Evaluation of Systemic Insecticides in Protecting Container-Grown Nursery Plants from Damage Caused by Field-Collected Populations of Redheaded Flea Beetle, *Systena frontalis* (Coleoptera: Chrysomelidae), Adults[1]

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Abstract *Systena frontalis* (F.) is a major insect pest of nursery production systems in the Midwest, Northeast, and Southeast regions of the United States. Adults feed on plant leaves, which reduces salability of nursery-grown plants. There are limited options available to protect plants from *S. frontalis* adult feeding damage, and foliar insecticide applications are labor intensive. Systemic insecticides applied to the growing medium may protect plants from *S. frontalis* adult feeding. Consequently, in 2021 and 2022, we conducted two laboratory and two greenhouse experiments to determine if the systemic insecticides thiamethoxam, dinotefuran, cyantraniliprole, acephate, imidacloprid, and cyfluthrin + imidalcoprid protect plants from feeding by field-collected populations of *S. frontalis* adults. In the laboratory experiments, growing medium containing *Itea* plants was treated with the aforementioned systemic insecticides. Seven and 25 d after the treatments were applied, leaves were collected and placed into Petri dishes with a single *S. frontalis* adult. In the greenhouse experiments, *Itea* plants were placed into observation cages. Eight *S. frontalis* adults were released into each cage with an *Itea* plant. In the laboratory experiments, treatments associated with thiamethoxam and dinotefuran resulted in 100% mortality of *S. frontalis* adults after 72 h. In the greenhouse experiments, thiamethoxam, dinotefuran, and acephate protected plants from *S. frontalis* adult feeding 7 d after applying the systemic insecticide treatments. Therefore, systemic insecticides can mitigate feeding damage caused by *S. frontalis* adults on nursery-grown plants.

Key Words dinotefuran, thiamethoxam, acephate, imidacloprid, cyantraniliprole

Systena frontalis (F.) (Coleoptera: Chrysomelidae), commonly referred to as the redheaded flea beetle, is a major insect pest of contain-grown nursery production systems in the Midwest, Northeast, and Southeast regions of the United States. Redheaded flea beetle adults feed on the foliage of a wide range of ornamental plants grown in nursery production systems. Susceptible plants include, but are not limited to *Cornus* spp., *Hydrangea* spp., *Itea* spp., and *Weigela* spp. (Cloyd and Herrick 2018). Redheaded flea beetle adults cause damage when feeding on the foliage of ornamental plants, which reduces aesthetic quality and salability, resulting

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in an economic loss. For example, redheaded flea beetle adult feeding damage caused losses of $483,871 or 11% of overall sale of plant material in 2020 at Loma Vista Nursery (Ottawa, KS) (Herrick and Cloyd 2020).

Redheaded flea beetle adults are 5 mm in length, shiny black, with a red head. They have enlarged hind femora that allow them to jump like a flea, hence the common name (Cloyd and Herrick 2018). Adults feed on the upper and lower leaf surfaces, which results in necrotic leaf spotting and/or holes in leaves. The extent of feeding damage can vary depending on the plant species (Herrick and Cloyd, pers. obs.). Redheaded flea beetle adults are difficult to manage with foliar-applied insecticides because their jumping behavior and propensity to fall onto the growing medium surface when disturbed allows them to escape exposure from insecticide sprays (Cloyd, pers. obs.).

Foliar applications of insecticides are intended to protect foliage from feeding damage as opposed to directly killing redheaded flea beetle adults. However, as Herrick and Cloyd (2020) demonstrated, foliar applications of insecticides do not provide adequate protection of foliage from redheaded flea beetle adult feeding damage. Furthermore, insecticide spray applications need to be conducted on a weekly basis, which is too labor intensive and not cost efficient for large nursery operations (Herrick and Cloyd 2020).

Systemic insecticides are substances that when applied to the growing medium are absorbed by plant roots and then translocated through the vascular system (i.e., xylem and phloem) into aboveground plant parts (e.g., leaves) where insects feed (Bennett 1949). Insects are killed when they ingest a lethal concentration of the systemic insecticide active ingredient during feeding (Ahmed et al. 1954, Reynolds 1954). One of the primary benefits of systemic insecticides is that plants are protected for extended periods of time (e.g., 8 to 10 weeks, depending on the host plant) from feeding by insect pests (Byrne et al. 2010, Reynolds 1954), which can reduce inputs from foliar insecticide spray applications (Cloyd et al. 2011, Jeppson 1953). Systemic insecticides are primarily used to protect plants from phloem and/or xylem-feeding insect pests such as aphids, whiteflies and leafhoppers (Jeppson 1953). In addition, some species of leaf-feeding beetles may be susceptible to systemic insecticides (Jeschke and Nauen 2008). However, there is no information available on the effects of systemic insecticides on redheaded flea beetle adults. Therefore, the objective of our study was to determine if the systemic insecticides thiamethoxam, dinotefuran, acephate, cyantraniliprole, imidacloprid, and cyfluthrin + imidacloprid provide sufficient mortality and protect plants from feeding by field-collected populations of redheaded flea beetle adults under laboratory and greenhouse conditions.

Materials and Methods

The following study involved four experiments conducted under laboratory and greenhouse conditions at Kansas State University (Manhattan, KS) in 2021 and 2022. The active ingredient, trade name, rate used, and manufacturer information for materials used in all four experiments are listed in Table 1.

Laboratory experiment 2021. Redheaded flea beetle, *S. frontalis* (F.) (Coleoptera: Chrysomelidae), adults used in the experiment were collected on 29

Table 1. Active ingredient, trade name, rate used, and manufacturer information of treatments associated with the four experiments.

Active Ingredient	Trade Name	Rate Used (per 946 mL)	Manufacturer
Laboratory Experiment 2021			
Thiamethoxam	Flagship®	0.49 g	Syngenta Crop Protection, LLC; Greensboro, NC
Dinotefuran	Safari®	1.27 g	Valent USA, Corp.; Walnut Creek, CA
Cyantraniliprole	Mainspring®	0.88 ml	Syngenta Crop Protection, LLC; Greensboro, NC
Imidacloprid	Marathon® II	0.12 ml	OHP, Inc.; Bluffton, SC
Untreated control			
Greenhouse Experiment 2021			
Thiamethoxam	Flagship	0.49 g	Syngenta Crop Protection, LLC; Greensboro, NC
Dinotefuran	Safari	1.27 g	Valent USA, Corp.; Walnut Creek, CA
Cyantraniliprole	Mainspring	0.88 ml	Syngenta Crop Protection, LLC; Greensboro, NC
Imidacloprid	Marathon II	0.12 ml	OHP, Inc.; Bluffton, SC
Acephate	Acephate®	0.85 g	Loveland Products, Inc.; Greeley, CO
Cyfluthrin + Imidacloprid	Discus™	1 tablet/4.5 L container	OHP, Inc.; Bluffton, SC
Untreated control			
Laboratory Experiment 2022			
Thiamethoxam	Flagship	0.49 g	Syngenta Crop Protection, LLC; Greensboro, NC
Dinotefuran	Safari	1.27 g	Valent USA, Corp.; Walnut Creek, CA
Cyantraniliprole	Mainspring	0.88 ml	Syngenta Crop Protection, LLC; Greensboro, NC
Imidacloprid	Marathon II	0.12 ml	OHP, Inc.; Bluffton, SC
Untreated control			

Table 1. Continued.

Active Ingredient	Trade Name	Rate Used (per 946 mL)	Manufacturer
Greenhouse Experiment 2022			
Thiamethoxam	Flagship	0.49 g	Syngenta Crop Protection, LLC; Greensboro, NC
Dinotefuran	Safari	1.27 g	Valent USA, Corp.; Walnut Creek, CA
Cyantraniliprole	Mainspring	0.88 ml	Syngenta Crop Protection, LLC; Greensboro, NC
Imidacloprid	Marathon II	0.12 ml	OHP, Inc.; Bluffton, SC
Acephate	Acephate	0.85 g	Loveland Products, Inc.; Greeley, CO
Cyfluthrin + Imidacloprid	Discus	1 tablet/4.5 L container	OHP, Inc.; Bluffton, SC
Untreated control			

September 2021, from container-grown *Hydrangea paniculata* Siebold 'Little Lime' plants at Loma Vista Nursery (Ottawa, KS). Loma Vista Nursery is a 125-ha wholesale, container production facility of ornamental plants (woody and herbaceous). The adults collected were transported to the Horticultural Entomology and Plant Protection Laboratory in the Department of Entomology at Kansas State University, aspirated into 33-ml vials, and starved for 24 h at 18 to 26°C, 48 to 61% relative humidity (RH), and under constant light.

Leaves were collected from five *Itea virginica* L. 'Little Henry' plants obtained from Loma Vista Nursery on 2 July 2021. The plants were started from cuttings using existing stock plants. The cuttings were transplanted on 10 June 2021 into 4.5-L containers with a growing medium consisting of 90% pine bark and 10% sand. The plants were fertilized with 18-2-7 (N:P:K) Nursery Polyon™ Controlled-Release Fertilizer (Harrell's, LLC; Lakeland, FL), with each 4.5-L container receiving 15 g of fertilizer.

There were four systemic insecticide treatments including thiamethoxam (Flagship®), dinotefuran (Safari®), cyantraniliprole (Mainspring®), and imidacloprid (Marathon® II) (Table 1). On 23 September 2021, the insecticide treatments were prepared in 946-ml (32 oz) plastic spray bottles (Spraymaster®: Delta Industries™; King of Prussia, PA), and 300 ml of each treatment solution was applied as a drench to the growing medium of each plant using a 600-ml glass beaker. Plants were grown in a greenhouse at 18 to 41°C, 31 to 100% RH, and under natural light. There were five treatments, including an untreated control, with 10 replications per treatment.

The experiment was set up as a completely randomized design using glass Petri dishes (100 × 15 mm). On 30 September 2021, 7 d after applying the treatments, 10 leaves were randomly collected from each plant (n = 35) and placed into a 3.8-L plastic storage bag (Hefty®: Reynolds Consumer Products, LLC; Lake Forest, IL). The storage bags containing the leaves were transported from the greenhouse to the laboratory. One leaf, as well as one redheaded flea beetle adult, were randomly selected from the individuals collected and transferred into each Petri dish based on the appropriate treatment. The Petri dishes were covered with a lid and maintained in the laboratory at 18 to 26°C, 48 to 61% RH, and under constant light for 96 h. The numbers of live or dead redheaded flea beetle adults were recorded 24, 48, 72, and 96 h after exposure to the *I. virginica* 'Little Henry' leaves to determine the effects of the systemic insecticide treatments on the redheaded flea beetle adults.

Percent redheaded flea beetle adult mortality was calculated. The data conformed to the assumptions of analysis of variance (ANOVA) based on normality and homogeneity of variances (Little and Hills 1978). Data were analyzed using PROC GLIMMIX ($\alpha = 0.05$) with treatment and exposure time (i.e., 24, 48, 72, and 96 h) as the main effects. Treatment means were separated using the Tukey's honestly significant difference test when ANOVA indicated a significant main effect (SAS Institute 2012).

Greenhouse experiment 2021. Redheaded flea beetle adults used in the experiment were collected on 15 September 2021 from container-grown *H. paniculata* 'Limelight Prime' plants at Loma Vista Nursery. The adults collected were transported to the Horticultural Entomology and Plant Protection Laboratory in the Department of Entomology at Kansas State University, aspirated into 33-ml vials, and starved for 24 h at 18 to 26°C, 48 to 61% RH, and under constant light.

Thirty-five *I. virginica* 'Little Henry' plants were obtained from Loma Vista Nursery on 2 July 2021. The plants were started from cuttings using existing stock plants. The cuttings were transplanted on 10 June 2021 into 4.5-L containers with a growing medium consisting of 90% pine bark and 10% sand. The plants were fertilized with 18:2:7 (N:P:K) Nursery Polyon Controlled-Release Fertilizer (Harrell's, LLC) with each 4.5-L container receiving 15 g of fertilizer.

There were six systemic insecticide treatments including thiamethoxam (Flagship), dinotefuran (Safari), cyantraniliprole (Mainspring), imidacloprid (Marathon II), acephate (Acephate®), and cyfluthrin + imidacloprid (Discus™) (Table 1). On 9 September 2021, the systemic insecticide treatments were prepared in 946-ml plastic spray bottles (Spraymaster: Delta Industries), and 300 ml of each treatment solution was applied as a drench to the growing medium of each plant using a 600-ml glass beaker. For the cyfluthrin + imidacloprid (Discus) treatment, one tablet was inserted 5 mm into the growing medium of each 4.5-L container. Three hundred milliliters of tap water were applied to remove the active ingredients from the tablet so they could be absorbed by the plant roots in the growing medium. Plants were grown in a greenhouse at 18 to 41°C, 31 to 100% RH, and under natural light. There were seven treatments, including an untreated control, with five replications per treatment.

The experiment was set up as a completely randomized design using 35 clear plastic observation cages (45.7 L × 45.7 W × 60.9 H cm) arranged in rows on top of two wire-mesh greenhouse benches (4.3 × 1.1 m). Each cage had a lid with a hole and two holes (12.7 cm diameter) on opposing sides covered with insect exclusion screening (0.15 × 0.15 mm: Green-Tek; Janesville, WI) to allow for ventilation and prevent redheaded flea beetle adults from escaping.

The treated *Itea* plants [17.8 ± 0.6 cm (mean ± SEM) in height] were randomly placed among the 35 plastic observation cages 7 d after application of the treatments. A 15.2-cm plastic dish was placed under each container to collect any leachate after watering. Plants were watered as needed with 200 to 300 ml of tap water to minimize leachate. On 16 September 2021, after the 24-h starvation period, eight field-collected redheaded flea beetle adults were released into each plastic observation cage with an *Itea* plant. The temperature and RH in the cages were recorded over the duration of the experiment using a data logger (Traceable® Thermo-Hygro: Fisher Scientific; Hampton, NH). The temperature and RH in the plastic observation cages during the course of the experiment were 19 to 34°C and 68 to 100%, under natural day light conditions.

On 30 September 2021, 15 d after releasing the redheaded flea beetle adults into the plastic observation cages with the *Itea* plants, a damage rating scale from 0 to 10 was used to quantify redheaded flea beetle adult leaf feeding where 0 = 0% leaf damage, 1 = <1 to 10% leaf damage, 2 = 11 to 20% leaf damage, 3 = 21 to 30% leaf damage, 4 = 31 to 40% leaf damage, 5 = 41 to 50% leaf damage, 6 = 51 to 60% leaf damage, 7 = 61 to 70% leaf damage, 8 = 71 to 80% leaf damage, 9 = 81 to 90% leaf damage, and 10 = 91 to 100% leaf damage. In addition, for each treatment, the number of leaves fed upon was recorded and then the leaves were removed and placed into a 3.8-L plastic storage bag (Hefty, Reynolds Consumer Products, LLC). The storage bags containing the leaves were transported from the greenhouse to the laboratory where they were frozen for 48 h, then placed into a plant press, and dried for 2 weeks. After drying, the amount of leaf area fed upon was assessed by placing a transparent section of graph paper, containing 4-mm^2 squares, over each leaf. The technique used to determine the total leaf area fed upon (mm^2) by redheaded flea beetle adults was similar to that used by Herrick et al. (2012).

Rating damage data associated with redheaded flea beetle adult feeding, the number of leaves fed upon, and leaf area fed upon (mm^2) by the adults were normalized using a Log_{10+1} transformation procedure. The data conformed to the assumptions of an ANOVA based on normality and homogeneity of variances (Little and Hills 1978). Data were analyzed using PROC GLIMMIX ($\alpha = 0.05$) with treatment as the main effect. Treatment means were separated using the Tukey's honestly significant difference test when ANOVA indicated a significant main effect (SAS Institute 2012). Parametric statistics were used to analyze the rating data (i.e., categorical/ordinal data) to avoid a type I error (Larrabee et al. 2014). All data presented are nontransformed.

Laboratory experiment 2022. The procedures for the 2022 laboratory experiment were similar to the 2021 laboratory experiment previously described. Redheaded flea beetle adults used in the experiment were collected on 3 October 2022 from container-grown *H. paniculata* 'Little Lime Punch' and 'Fire Light Tidbit' plants at Loma Vista Nursery. The adults collected were starved for 24 h at 20 to 22°C, 31 to 55% RH, and under constant light. Leaves were collected from 5 *I. virginica* 'Little Henry' plants obtained from Loma Vista Nursery on 11 July 2022. The plants were started from cuttings using existing stock plants. The cuttings were transplanted on 2 May 2022 into 4.5-L containers.

There were four systemic insecticide treatments including thiamethoxam (Flagship), dinotefuran (Safari), cyantraniliprole (Mainspring), and imidacloprid (Marathon II) (Table 1). On 9 September 2022, the treatments were applied as a drench to the growing medium of each container. Plants were grown in a greenhouse at 19 to 47°C, 26 to 92% RH, and under natural light. There were five treatments, including an untreated control, with 10 replications per treatment.

On 4 October 2022, 25 d after applying the treatments, 10 leaves were randomly collected from each plant ($n = 35$) and placed into a 3.8-L plastic storage bag (Hefty, Reynolds Consumer Products, LLC). The storage bags containing the leaves were transported from the greenhouse to the laboratory. One leaf, as well as one redheaded flea beetle adult, were randomly selected from the individuals collected and transferred into each Petri dish based on the appropriate treatment. The Petri dishes were covered with a lid and maintained in the laboratory at 20 to 22°C, 31 to 55% RH, and under constant light for 72 h. The numbers of live or dead redheaded flea beetle adults were recorded 24, 48, and 72 h after exposure to the *I. virginica* 'Little Henry' leaves to determine the effects of the treatments on the redheaded flea beetle adults. Data analysis was identical to the 2021 laboratory experiment as described previously.

Greenhouse experiment 2022. The procedures for the 2022 greenhouse experiment were similar to the 2021 greenhouse experiment described above. Redheaded flea beetle adults used in the experiment were collected on 16 September 2022 from container-grown *H. paniculata* 'Little Lime Punch' plants at Loma Vista Nursery and starved for 24 h at 18 to 26°C, 48 to 61% RH, and under constant light. Thirty-five *I. virginica* 'Little Henry' plants were obtained from Loma Vista Nursery on 11 July 2022. The plants were started from cuttings using existing stock plants. The cuttings were transplanted on 2 May 2022 into 4.5-L containers.

There were six systemic insecticide treatments including thiamethoxam (Flagship), dinotefuran (Safari), cyantraniliprole (Mainspring), imidacloprid (Marathon II), acephate (Acephate), and cyfluthrin + imidacloprid (Discus) (Table 1). On 9 September 2022, the insecticide treatments were applied as a drench to the growing medium, except for the cyfluthrin + imidacloprid (Discus) treatment (see greenhouse experiment 2021). Plants were grown in a greenhouse at 22 to 46°C, 40 to 91% RH, and under natural light. There were seven treatments, including an untreated control, with five replications per treatment.

The treated *Itea* plants (23.2 ± 0.6 cm in height) were randomly placed among the 35 plastic observation cages 7 d after application of the treatments. On 17 September 2022, after the 24-h starvation period, eight field-collected redheaded flea beetle adults were released into each plastic observation cage with an *Itea* plant. The temperature and RH in the plastic observation cages during the course of the experiment were 22 to 37°C and 0 to 100% RH, under natural day light conditions.

On 2 October 2022, 15 d after releasing the redheaded flea beetle adults into the plastic observation cages with *Itea* plants, the damage rating scale described in the 2021 greenhouse experiment was used to quantify redheaded flea beetle adult leaf feeding. Data analysis was identical to the 2021 greenhouse experiment as described previously.

Results

Laboratory experiment 2021. Redheaded flea beetle adult mortality was 60% ($n = 10$) in the untreated control at 96 h, so only data collected at 24, 48, and 72 h

Table 2. Mean (±SEM) percent adult redheaded flea beetle mortality at 24, 48, and 72 h after placement on leaves of *I. virginica* plants treated with systemic insecticides 7 d earlier, Laboratory Experiment 2021.*

Treatment	24 h	48 h	72 h
Thiamethoxam, 0.49 g/946 ml	50±16.7 a	80±13.3 a	100±0.0 a
Dinotefuran, 1.27 g/946 ml	50±16.7 a	90±10.0 a	100±0.0 a
Cyantraniliprole, 0.88 ml/946 ml	0±0 b	10±10.0 b	10±10.0 b
Imidacloprid, 0.12 ml/946 ml	0±0 b	0±0 b	0±0 b
Untreated control	0±0 b	0±0 b	30±15.3 b

* Means followed by the same lowercase letter within a column of percentage mortality are not significantly different ($P > 0.05$) as determined by Tukey's honestly significant difference test.

were included in the analysis. Herrick and Cloyd (2020) found that mortality of field-collected redheaded flea beetle adults significantly increases after 72 h under laboratory conditions, which is likely associated with unknown age of redheaded flea beetle adults and desiccation of the leaves over time. Nonetheless, there was a significant effect of exposure time on redheaded flea beetle adult mortality ($F = 10.67$; df = 134, 2; $P < 0.0001$). Redheaded flea beetle adult mortality was 20.0 ± 5.7% (mean ± SEM; $n = 50$) after 24 h, 36.0 ± 6.9% ($n = 50$) after 48 h, and 48.0 ± 7.1% ($n = 50$) after 72 h of exposure to the *I. virginica* 'Little Henry' leaves in the Petri dishes.

There were significant differences in percent redheaded flea beetle adult mortality across the treatments within each exposure time ($F = 52.03$; df = 134, 4; $P < 0.0001$) (Table 2). The thiamethoxam (Flagship) at 0.49 g/946 ml and dinotefuran (Safari) at 1.27 g/946 ml treatments resulted in a significantly higher redheaded flea beetle adult mortality after 24, 48, and 72 h than the other treatments (Table 2).

Greenhouse experiment 2021. Redheaded flea beetle adult feeding damage ratings ($F = 13.1$; df = 24, 6; $P < 0.0001$), the number of leaves fed upon ($F = 10.12$; df = 24, 6; $P < 0.0001$), and leaf area (mm^2) fed upon ($F = 10.05$; df = 24, 6; $P < 0.0001$) were significantly different across the treatments. Overall, *Itea* plants associated with the thiamethoxam (Flagship) at 0.49 g/946 ml, dinotefuran (Safari) at 1.27 g/946 ml, and acephate (Acephate) at 0.85 g/946 ml treatments had the least amount of leaf area fed upon (<50 mm^2) by redheaded flea beetle adults (Table 3).

Laboratory experiment 2022. There was a significant effect of exposure time on redheaded flea beetle adult mortality ($F = 5.14$; df = 134, 2; $P = 0.0070$). Redheaded flea beetle adult mortality was 44.0 ± 7.1% ($n = 50$) after 24 h, 56.0 ± 7.1% ($n = 50$) after 48 h, and 58.0 ± 7.1% ($n = 50$) after 72 h of exposure to the *I. virginica* 'Little Henry' leaves in the Petri dishes.

There were significant differences in percent redheaded flea beetle adult mortality across the treatments within each exposure time ($F = 127.24$; df = 134, 4; $P < 0.0001$) (Table 4). The thiamethoxam (Flagship) at 0.49 g/946 ml, dinotefuran (Safari) at 1.27 g/946 ml, and imidacloprid (Marathon II) at 0.12 ml/946 ml

Table 3. Mean plant damage associated with field-collected redheaded flea beetle adults feeding following placement on leaves of *I. virginica* plants treated with systemic insecticides 7 d earlier, Greenhouse Experiment 2021.*

Treatment	Mean Damage Rating**	Mean ± SEM No. Leaves Fed Upon	Mean ± SEM Leaf Area Fed Upon (mm^2)
Untreated control	2.4 a	34.0 ± 8.9 a	418.6 ± 106.4 a
Thiamethoxam, 0.49 g/946 ml	0.0 b	2.4 ± 1.2 c	24.8 ± 18.9 c
Dinotefuran, 1.27 g/946 ml	0.0 b	2.6 ± 3.6 c	16.8 ± 11.8 c
Cyantraniliprole, 0.88 ml/946 ml	1.2 b	30.8 ± 11.9 ab	354.4 ± 106.3 ab
Imidacloprid, 0.12 ml/946 ml	1.4 b	24.2 ± 6.3 a	465.6 ± 146.0 a
Acephate, 0.85 g/946 ml	0.4 b	3.0 ± 0.8b c	48.0 ± 32.5 bc
Cyfluthrin + Imidacloprid, 1 tablet/ 4.5-L container	2.4 a	35.0 ± 5.4 a	854.0 ± 188.6 a

* Means followed by the same lowercase letter within a column are not significantly different ($P > 0.05$) as determined by the Tukey honestly significant difference test.

** Damage ratings: 0 = 0% leaf damage, 1 = <1 to 10% leaf damage, 2 = 11 to 20% leaf damage, 3 = 21 to 30% leaf damage, 4 = 31 to 40% leaf damage, 5 = 41 to 50% leaf damage, 6 = 51 to 60% leaf damage, 7 = 61 to 70% leaf damage, 8 = 71 to 80% leaf damage, 9 = 81 to 90% leaf damage, and 10 = 91 to 100% leaf damage.

treatments resulted in a significantly higher redheaded flea beetle adult mortality after 24, 48, and 72 h than the other treatments (Table 4).

Greenhouse experiment 2022. Redheaded flea beetle adult feeding damage rankings ($F = 7.6$; df = 24, 6; $P = 0.0001$), number of leaves fed upon ($F = 15.08$; df = 24, 6; $P < 0.0001$), and leaf area (mm^2) fed upon ($F = 20.11$; df = 24, 6; $P < 0.0001$)

Table 4. Mean (± SEM) percent adult redheaded flea beetle mortality at 24, 48, and 72 h after placement on leaves of *I. virginica* plants treated with systemic insecticides 25 d earlier, Laboratory Experiment 2022.*

Treatment	24 h	48 h	72 h
Thiamethoxam, 0.49 g/946 ml	90 ± 10.0 a	100 ± 0.0 a	100± 0.0 a
Dinotefuran, 1.27 g/946 ml	80 ± 13.3 a	90 ± 10.0 a	100 ± 0.0 a
Cyantraniliprole, 0.88 ml/946 ml	0 ± 0 b	0 ± 0 b	0 ± 0 b
Imidacloprid, 0.12 ml/946 ml	50 ± 16.7 a	90 ± 10.0 a	90 ± 10.0 a
Untreated control	0 ± 0 b	0 ± 0 b	0 ± 0 b

* Means followed by the same lowercase letter within a column of percentage mortality are not significantly different ($P > 0.05$) as determined by Tukey's honestly significant difference test.

Table 5. Mean plant damage associated with field-collected redheaded flea beetle adults feeding following placement on *I. virginica* plants treated with systemic insecticides 7 d earlier, Greenhouse Experiment 2022.*

Treatment	Mean Damage Rating**	Mean ± SEM No. Leaves Fed Upon	Mean ± SEM Leaf Area Fed Upon (mm^2)
Untreated control	2.0 a	28.8 ± 8.3 a	478.8 ± 115.2 a
Thiamethoxam, 0.49 g/946 ml	0.4 b	0.8 ± 1.6 c	1.6 ± 1.0 c
Dinotefuran, 1.27 g/946 ml	0.2 b	0.6 ± 0.6 c	1.4 ± 1.4 c
Cyantraniliprole, 0.88 ml/946 ml	2.0 a	37.0 ± 6.6 a	406.8 ± 80.5 a
Imidacloprid, 0.12 ml/946 ml	1.4 ab	21.4 ± 9.4 ab	227.8 ± 90.4 ab
Acephate, 0.85 g/946 ml	0.8 ab	3.6 ± 1.4 bc	31.6 ± 20.5 bc
Cyfluthrin + Imidacloprid, 1 tablet/ 4.5-L container	2.2 a	35.8 ± 8.6 a	636.4 ± 193.7 a

* Means followed by the same lowercase letter within a column are not significantly different ($P > 0.05$) as determined by Tukey's honestly significant difference test.

** Damage ratings: 0 = 0% leaf damage, 1 = <1 to 10% leaf damage, 2 = 11 to 20% leaf damage, 3 = 21 to 30% leaf damage, 4 = 31 to 40% leaf damage, 5 = 41 to 50% leaf damage, 6 = 51 to 60% leaf damage, 7 = 61 to 70% leaf damage, 8 = 71 to 80% leaf damage, 9 = 81 to 90% leaf damage, and 10 = 91 to 100% leaf damage.

were significantly different across the treatments. Overall, *Itea* plants associated with the thiamethoxam (Flagship) at 0.49 g/946 ml, dinotefuran (Safari) at 1.27 g/ 946 ml, and acephate (Acephate) at 0.85 g/946 ml treatments had the least amount of leaf area fed upon (<32 mm^2) by redheaded flea beetle adults (Table 5).

Discussion

The results from our study demonstrate that the systemic insecticides, thiamethoxam (Flagship), dinotefuran (Safari), and acephate (Acephate), provide sufficient mortality of redheaded flea beetle adults and reduce the number of leaves and leaf area (mm^2) fed upon by redheaded flea beetle adults. The information from our study is important to nursery producers because we found that these three systemic insecticides provide sufficient management of redheaded flea beetle adults. The three systemic insecticides reduced redheaded flea beetle adult feeding damage, which may allow for salability of nursery-grown crops that are susceptible to redheaded flea beetle adult feeding including *Hydrangea* spp., *Itea* spp., *Weigela* spp., and *Cornus* spp. (Cloyd and Herrick 2018).

Thiamethoxam (Flagship) and dinotefuran (Safari) are neonicotinoid insecticides with similar physical and molecular properties and mode of action, which involves modulation of the nicotinic acetylcholine receptor (Ihara and Matsuda 2018). However, the systemic insecticides differ in water solubility. For example, the water solubility of thiamethoxam (Flagship) and dinotefuran (Safari) is 4,100 and 39,830 ppm (4.1 and 39.0 g/L at 20°C), respectively (Byrne et al. 2010, Jeschke and Nauen 2008, Wakita et al. 2005). Furthermore, the systemic insecticides are converted into metabolites that, in general, are more toxic to insects than the original active ingredients (Cloyd et al. 2011). For example, thiamethoxam (Flagship) is converted into clothianidin (Nauen et al. 2003) and dinotefuran (Safari) is converted into UF [1-methyl-3-(tetrahydro-3-furylmethyl) urea] and DN [1-methyl-3-(tetrahydro-3-furylmethyl) guanidium dihydrogen] (Liu et al. 2018).

Acephate (Acephate) is an organophosphate systemic insecticide that is converted into the metabolite methamidophos in plant leaves (Bull 1979, Trevizan et al. 2005). Methamidophos is more toxic to chewing and sucking insect pests than acephate (Bull 1979, Lin et al. 2020). The water solubility of acephate (Acephate) is 790,000 ppm (79 g/L at 20°C) (Tomlin 1994), so the systemic insecticide moves quickly throughout the plant. Systemic insecticides that have a high water solubility are rapidly translocated throughout plants and reach plant tissues (e.g., leaves and stems) fed upon by insect pests (Cloyd et al. 2011).

The reason for the differences in activity of imidacloprid (Marathon II) on redheaded flea beetle adults between the two laboratory experiments is that in the 2021 laboratory experiment leaves were removed 7 d after application of the treatments, whereas in the 2022 laboratory experiment leaves were removed 25 d after application of the treatments. The water solubility of imidacloprid (Marathon II) is 610 ppm (0.61 g/L at 20°C) (Jeschke and Nauen 2008), which is much lower than thiamethoxam (Flagship), dinotefuran (Safari), and acephate (Acephate). Consequently, imidacloprid takes longer to translocate through the vascular system (i.e., xylem and phloem) and spread throughout plant tissues (Hale and Shorey 1965, Tomlin 1994), especially in woody plant tissue (Byrne and Toscano 2006). Due to the woodiness of the *Itea* plants, a lethal concentration of active ingredient may have taken longer to reach and accumulate in plant leaves where redheaded flea beetle adults feed (Cowles 2010), which likely accounted for the differences in redheaded flea beetle adult mortality between the two laboratory experiments.

Cloyd et al. (2012) demonstrated that imidacloprid (Marathon 1 G: OHP, Inc.; Bluffton, SC) took longer to translocate through poinsettia, *Euphorbia pulcherrima* Willd., plants than dinotefuran (Safari) due to differences in water solubility and plant age. Therefore, imidacloprid (Marathon II) needs to be applied earlier in the growing season than thiamethoxam (Flagship), dinotefuran (Safari), and acephate (Acephate) to protect plants from feeding damage by redheaded flea beetle adults.

Herrick and Cloyd (2020) determined that redheaded flea beetles can overwinter in the containers of plants grown under nursery conditions. Consequently, the application of systemic insecticides may kill redheaded flea beetle adults before they emerge from the growing medium, which would reduce the number of adults feeding on plant foliage. In addition, the systemic insecticides will likely kill the larval stages of the redheaded flea beetle, thus reducing the number of adults emerging from the growing medium.

In conclusion, our study demonstrates that the systemic insecticides thiamethoxam (Flagship), dinotefuran (Safari), and acephate (Acephate) provide sufficient mortality of redheaded flea beetle adults, which can lead to short and long-term protection (7 and 25 d) of plants from redheaded flea beetle adult feeding.

Therefore, applications of any one of the three systemic insecticides may contribute to less plant damage from redheaded flea beetle adults during the growing season. Future studies will assess the length of residual activity of the systemic insecticides in protecting plants from redheaded flea beetle adult feeding and determine the number of applications that are needed during the growing season.

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