.3)c	0.03 (0.02)c
Dinotefuran	1.9 (1.3)c	0.02 (0.01)c
Acetamiprid	1.3 (0.8)c	0.01 (0.01)c

Means are pooled across treatments that received either a transplant treatment of spinosad (Entrust SC) before transplanting or no transplant treatment.

[a] Active ingredients followed by an (*) are listed by the Organic Materials Review Institute.

[b] Means followed by the same letter within a column are not significantly different (Tukey HSD; $P > 0.05$; $n = 8$). Damage data and count data were transformed using a sqrt ($x + 0.001$) function and a log ($x + 1$) function before analysis, respectively; untransformed means are presented.

[c] A plant was considered damaged if it had ≥ 1 larva and/or ≥ 1 pupa.

percentages of those that did not (mean [±SEM] for transplant treatment: 1.6 ± 0.5; mean [±SEM] for those without transplant treatment: 13.8 ± 2.1) ($F = 90.6$; df = 1, 45; $P < 0.0001$). Similarly, densities of *P. gymnostoma* in plots that received the transplant treatment were significantly lower, 90%, than densities in those that did not (mean [±SEM] for transplant treatment: 0.02 ± 0.01; mean [±SEM] for those without transplant treatment: 0.18 ± 0.03) ($F = 64.2$; df = 1, 45; $P < 0.0001$).

Foliar Applications in Leek Experiments (C)

In 2018, percentages of leeks damaged by *P. gymnostoma* in plots treated with cyantraniliprole and dinotefuran were significantly lower (73 to 85%) than those damaged in the untreated control ($F = 5.8$; df = 11, 33; $P < 0.0001$) (Table 4). Both products provided a similar level of reduction in damage. Densities of *P. gymnostoma* in plots treated with all insecticides, except pyrethrin and azadirachtin, were significantly lower (64 to 99%) than those in the untreated control ($F = 15.1$; df = 11, 33; $P < 0.0001$) (Table 4). Densities of *P. gymnostoma* among all effective insecticide treatments were statistically similar. The fewest numbers of *P. gymnostoma* were detected in plots treated with spinetoram, spinosad, acetamiprid, lambda-cyhalothrin, cyantraniliprole, and dinotefuran (Table 4).

In 2019, the percentage of leeks damaged by *P. gymnostoma* in plots treated with spinosad was significantly lower (48%) than those damaged in the untreated control (mean [±SEM] for spinosad: 52.3 ± 10.3; mean [±SEM] for untreated control: 100 ± 0) ($F = 16.3$; df = 1, 3; $P = 0.0274$). Similarly, densities of *P. gymnostoma* in plots treated with spinosad were significantly lower (93%) than densities in the untreated control (mean [±SEM] for spinosad: 1.2 ± 0.3; mean [±SEM] for untreated control: 16.6 ± 1.9) ($F = 386.8$; df = 1, 3; $P = 0.0003$).

Foliar Sprays in Scallion Experiment (D)

Percentages of scallions damaged by *P. gymnostoma* in plots treated with spinetoram, cyantraniliprole, dinotefuran and lambda-cyhalothrin were significantly lower (98 to 100%) than those damaged in the untreated control ($F = 7.6$; df = 12, 36; $P < 0.0001$) (Table 5). All four products provided a similar level of control, but did not provide significantly better control than that provided by all other treatments, except azadirachtin and pyrethrin. Densities of *P. gymnostoma* in plots treated with and without insecticides were similar (Table 5). However, densities of *P. gymnostoma* in azadirachtin plots were significantly higher than those in all other treatments, except pyrethrin and cyromazine ($F = 3.0$; df = 12, 36; $P = 0.0058$) (Table 5).

Foliar Applications With Different Adjuvants in Scallion Experiment (E)

In 2018, percentages of scallions damaged by *P. gymnostoma* that were treated with spinosad were significantly lower (88 to 92%) than those damaged in the untreated control ($F = 8.1$; df = 2, 6; $P = 0.0198$) (Fig. 2A). However, percent damage in the spinosad + Nu Film P treatment was not significantly different from damage in the spinosad + M-Pede treatment (Fig. 2A). Densities of *P. gymnostoma* in plots treated with spinosad + M-Pede were significantly lower than those in the untreated control, but not from those in the spinosad + Nu Film P treatment ($F = 5.7$; df = 2, 6; $P = 0.0416$) (Fig. 2C). Densities of *P. gymnostoma* in the spinosad + Nu Film P treatment were similar to those in the untreated control.

In 2019, percentages of scallions damaged by *P. gymnostoma* that were treated with spinosad were significantly lower (39 to 75%) than those damaged in the untreated control ($F = 41.8$; df = 2, 6; $P = 0.0003$) (Fig. 2B). Percent damage in the spinosad + M-Pede treatment was significantly lower than damage in the spinosad + Nu Film P treatment (Fig. 2B). Similarly, densities of *P. gymnostoma* in plots treated with spinosad were significantly lower than those in the

Table 4. Mean (±SEM) percentage of leek plants, *Allium porrum*, damaged by *Phytomyza gymnostoma* as well as mean density (±SEM) of larvae + pupae per plant after six weekly foliar applications of various insecticides in fall 2018 in New York

Active ingredient[a]	Percentage of damaged plants[b,c]	Number of larva + pupae per plant[b]
Untreated control	100 (0)a	7.7 (1.8)a
Pyrethrin*	100 (0)a	6.4 (1.3)a
Azadirachtin*	97 (3)a	4.8 (0.7)ab
Imidacloprid	67 (14)a	1.5 (0.3)bc
Spinetoram	55 (20)ab	0.2 (0.1)c
Spinosad*	50 (9)ab	0.4 (0.1)c
Abamectin	52 (17)ab	2.8 (2.2)bc
Cyromazine	47 (16)ab	1.4 (0.5)bc
Acetamiprid	45 (14)ab	0.7 (0.2)c
Lambda-cyhalothrin	43 (21)ab	0.2 (0.1)c
Cyantraniliprole	27 (24)b	0.1 (0.1)c
Dinotefuran	15 (7)b	0.03 (0.03)c

[a] Active ingredients followed by a (*) are listed by the Organic Materials Review Institute

[b] Means followed by the same letter within a column are not significantly different (Tukey HSD; $P > 0.05$; $n = 4$). Damage data and count data were transformed using a sqrt ($x + 0.001$) function and a log ($x + 1$) function before analysis, respectively; untransformed means are presented.

[c] A plant was considered damaged if it had ≥ 1 larva and/or ≥ 1 pupa.

Table 5. Mean (±SEM) percentage of scallion plants, *Allium fistulosum*, damaged by *Phytomyza gymnostoma* as well as mean density (±SEM) of larvae + pupae per plant after six weekly foliar applications of various insecticides in fall 2018 in New York

Active ingredient[a]	Percentage of damaged plants (%)[b,c]	Number of larvae + pupae per plant[b]
Untreated control	20.3 (5.2)abc	0.12 (0.04)ab
Azadirachtin*	37.8 (21.8)ab	0.49 (0.33)a
Pyrethrin*	32.0 (4.9)a	0.20 (0.04)ab
Cyromazine	7.0 (3.1)a–d	0.06 (0.03)ab
Imidacloprid	6.7 (4.8)bcd	0.02 (0.01)b
Abamectin	3.5 (2.2)cd	0.04 (0.02)b
Methomyl	3.5 (2.9)cd	0 (0)b
Acetamiprid	3.0 (1.3)cd	0.02 (0.01)b
Spinosad*	2.5 (1.5)cd	0.03 (0.02)b
Spinetoram	0.5 (0.5)d	0 (0)b
Cyantraniliprole	0.5 (0.5)d	0 (0)b
Dinotefuran	0.5 (0.5)d	0 (0)b
Lambda-cyhalothrin	0 (0)d	0 (0)b

[a] Active ingredients followed by an (*) are listed by the Organic Materials Review Institute.

[b] Means followed by the same letter within a column are not significantly different (Tukey HSD; $P > 0.05$; $n = 4$). Damage data and count data were transformed using a sqrt ($x + 0.001$) function and a log ($x + 1$) function before analysis, respectively; untransformed means are presented.

[c] A plant was considered damaged if it had ≥ 1 larva and/or ≥ 1 pupa.

untreated control, with densities in the spinosad + M-Pede treatment significantly lower than those in the spinosad + Nu Film P treatment ($F = 47.4$; df = 2, 6; $P = 0.0002$) (Fig. 2D).

Transplant Treatments in Scallion Experiment (F)

In 2018, the percentage of scallions damaged by *P. gymnostoma* in plots that received a transplant treatment was nearly half the level of damage in untreated plots, but this difference was not statistically significant ($P > 0.05$) (Table 6). Densities of *P. gymnostoma* were similar between treated and untreated plots (Table 6).

In 2019, percentages of scallions damaged by *P. gymnostoma* in plots that received transplant treatments were significantly lower (91 to 92%) than those in the untreated control ($F = 24$; df = 2, 6; $P = 0.0014$) (Table 6). Damage levels in plots established with the bare-root transplant treatment and the plug-tray transplant treatment were nearly identical. Densities of *P. gymnostoma* in transplant-treated plots also were similar and significantly lower (92 to 95%) than those in untreated plots ($F = 78.8$; df = 2, 6; $P < 0.0001$) (Table 6).

Discussion

Insecticide use is one of the most important tactics for managing newly introduced invasive pests. Active ingredients and application techniques were successfully identified for effectively managing the newest invasive pest of allium crops in North America, *P. gymnostoma*. This is the first study documenting success of managing *P. gymnostoma* with dinotefuran, cyantraniliprole, and spinetoram, which were the top-performing products applied via foliar sprays. Among the OMRI-Listed products, spinosad was the most effective, especially when co-applied with M-Pede. This is also the first study documenting the efficacy of spinosad applied as a transplant treatment for effectively managing *P. gymnostoma*. Neither dinotefuran nor cyantraniliprole applied via drip chemigation were effective for controlling *P. gymnostoma* in a leek production system.

Foliar sprays of dinotefuran, a neonicotinoid insecticide, reduced *P. gymnostoma* damage in four of four studies and its densities in three of four studies; percent reduction in damage relative to the untreated control was 89% and percent reduction in densities of *P. gymnostoma* relative to the untreated control was 95%. Foliar applications of spinetoram, a spinosyn insecticide, reduced damage in three of four studies and *P. gymnostoma* densities in three of four studies; percent reduction in damage relative to the untreated control was 89% and percent reduction in densities of *P. gymnostoma* relative to the untreated control was 95%. Foliar sprays of cyantraniliprole, an anthranilic diamide insecticide, also reduced damage in three of four studies and *P. gymnostoma* densities in three of four studies; percent reduction in damage relative to the untreated control was 84% and percent reduction in densities of *P. gymnostoma* relative to the untreated control was 95%. All three insecticides are labeled for use on bulb vegetable crops and include (dipteran) leafminers among the pests that can be controlled (dinotefuran: Crop Subgroups 3-07A and 3-07B; cyantraniliprole: Crop group 3-07; spinetoram: Crop Subgroups 3-07A and 3-07B). Currently, only the cyantraniliprole 2(ee) label specifies *P. gymnostoma*, while the others simply list leafminers. These products will provide conventional allium crop growers with excellent options for managing infestations of *P. gymnostoma*.

Other foliar-applied products that significantly reduced *P. gymnostoma* densities in one or two experiments included abamectin, acetamiprid, cyromazine, imidacloprid, lambda-cyhalothrin, methomyl, and spinosad. With the exception of lambda-cyhalothin and methomyl, which were not evaluated, these five insecticides were successful in managing *P. gymnostoma* in allium crops in Italy and Romania (Talotti et al. 2003, 2004; Coman and Rosca 2011a).

Spinosad is the only OMRI-Listed product among those evaluated that showed efficacy against *P. gymnostoma* when applied as a foliar

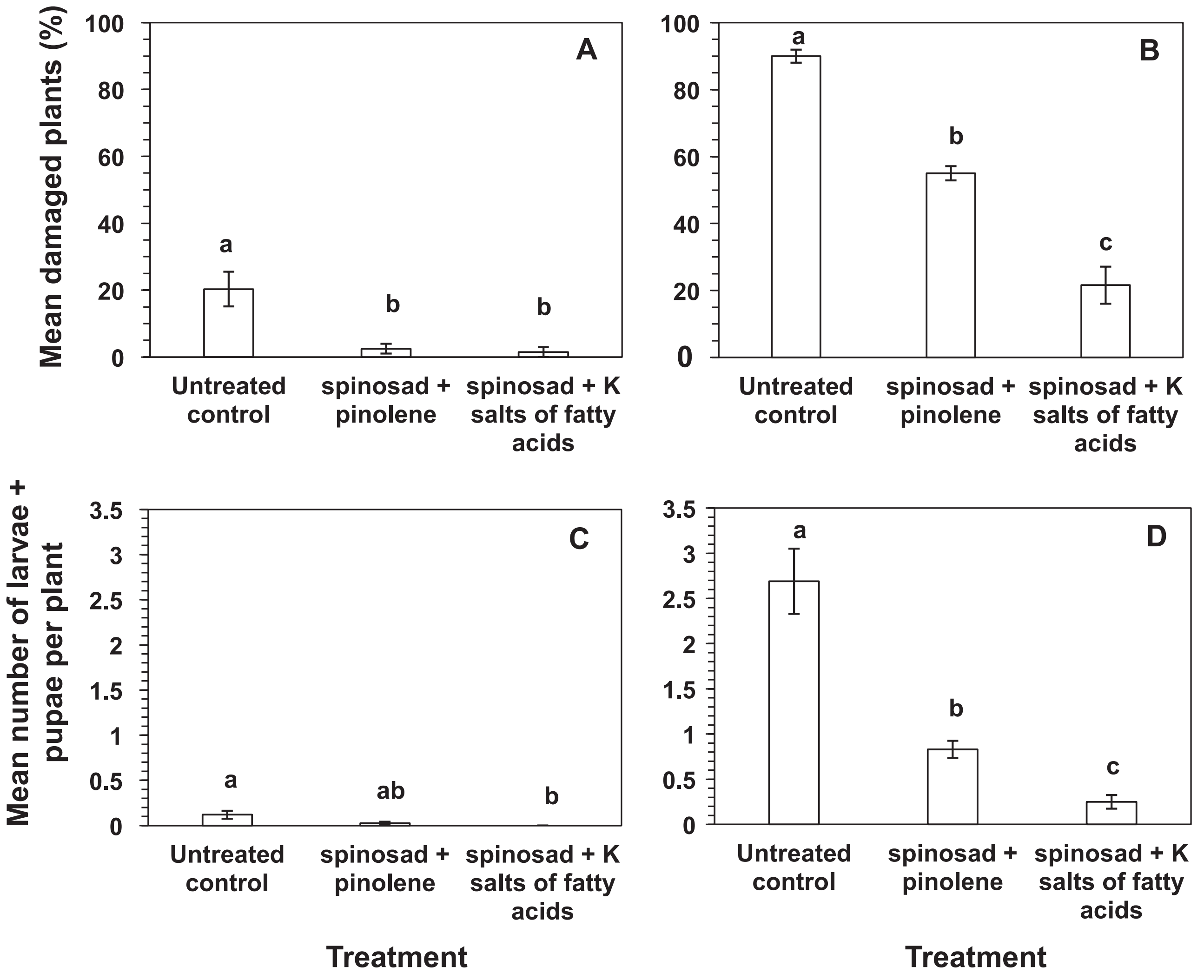

Fig. 2. Mean (±SEM) percentage of scallion plants, *Allium fistulosum*, damaged by *Phytomyza gymnostoma* in 2018 (A) and 2019 (B) as well as mean (±SEM) number infested (larva + pupae) in 2018 (C) and 2019 (D) in Red Hook, NY. Plants were co-applied with weekly foliar applications of either spinosad (Entrust SC) + Pinolene (Nu Film P) or spinosad + K salts of fatty acids (M-Pede) or not treated in New York in fall 2019. Means followed by different letters indicate means are significantly different from each other (Tukey HSD; $P < 0.05$; $n = 4$).

spray. Spinosad significantly reduced *P. gymnostoma* densities in leek by 93 and 95% relative to the untreated control in the Pennsylvania and New York experiments, respectively. In the New York experiments, spinosad also numerically reduced densities in onion by 56% and in scallion by up to 91%. The adjuvant co-applied with spinosad also influenced the level of *P. gymnostoma* control. In both years, spinosad co-applied with M-Pede was more effective reducing *P. gymnostoma* damage than co-applications with Nu Film P, but differences were only statistically significant in 1 of 2 yr. The rationale for obtaining better *P. gymnostoma* control using co-applications of spinosad and M-Pede rather than with Nu Film P is not known; however, similar results have been observed for managing onion thrips, *Thrips tabaci*, in onion (BAN, personal observation). While foliar applications of spinosad should be considered as an option for *P. gymnostoma* management on organic farms, more research is needed to identify other efficacious products that could be used to protect organically produced allium crops.

Active ingredients applied as foliar sprays that never reduced *P. gymnostoma* damage or their densities included azadirachtin, kaolin clay, pyrethrin, and spirotetramat. To our knowledge, none of these crop protectants have shown success in managing *P. gymnostoma* in Europe; it is also possible that these crop protectants were never evaluated until our study. Among these four protectants, only spirotetramat is systemic, even when applied to foliage (Nauen et al. 2008). Systemic activity provided by a foliar-applied product would be ideal for managing a pest like *P. gymnostoma* that mines within foliage and is not likely to come into contact with lethal residues on leaf surfaces. Unfortunately, spirotetramat has been ineffective against dipteran leafminers, as has been the case against *L. trifollii* on cucumber (Sabry et al. 2015).

The frequency of foliar applications in our experiments was based on activity of *P. gymnostoma* adults and oviposition marks on leaves. The spring generation was active for approximately 4 wk, while the fall generation was active for 5 to 6 wk. Numbers of foliar applications varied from four to six, typically made on a weekly basis. Application frequency was determined based on the frequency that has been used to manage other foliar-feeding insect pests of allium crops, like onion thrips, *Thrips tabaci* Lindeman. For many products evaluated in our studies, numbers of applications per crop per season are restricted to fewer than four to six and

Table 6. Mean (±SEM) percentage of scallion plants, *Allium fistulosum*, damaged by *Phytomyza gymnostoma* as well as mean density (±SEM) of larvae + pupae per plant when transplants were treated with spinosad (Entrust SC) immediately before transplanting or not treated in fall 2018 and 2019 in New York

Year	Active ingredient	Transplant treatment type (rate)	Percentage of damaged plants[a,b]	Number of larvae + pupae per plant[a]
2018	Untreated control	-	20.3 (5.2)a	0.12 (0.04)a
	Spinosad	Tray drench (7.09 g a.i. per 10,000 plants)	10.5 (7.4)a	0.11 (0.09)a
2019	Untreated control	-	64.2 (5.3)a	1.15 (0.16)a
	Spinosad	Tray drench (7.09 g a.i. per 10,000 plants)	5.8 (2.1)b	0.09 (0.03)b
	Spinosad	Root dip (7.09 g a.i. per 10,000 plants)	5.0 (3.2)b	0.06 (0.04)b

[a] Means followed by the same letter within a column in the same year are not significantly different (Tukey HSD; $P > 0.05$; $n = 4$). Damage data and count data were transformed using a sqrt ($x + 0.001$) function and a log ($x + 1$) function before analysis, respectively; untransformed means are presented.

[b] A plant was considered damaged if it had ≥ 1 larva and/or ≥ 1 pupa.

required rotating to a different product after two consecutive applications. For the purposes of our study, it was important to identify efficacious active ingredients, regardless of the limitations on application frequency stated on the labels; thus, we made applications throughout the time adults were actively infesting the crops. Future research will be needed to identify the optimal frequency of insecticide use to manage this pest, but also the use of multiple efficacious insecticides adhering to the restrictions described on their labels.

Despite the success of using foliar applications of dinotefuran and cyantraniliprole to control *P. gymnostoma*, neither was effective in reducing damage when administered through drip chemigation in leeks. Thus, delivery of these insecticides via chemigation was the issue, not the efficacy of these active ingredients against *P. gymnostoma*. While a number of factors can impact the ability of using drip chemigation successfully for insect control (Reddy 2016), the large size and maturity of the leeks at the time applications were administered may have been the most critical. When plants are large with deep, massive root systems, insecticides delivered to the soil surface may not be taken up and translocated readily to above-ground foliage. Moreover, systemic insecticides may not be efficiently translocated to leaf tissue in mature plants compared with young, actively growing plants. Thus, administering drip chemigation with dinotefuran and cyantraniliprole to younger allium plants may be successful for managing this pest and should be explored.

Spinosad applied to bare-root and plug-tray transplants immediately before transplanting in the field significantly reduced densities of *P. gymnostoma*. In two of two studies with bare-root transplants, spinosad reduced damage by 90% and densities of *P. gymnostoma* by 93%. In one of two studies with plug-tray transplants, spinosad significantly reduced damage by 91% and densities of *P. gymnostoma* by 92%. In the less successful experiment, damage was numerically reduced by 48%. Variability in successfully managing insect pests by treating plug-tray plants with systemic insecticides is not uncommon. Cameron et al. (2015) experienced variability in control of *T. ni* with chlorantraniliprole on cabbage seedlings using a tray soak method. Similar success and variability managing onion maggot, *D. antiqua*, using spinosad (Entrust SC) as a plug-tray drench for bulb onion also has been observed (BAN pers. observation). Currently, Entrust SC is registered for use on bulb vegetables (Crop group 3-07A and 3-07B) to manage insect pests, including dipteran leafminers. However, the use of Entrust SC is restricted to foliar applications only. Expansion of the Entrust SC label to include a transplant application treatment is needed for growers to be able to use this highly effective tactic.

Allium crop growers in the northeastern United States have established tolerance thresholds for densities of larvae and pupae in the marketable portion of the crop after harvest. For example, growers may remove by hand the outermost layers of leaves from leek and scallion plants, which also may remove *P. gymnostoma* larvae and pupae, leaving a blemish-free product. These tolerance thresholds are subject to change especially when infested produce is concomitantly diseased. Nevertheless, tolerance thresholds for *P. gymnostoma* densities in leek and scallion are approximately 4 and 2 per plant, respectively. Because *P. gymnostoma* larvae and pupae are rarely found in onion at harvest, a tolerance threshold has not been identified. In our study, leek plants had *P. gymnostoma* damage levels as high as 90 to 100%, but a majority of these plants could have been salvaged because densities of larvae and pupae were below the tolerance threshold of 4 per plant (Fig. 1A and B). Similarly, scallion plants had *P. gymnostoma* damage levels as high as 40 to 100%, but a majority of the crop could have been salvaged because densities of larvae and pupae were below the tolerance threshold of 2 per plant (Fig. 1D). These results indicate that success of *P. gymnostoma* control in allium crops like leek and scallion should focus on reducing densities of insects per plant rather than on the percentage of plants damaged.

Results from these studies identified three conventional insecticides (dinotefuran, cyantraniliprole and spinetoram) and one OMRI-Listed insecticide (spinosad) that can be applied to allium crop foliage for effectively managing infestations of the new invasive *P. gymnostoma*. Future research will be needed to identify how to optimize the use of these insecticides such that they are used in a manner consistent with their labels, are economically feasible, and consider insecticide resistance principles. We also showed that spinosad could be used as a transplant treatment to provide season-long protection of allium crops from *P. gymnostoma*; however, the use of spinosad in this manner is not currently labeled.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

Acknowledgments

We thank K. Migliorelli, who allowed us to conduct research on his farm in Dutchess County, NY. We also are grateful for those who helped with field trials and data collection, especially L. Briggs, M. Clark, K. Damann, D. Doeblin, E. Equinozzi, M. Kelly, A. Leach, N. Mengaziol, E. Moretti and K. Regan. This study was partially funded by grants from the Foundation for Food and Agriculture Research's Rapid Outcomes Agriculture Research Program, New York Farm Viability Institute and USDA NIFA Crop Protection Pest Management Program award 2018-70006-28920, Solutions for managing Allium leafminer: a new invasive threat to allium crops in North America.

References Cited

Agallou, E., R. Cannon, S. Cheek, D. Collins, and L. Matthews. 2004. Plant pest notice: Allium leaf miner - *Phytomyza gymnostoma* (No. 35). Department for Environment, Food and Rural Affairs, Central Science Laboratory, Sand Hutton, York, UK. 7 pp.

Arrington, A., G. Kennedy, and M. Abney. 2016. Applying insecticides through drip irrigation to reduce wireworm (Coleoptera: Elateridae) feeding damage in sweet potato. Pest Manag. Sci. 72: 1133–1140.

Barringer, L. E., S. J. Fleischer, D. Roberts, S.-E. Spichiger, and T. Elkner. 2018. The first North American record of the Allium leafminer. J. Integrated Pest Management 9: 8; 1–8.

Cameron, R. A., C. J. Williams, H. E. Portillo, P. C. Marçon, and L. A. Teixeira. 2015. Systemic application of chlorantraniliprole to cabbage transplants for control of foliar-feeding lepidopteran pests. Crop Prot. 67: 13–19.

Collins, D. W., and M. Lole. 2005. *Phytomyza gymnostoma* Loew (Diptera: Agromyzidae), a leaf mining pest of leek and onion new to Britain. Entomologist's Monthly Magazine 141: 131–137.

Coman, M., and I. Rosca. 2011a. Allium crops protection plant management for *Napomyza gymnostoma* Loew pest. Scientific Papers Series Management, Economic Engineering in Agriculture and Rural Development 11: 26–29.

Coman, M., and I. Rosca. 2011b. Biology and life cycle of leafminer *Napomyza* (*Phytomyza*) *gymnostoma* Loew, a new pest of allium plants in Romania. South–West. J. Hortic. Biol. Environ. 2: 57–64.

Duric´, Z., and S. Hrnčic´. 2014. *Napomyza gymnostoma* Loew. (Diptera, Agromyzidae) napodručju Banja Luke (Republika Srpska, Bosna i Hercegovina) [Abstract: *Napomyza gymnostoma* Loew. (Diptera, Agromyzidae) in Banja Luka region (Republic of Srpska, Bosnia and Herzegovina)]. Agroznanje - Agro-knowledge Journal 15: 383–392.

Durlin, L., S. Oste, F. Delassus, F. Couloumies, and J. Bruyere. 2015. Detection et protection alternative contre la mouche mineuse du poireau (*Phytoma gymnostoma* Loew) [Abstract: Detection and alternative protection against the Allium leaf miner (*Phytomyza gymnostoma*, Loew)]. *In* 5th Conférence Internationale sur les Méthodes Alternatives de Protection des Plantes, 11–13 mars, 2015, Nouceau Siècle, Lille, France, 783–792.

Fleischer, S. J., M. D. Orzolek, D. de Mackiewicz, and L. Otjen. 1998. Imidacloprid effects on *Acalymma vittata* (Coleoptera: Chrysomelidae) and bacterial wilt in cantaloupe. J. Econ. Entomol. 91: 940–949.

Ghidiu, J., T. Kuhar, J. Palumbo, and D. Schuster. 2012. Drip chemigation of insecticides as a pest management tool in vegetable production. J. Integ. Pest Mngmt. 3: 2012.

Hallett, R. H., M. Chen, M. K. Sears, and A. M. Shelton. 2009. Insecticide management strategies for control of swede midge (Diptera: Cecidomyiidae) on cole crops. J. Econ. Entomol. 102: 2241–2254.

Iglesias, L., and B. Nault. 2020a. Allium leafminer is no minor inconvenience: updates from the northeastern U.S. Onion World. 36: 7–9.

Iglesias, L., and B. Nault. 2020b. Onion maggot control using insecticide transplant treatments for onion, 2019. Arthropod. Manag. Tests doi:10.1093/amt/tsaa069.

Kuhar, T. P., and J. Speese. 2002. Evaluation of drip line injected and foliar insecticides for controlling cucumber beetle in melons, 2001. Arthropod. Manag. Tests. 27: E46.

Kuhar, T. P., J. F. Walgenbach, and H. B. Doughty. 2010. Control of *Helicoverpa zea* in tomatoes with chlorantraniliprole applied through drip chemigation. Plant Health Progress. 11: 21. doi: 10.1094/PHP-2009-0407-01-RS.

(MACVPG) Mid-Atlantic Commercial Vegetable Recommendations. 2020. https://extension.psu.edu/mid-atlantic-commercial-vegetable-production-recommendations-sections

MacLeod, A. 2007. CSL Pest risk analysis for *Phytomyza gymnostoma*. Central Science Laboratory, Sand Hutton, York, United Kingdom. 13 pp.

McLaughlin, G. M., and P. K. Dearden. 2019. Invasive insects: management methods explored. J. Insect Sci. 19: 17; 1–9.

Nauen, R., U. Reckmann, J. Thomzik, and W. Thielert. 2008. Biological profile of spirotetramat (Movento®) – a new two-way systemic (ambimobile) insecticide against sucking pest species. Bayer CropSci J. 61: 245–278.

Palumbo, J. C. 1997. Evaluation of aphid control in lettuce with Admire applied through drip irrigation. Arthropod. Manag. Tests. 22: 61E.

Palumbo, J. C. 2008. Systemic efficacy of Coragen applied through drip irrigation on romaine lettuce, fall 2007. Arthropod. Manag. Tests. 33: E24.

Reddy, P. P. 2016. Drip chemigation for insect pest management, pp. 109–119. In Sustainable crop protection under protected cultivation. Springer, Singapore.

Reiners, S., P. D. Curtis, M. Helms, M. T. McGrath, B. A. Nault, A. Seaman, and L. Sosnoskie. 2020. Cornell integrated crop and pest management guidelines for commercial vegetable production. Cornell Cooperative Extension, Ithaca, NY. 417 pp.

Sabry, Al-K. H., T. A. Abd-El-Rahman, and S. M. Abolmaaty. 2015. Influence of some new insecticides on sweetpotato whitefly, *Bemisia tabaci* and American serpentine leafminer, *Liriomyza trifolii* and their residues in cucumber fruits. Int. J. Adv. Res. 3: 1874–1881.

SAS Institute. 2016. SAS Version 9.4. SAS Institute, Cary, NC.

Schuster, D. J., A. Shurtleff, and S. Kalb. 2009. Management of armyworms and leafminers on fresh market tomatoes, fall 2007. Arthropod. Manag. Tests. 34: E79.

Stansley, P. A., T.-X. Liu, and C. S. Vavrina. 1998. Response of *Bemisia argentifolii* (Homoptera: Aleyrodidae) to imidacloprid under greenhouse, field, and laboratory conditions. J. Econ. Entomol. 91: 686–692.

Sun, Y.-X., and T.-X. Liu. 2016. Effectiveness of imidacloprid in combination with a root nitrogen fertilizer applied to tomato seedlings against *Bemisia tabaci* (Hemiptera: Aleyrodidae). Crop Prot. 80: 56–64.

Talotti, C., P. Sivilotti, and M. T. Barbina. 2003. Leek mining fly 2. Experiences of the fight against leek fly. Notiziario ERSA 16: 49–52.

Talotti, C., P. Sivilotti, P. G. Coceano, E. D. Donna, E. Pizza, and M. T. Barbina. 2004. Trials for control of the leek miner fly. Infor. Agr. 60: 83–86.

Weintraub, P., and N. Mujica. 2006. Systemic effects of a spinosad insecticide on *Liriomyza huidobrensis* larvae. Phytoparasitica 34: 21–24.

Zandigiacomo, P., and L. D. Monta. 2002. Occurrence in Northern Italy of the leek mining fly *Napomyza gymnostoma* (Loew) (Diptera, Agromyzidae). Boll. Zool. Agrar. Bachic. 34: 265–268.