Residual Activity of Systemic Insecticides against Field-Collected Populations of Redheaded Flea Beetle (Coleoptera: Chrysomelidae), *Systena frontalis*, Adults under Laboratory and Greenhouse Conditions[1]

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Abstract *Systena frontalis* (F.) is an insect pest of nursery production systems in the Midwest, Southeast, and Northeast regions of the United States. Adults feed on plant leaves and can reduce salability of container-grown nursery plants. Limited management options are available to protect plants from *S. frontalis* adult feeding damage. Insecticide spray applications to plant leaves are labor-intensive and not cost-efficient. Systemic insecticide applications to the growing medium may protect plants from *S. frontalis* adult feeding. In 2023, we conducted two laboratory and two greenhouse experiments to assess the residual activity of the systemic insecticides dinotefuran, thiamethoxam, and acephate against field-collected populations of *S. frontalis* adults. In the laboratory experiments, growing medium containing *Itea virginica* L. 'Little Henry' plants were treated with these three systemic insecticides. Twenty-five and 45 d after 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 plastic observation cages. Eight *S. frontalis* adults were released into each cage with a single *Itea* plant. In the laboratory experiments 25 and 45 d after application of dinotefuran and thiamethoxam, the *S. frontalis* adults in the dishes with treated leaves had 66–90% mortality after 72 h. In the greenhouse experiments, dinotefuran and thiamethoxam protected *Itea* plants from *S. frontalis* adult feeding 45 d after application; 2.4 and 2.8 mm^2 of leaf area were fed upon by *S. frontalis* adults. These results indicate that systemic insecticides can reduce feeding damage by *S. frontalis* adults on container-grown nursery plants.

Key Words dinotefuran, thiamethoxam, acephate, nursery production, leaf damage

Systena frontalis (F.) (Coleoptera: Chrysomelidae), commonly known as the redheaded flea beetle, is an insect pest of container-grown nursery production systems in the Midwest, Southeast, and Northeast regions of the United States. Redheaded flea beetle adults feed on the leaves of a wide range of ornamental plants grown in nursery production systems. Some plants that are susceptible to redheaded flea beetle adult feeding in nursery production systems include *Cornus* spp., *Hydrangea* spp., *Itea* spp., and *Weigela* spp. (Cloyd and Herrick 2018). Damage caused by the redheaded flea beetle occurs when adults feed on the

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leaves of ornamental plants, thus reducing the aesthetic quality and salability. Consequently, adult feeding damage can lead to economic losses. For instance, damage associated with redheaded flea beetle adults resulted in losses of $483,871 or 11% of overall plant sales at Loma Vista Nursery (Ottawa, KS) in 2020 (Herrick and Cloyd 2020).

Redheaded flea beetle adults are approximately 5 mm long, shiny black, with a distinct red head. Adults possess large hind femora, which allow them to jump like a flea, hence the common name (Cloyd and Herrick 2018). Adults feed on the upper and lower leaf surfaces, resulting in holes in leaves and/or necrotic leaf spotting. The amount of leaf damage affiliated with adult feeding varies depending on plant species (N.J.H. and R.A.C., pers. obs.), but there is no apparent preference (Herrick and Cloyd 2020).

Redheaded flea beetle adult populations are difficult to manage with insecticides applied to plant leaves because the beetles jump and/or fall onto the growing medium surface when disturbed, which allows the adults to avoid exposure to insecticide sprays (R.A.C., pers. obs.). Spray applications of insecticides are intended to protect plant leaves from redheaded flea beetle adult feeding damage as opposed to directly killing adults. However, Herrick and Cloyd (2020) determined that spray applications of insecticides fail to protect plant leaves from redheaded flea beetle adult feeding damage. When redheaded flea beetle adults are present during the growing season, insecticide spray applications are required on a weekly basis, which is not cost-efficient and is too labor-intensive for large nursery operations (Herrick and Cloyd 2020). However, systemic insecticides can protect plants from redheaded flea beetle adult feeding damage (Cloyd and Herrick 2023).

Systemic insecticides are applied to the growing medium, absorbed by plant roots, and translocated through the plant vascular system (xylem and phloem) into plant leaves, where insects feed (Bennett 1949, Poe and Marousky 1971). Insects are killed after ingesting lethal concentrations of the systemic insecticide active ingredient when feeding (Ahmed et al. 1954, Reynolds 1954). Systemic insecticides may protect plants from insect feeding damage for extended periods (e.g., 8 to 10 weeks) during the growing season (Schuster and Morris 2002), which can reduce costs associated with insecticide spray applications (Cloyd et al. 2011, Jeppson 1953, Reynolds 1954). However, the extent of protection varies depending on the plant fed upon (Byrne et al. 2010, Reynolds 1954, Rudinsky 1959).

Systemic insecticides protect plants from xylem- and/or phloem-feeding insect pests, including aphids, leafhoppers, soft scales, and whiteflies (Jeppson 1953, Perier et al. 2023), and populations of certain species of leaf-feeding beetles can be managed using systemic insecticides (Jeschke and Nauen 2008). In greenhouse experiments, Cloyd and Herrick (2023) found that systemic insecticide products containing the active ingredients dinotefuran, thiamethoxam, and acephate protected *Itea virginica* L. 'Little Henry' plants from redheaded flea beetle adult feeding 7 d after application. However, systemic insecticides need to provide extended residual activity to protect plants from redheaded flea beetle adult feeding damage throughout the growing season. Applying systemic insecticides as drenches to the growing medium is labor-intensive, so the systemic insecticides need to provide protection from redheaded flea beetle adult feeding for most of the growing season, which will allow container-grown nursery plants to be sold.

The objective of our study was to determine the residual activity of the systemic insecticides dinotefuran, thiamethoxam, and acephate against populations of field-collected redheaded flea beetle adults under laboratory and greenhouse conditions.

Materials and Methods

The following study consisted of four experiments conducted under laboratory and greenhouse conditions at Kansas State University (Manhattan, KS) in 2023.

Laboratory experiments. Redheaded flea beetle adults used in the two experiments were collected on 14 September ($n = 271$) and 4 October ($n = 371$) 2023 from container-grown *I. virginica* 'Little Henry' plants at Loma Vista Nursery (Ottawa, KS). Loma Vista Nursery is a 125-ha wholesale production facility of container 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. Adults were starved for 24 h at 20 to 24°C and 33–69% relative humidity (RH) under constant light. Specimens used in this research are deposited as voucher number 267 in the Kansas State University Museum of Entomological and Prairie Arthropod Research.

Leaves were collected from *I. virginica* plants ($n = 40$) initially obtained from Loma Vista Nursery on 11 July 2023. The plants were started from cuttings taken from existing stock plants. The cuttings were transplanted on 10 May 2023 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.

Two groups of experiments were conducted with two application intervals (25 and 45 days after application [DAA] of the treatments) and three systemic insecticide treatments: dinotefuran (Safari®, Valent USA, Corp., Walnut Creek, CA), thiamethoxam (Flagship®, Syngenta Crop Protection, LLC, Greensboro, NC), and acephate (Acephate®, Loveland Products, Inc., Greeley, CO). Acephate was tested at 15 DAA in the second experiment instead of 45 DAA because of results obtained in the first experiment at 25 DAA. The systemic insecticides and application intervals were selected based on significant redheaded flea beetle adult mortality after adults fed on leaves removed from plants treated with drench applications of dinotefuran and thiamethoxam 7 and 25 DAA in laboratory experiments (Cloyd and Herrick 2023). Plants treated with drench applications of dinotefuran, thiamethoxam, and acephate in greenhouse experiments also were protected from redheaded flea beetle adult feeding damage 7 DAA (Cloyd and Herrick 2023).

On 22 August 2023, the treatments were prepared in 946-ml plastic spray bottles (Spraymaster®, Delta Industries, King of Prussia, PA). Three hundred milliliters of each treatment solution was applied with a 600-ml glass beaker as a drench to the growing medium of each container. The acephate 15 DAA treatment was prepared similarly, but applications were made on 20 September 2023. The label rates of the systemic insecticides associated with drench applications were used. Plants were grown in a greenhouse at 22 to 50°C and 0–100% RH under natural light. The two groups of experiments each consisted of four treatments, including a water control, with 10 replications per treatment. The experiment groups, treatments, application rates, and application intervals (25, 45, and 15 DAA) were as follows:

Group 1

1. Dinotefuran (Safari) at 1.27 g/946 ml (25 DAA)
2. Thiamethoxam (Flagship) at 0.49 g/946 ml (25 DAA)
3. Acephate at 0.85 g/946 ml (25 DAA)
4. Water control

Group 2

1. Dinotefuran (Safari) at 1.27 g/946 ml (45 DAA)
2. Thiamethoxam (Flagship) at 0.49 g/946 ml (45 DAA)
3. Acephate at 0.85 g/946 ml (15 DAA)
4. Water control

The experiments were set up as a completely randomized, repeated measures design with glass petri dishes (100 × 15 mm). On 15 September 2023, for Group 1 (25 DAA), 10 leaves were randomly collected from the treated plants and placed into a 3.8-L plastic storage bag (Hefty®, Reynolds Consumer Products, LLC, Lake Forest, IL) associated with the appropriate treatment. The plastic storage bag was transported from the greenhouse to the laboratory. One leaf and 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 24°C and 33–69% RH under constant light for 72 h. The number of live or dead redheaded flea beetle adults was recorded 24, 48, and 72 h after exposure to the *I. virginica* leaves to determine the effect of the treatments on the redheaded flea beetle adults. The same procedure was performed on 5 October 2023 for Group 2, which included the 45 DAA treatments with dinotefuran and thiamethoxam and 15 DAA treatment with acephate.

The amount of leaf area fed upon by redheaded flea beetle adults was assessed for each leaf associated with each treatment after 72 h by placing a transparent section of graph paper, containing 4-mm 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 of Herrick et al. (2012).

The percentage of redheaded flea beetle adult mortality was calculated by dividing the number of dead redheaded flea beetle adults per treatment by the total number of redheaded flea beetle adults in each treatment and then multiplying by 100. Data were analyzed using PROC GLIMMIX ($\alpha = 0.05$) with treatment, exposure time (24, 48, and 72 h), and DAA (15, 25, and 45) as the main effects. Treatment means were separated using Tukey's honestly significant difference test when the analysis of variance indicated a significant main effect (SAS Institute 2012).

Greenhouse experiments. The initial procedures for the greenhouse experiments were similar to those of the laboratory experiments. The experimental groups and systemic insecticide treatments were also the same as in the laboratory experiment. The greenhouse experiments were set up as a completely randomized design with 35 clear plastic observation cages (45.7 × 45.7 × 60.9 cm [length × width × height]) 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 of each cage were 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 (24.4 ± 0.4 cm [mean $\pm$ SEM] high) were placed randomly among the 35 plastic observation cages at 15 DAA (acephate only), 25 DAA, or 45 DAA. 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 15 September and 5 October 2023, after the 24-h starvation period, eight field-collected redheaded flea beetle adults were released into each cage with an *Itea* plant. The number of adults released into each cage was based on the number observed on plants under nursery conditions (R.A.C., pers. obs.).

The temperature and RH in the cages were recorded during the experiments with a data logger (Traceable® Thermo-Hygro, Fisher Scientific, Hampton, NH). During the experiments, the conditions in the cages were 22 to 46°C and 0–100% RH under natural daylight conditions.

On 30 September 2023 (first greenhouse experiment) and 20 October 2023 (second greenhouse experiment), 15 d after releasing the redheaded flea beetle adults into the plastic observation cages with the *Itea* plants, a whole plant damage rating scale from 0 to 10 was used to quantify redheaded flea beetle adult leaf feeding, where 0 = 0% leaf damage, 1 = 1–10% leaf damage, 2 = 11–20% leaf damage, 3 = 21–30% leaf damage, 4 = 31–40% leaf damage, 5 = 41–50% leaf damage, 6 = 51–60% leaf damage, 7 = 61–70% leaf damage, 8 = 71–80% leaf damage, 9 = 81–90% leaf damage, and 10 = 91–100% leaf damage. Plants that had $<$1% leaf damage were rated as 0. The number of leaves fed upon was recorded, then leaves were removed and placed into a 3.8-L plastic storage bag (Hefty®, Reynolds Consumer Products, LLC, Lake Forest, IL) based on the appropriate treatment. The leaves were transported from the greenhouse to the laboratory, where they were placed into a freezer for 2 d. After freezing, the amount of leaf area fed upon was assessed by placing a transparent section of graph paper containing 4-mm squares over each leaf as in the laboratory experiment.

The whole plant damage rating data associated with redheaded flea beetle adult feeding, the number of leaves fed upon, and the leaf area fed upon by the adults were analyzed using PROC GLIMMIX ($\alpha = 0.05$) with treatment as the main effect. Treatment means were separated using Tukey's honestly significant difference test when the analysis of variance indicated a significant main effect (SAS Institute 2012). The analysis of the whole plant damage rating data (i.e., categorical/ordinal data) using parametric statistics avoided a type I error (Larrabee et al. 2014).

Results

Laboratory experiments. Redheaded flea beetle adult mortality in the water control was 60% ($n = 10$) at 96 h in previous laboratory experiments conducted by Herrick and Cloyd (2020). Herrick and Cloyd (2020) also found that field-collected redheaded flea beetle adult mortality increased significantly after 72 h under laboratory conditions, which may be related to age of the redheaded flea beetle adults and/or desiccation of the leaves over time. Consequently, the laboratory experiments in the current study were conducted for 24, 48, and 72 h. Significant differences were found

Table 1. Laboratory experiments with treatment, days after application (DAA), and pooled mean percentage (%) of redheaded flea beetle, *Systena frontalis*, adult mortality 72 h after exposure to *Itea virginica* 'Little Henry' leaves from plants treated 15 (acephate only), 25, or 45 days previously with the systemic insecticides dinotefuran (Safari) at 1.27 g/946 ml, thiamethoxam (Flagship) at 0.49 g/946 ml, and acephate at 0.85 g/946 ml.

	Pooled Mean (± SEM) % *S. frontalis* Adult Mortality after 72 h*	
Treatment	**25 DAA**	**45 DAA**
Dinotefuran	90.0 ± 9.6 Aa	90.0 ± 9.6 Aa
Thiamethoxam	66.7 ± 15.2 Aa	70.0 ± 14.7 Aa
Acephate	26.7 ± 14.2 Bb	80.0 ± 12.9 Aa**
Water control	13.3 ± 10.9 Bb	13.3 ± 10.9 Bb

* Within a column for each application interval (25 or 45 DAA), mean values followed by the same uppercase letter are not significantly different ($P > 0.05$). Across rows, mean values followed by the same lowercase letter are not significantly different ($P > 0.05$). Significance was determined by Tukey's honestly significant difference test.

** Treatment with acephate at 0.85 g/946 ml at 45 DAA was replaced with treatment at 0.85 g/946 ml at 15 DAA due to reduced mortality of redheaded flea beetle adults 25 DAA.

across the main effects (treatment, exposure time, and DAA) on redheaded flea beetle adult mortality. Redheaded flea beetle adult mortality was significantly different ($F = 19.93$; df = 221, 2; $P < 0.0001$) after 24 h of feeding on leaves compared with mortality at 48 and 72 h. Redheaded flea beetle adult mortality was 36.3 ± 15.3% (mean ± SEM; $n = 40$) after 24 h, 61.3 ± 15.5% ($n = 40$) after 48 h, and 71.3 ± 14.4% ($n = 40$) after 72 h of exposure to the *I. virginica* leaves in the petri dishes. A significant difference ($F = 9.23$; df = 221, 2; $P = 0.0027$) in redheaded flea beetle adult mortality also was found across the application intervals, with 80.0 ± 12.9% (acephate only; $n = 10$) at 15 DAA, 49.2 ± 16.0% ($n = 40$) at 25 DAA, and 57.8 ± 16.0% ($n = 30$) at 45 DAA.

A significant two-way interaction ($F = 9.23$; df = 221, 2; $P = 0.0027$) was found between treatment and DAA (15, 25, and 45). However, no significant difference ($P > 0.05$) in the two-way interaction was found between treatment and exposure time (24, 48, and 72 h), so the data were pooled by exposure time (Table 1). The acephate treatment of 0.85 g/946 ml at 45 DAA was replaced with an acephate treatment of 0.85 g/946 mL treatment at 15 DAA due to reduced mortality of redheaded flea beetle adults at 25 DAA.

Treatments with dinotefuran at 1.27 g/946 ml and thiamethoxam at 0.49 g/946 ml resulted in a significantly higher redheaded flea beetle adult mortality than did the acephate treatment at 0.85 g/946 ml and the water control 25 DAA (Table 1). Similar results were obtained for the treatments with dinotefuran at 1.27 g/946 ml and thiamethoxam at 0.49 g/946 ml at 45 DAA. However, the acephate treatment at 0.85 g/946 ml at 15 DAA had a significantly higher redheaded flea beetle adult mortality than did

Table 2. Laboratory experiments with treatment, days after application (DAA), and mean leaf area fed upon by redheaded flea beetle, *Systena frontalis*, adults 72 h after exposure to *Itea virginica* 'Little Henry' leaves from plants treated 15 (acephate only), 25, or 45 days previously with the systemic insecticides dinotefuran (Safari) at 1.27 g/946 ml, thiamethoxam (Flagship) at 0.49 g/946 ml, and acephate at 0.85 g/946 ml.

	Mean (± SEM) Leaf Area (mm^2) Fed Upon by *S. frontalis* Adults after 72 h*	
Treatment	**25 DAA**	**45 DAA**
Thiamethoxam	1.1 ± 0.1 Bb	1.1 ± 0.1 Bb
Dinotefuran	2.6 ± 0.4 Bb	3.5 ± 0.7 Bb
Acephate	64.7 ± 14.0 Aa	13.8 ± 1.7 Bb**
Water control	89.3 ± 15.2 Aa	71.3 ± 10.0 Aa

* Within a column for each application interval (25 or 45 DAA), mean values followed by the same uppercase letter are not significantly different ($P > 0.05$). Across rows, mean values followed by the same lowercase letter are not significantly different ($P > 0.05$). Significance was determined by Tukey's honestly significant difference test.

** Treatment with acephate at 0.85 g/946 ml at 45 DAA was replaced with treatment at 0.85 g/946 ml at 15 DAA due to reduced mortality of redheaded flea beetle adults 25 DAA.

the water control and the acephate treatment applied at the same rate at 25 DAA (Table 1). Hence, the efficacy of acephate applied as a drench at 0.85 g/946 ml decreased between 15 and 25 DAA based on redheaded flea beetle adult mortality.

Significant differences ($F = 10.42$; df = 63, 2; $P = 0.0020$) were found across the main effects of treatment and DAA on the leaf area fed upon by redheaded flea beetle adults. The leaf area fed upon across the application intervals was 13.8 ± 1.7 mm^2 at 15 DAA (acephate only; $n = 10$), 39.4 ± 7.9 mm^2 ($n = 40$) at 25 DAA, and 23.3 ± 6.9 mm^2 ($n = 30$) at 45 DAA after 72 h of exposure to the *I. virginica* leaves in the petri dishes. A significant ($F = 5.29$; df = 63, 3; $P = 0.0026$) two-way interaction also was found between treatment and application interval (Table 2). The treatments with dinotefuran at 1.27 g/946 ml and thiamethoxam at 0.49 g/946 ml resulted in less leaf area fed upon by redheaded flea beetle adults compared with the acephate treatment at 0.85 g/946 ml and the water control 25 DAA (Table 2). The treatments with dinotefuran at 1.27 g/946 ml and thiamethoxam at 0.49 g/946 ml 45 DAA had significantly less leaf area fed upon by redheaded flea beetle adults compared with the water control. Acephate at 0.85 g/946 ml 15 DAA also resulted in significantly less leaf area fed upon by redheaded flea beetle adults compared with the water control and acephate applied at the same rate 25 DAA (Table 2).

Greenhouse experiments. Whole plant damage ratings were significantly different ($F = 69.87$; df = 31, 3; $P < 0.0001$) across the treatments, with higher whole plant damage ratings on *Itea* plants from the water control than those from the treatments with acephate at 0.85 g/946 ml, dinotefuran at 1.27 g/946 ml, and thiamethoxam at 0.49 g/946 ml. A significant effect of DAA ($F = 5.54$; df = 31, 2;

Table 3. Greenhouse experiments with treatment, days after application (DAA), and mean whole plant damage ratings of *Itea virginica* 'Little Henry' plants exposed to field-collected redheaded flea beetle, *Systena frontalis*, adults ($n = 8$) for 15 days. Plants were previously treated 15 (acephate only), 25, or 45 days with the systemic insecticides dinotefuran (Safari) at 1.27 g/946 ml, thiamethoxam (Flagship) at 0.49 g/946 ml, and acephate at 0.85 g/946 ml.

	Mean (± SEM) Whole Plant Damage Ratings of *I. virginica* Plants Exposed to *S. frontalis* Adults*	
Treatment	**25 DAA**	**45 DAA**
Dinotefuran	0.0 ± 0.0 c	0.0 ± 0.0 c
Thiamethoxam	0.0 ± 0.0 c	0.0 ± 0.0 c
Acephate	1.8 ± 0.2 b	0.8 ± 0.2 b**
Water control	2.8 ± 0.4 a	2.2 ± 0.2 a

* Mean whole plant damage ratings: 0 = 0% leaf damage, 1 = 1–10% leaf damage, 2 = 11–20% leaf damage, 3 = 21–30% leaf damage, 4 = 31–40% leaf damage, 5 = 41–50% leaf damage, 6 = 51–60% leaf damage, 7 = 61–70% leaf damage, 8 = 71–80% leaf damage, 9 = 81–90% leaf damage, and 10 = 91–100% leaf damage. A whole plant damage rating of <1% was rated as 0. Within a column for each application interval (25 or 45 DAA), mean values followed by the same letter are not significantly different ($P > 0.05$) as determined by Tukey's honestly significant difference test.

** Treatment with acephate at 0.85 g/946 ml at 45 DAA was replaced with treatment at 0.85 g/946 ml at 15 DAA due to an increase in the whole plant damage rating 25 DAA.

$P = 0.0250$) also was found on the whole plant damage ratings (Table 3). However, no significant ($P > 0.05$) two-way interaction (treatment × DAA) was found.

The number of leaves fed upon by redheaded flea beetle adults was significantly different ($F = 28.5$; df = 31, 3; $P < 0.0001$) across the treatments, with more leaves fed upon on *Itea* plants associated with the water control than with the treatments of acephate at 0.85 g/946 ml, dinotefuran at 1.27 g/946 ml, and thiamethoxam at 0.49 g/946 ml. A significant effect of DAA ($F = 6.14$; df = 31, 2; $P = 0.0189$) also was found on the number of leaves fed upon (Table 4). However, no significant ($P > 0.05$) two-way interaction (treatment × DAA) was found.

The leaf area fed upon by redheaded flea beetle adults was significantly different ($F = 108.54$; df = 28, 3; $P < 0.0001$) across the treatments, with more leaf area fed upon from leaves of *Itea* plants from the water control than those from the treatments with acephate at 0.85 g/946 ml, dinotefuran at 1.27 g/946 ml, and thiamethoxam at 0.49 g/946 ml. A significant effect of DAA ($F = 35.8$; df = 28, 2; $P < 0.0001$) also was found on the leaf area fed upon, and the two-way interaction (treatment × DAA) also was significant ($F = 12.05$; df = 28, 3; $P < 0.0001$) (Table 5).

Discussion

The results of our study demonstrate that the systemic insecticides dinotefuran and thiamethoxam provided sufficient mortality of redheaded flea beetle adults

Table 4. Greenhouse experiments with treatment, days after application (DAA), and mean number of leaves fed upon from *Itea virginica* 'Little Henry' plants exposed to field-collected redheaded flea beetle, *Systena frontalis*, adults ($n = 8$) for 15 days. Plants were previously treated 15 (acephate only), 25, or 45 days with the systemic insecticides dinotefuran (Safari) at 1.27 g/946 ml, thiamethoxam (Flagship) at 0.49 g/946 ml, and acephate at 0.85 g/946 ml.

	Mean (± SEM) Number of *I. virginica* Leaves Fed Upon by *S. frontalis* Adults*	
Treatment	**25 DAA**	**45 DAA**
Dinotefuran	2.4 ± 0.5 c	2.8 ± 0.6 b
Thiamethoxam	2.6 ± 0.2 c	3.0 ± 0.6 b
Acephate	17.8 ± 3.3 b	7.0 ± 1.6 b**
Water control	34.8 ± 7.2 a	22.2 ± 2.2 a

* Within a column for each application interval (25 or 45 DAA), mean values followed by the same letter are not significantly different ($P>0.05$) as determined by Tukey's honestly significant difference test.
** Treatment with acephate at 0.85 g/946 ml at 45 DAA was replaced with treatment at 0.85 g/946 ml at 15 DAA due to an increase in the number of leaves fed upon 25 DAA.

and protected leaves, based on the number of leaves and leaf area fed upon in the laboratory and greenhouse experiments, from redheaded flea beetle adult feeding damage for up to 45 DAA. The results of our study are important to nursery producers because we have determined that the systemic insecticides dinotefuran and thiamethoxam can protect plants for 45 DAA from damage caused by redheaded flea beetle adults. Therefore, application of these systemic insecticides may permit salability of container-grown nursery crops susceptible to redheaded flea beetle adult feeding, such as, *Cornus* spp., *Hydrangea* spp., *Itea* spp., and *Weigela* spp. (Cloyd and Herrick 2018).

Dinotefuran and thiamethoxam are neonicotinoid insecticides, with similar molecular and physical properties and modes of action. The mode of action involves modulation of the nicotinic acetylcholine receptor (Bai et al. 1991, Ihara and Matsuda 2018, Maienfisch et al. 2001). However, the water solubility of these systemic insecticides differs (Kurwadkar et al. 2013). For instance, the water solubilities of dinotefuran and thiamethoxam are 39,830 and 4,100 ppm (39.0 and 4.1 g/L at 20°C), respectively (Byrne et al. 2010, Jeschke and Nauen 2008, Wakita et al. 2005). These systemic insecticides are converted into metabolites, which are more toxic to insects than the original active ingredients (Bennett 1957, Casida 2010, Cloyd et al. 2011, Nauen et al. 1998, Sur and Stork 2003). For example, dinotefuran is converted into UF (1-methyl-3-(tetrahydro-3-furylmethyl) urea) and DN (1-methyl-3-(tetrahydro-3-furyl-methyl) guanidium dihydrogen) (Liu et al. 2018), and thiamethoxam is converted into clothianidin (Nauen et al. 2003).

Acephate is an organophosphate insecticide that has minimal systemic activity within plants but is converted into the metabolite methamidophos, which is highly mobile in plants and has greater activity against insect pests, such as whiteflies,

Table 5. Greenhouse experiments with treatment, days after application (DAA), and mean leaf area fed upon from *Itea virginica* 'Little Henry' plants exposed to field-collected redheaded flea beetle, *Systena frontalis*, adults ($n = 8$) for 15 days. Plants were previously treated 15 (acephate only), 25, or 45 days with the systemic insecticides dinotefuran (Safari) at 1.27 g/946 ml, thiamethoxam (Flagship) at 0.49 g/946 ml, and acephate at 0.85 g/946 ml.

	Mean (± SEM) Leaf Area (mm^2) Fed Upon by *S. frontalis* Adults*	
Treatment	**25 DAA**	**45 DAA**
Dinotefuran	2.2 ± 0.5 Cc	2.4 ± 0.4 Cc
Thiamethoxam	2.6 ± 0.6 Cc	2.8 ± 0.5 Cc
Acephate	238.4 ± 20.2 Bb	32.4 ± 22.0 Bc**
Water control	519.2 ± 32.1 Aa	289.6 ± 53.9 Ab

* Within a column for each application interval (25 or 45 DAA), mean values followed by the same uppercase letter are not significantly different ($P > 0.05$). Across rows, mean values followed by the same lowercase letter are not significantly different ($P > 0.05$). Significance was determined by Tukey's honestly significant difference test.
** Treatment with acephate at 0.85 g/946 ml at 45 DAA was replaced with treatment at 0.85 g/946 ml at 15 DAA due to an increase in the leaf area fed upon 25 DAA.

than does acephate (Bull 1979, Cresswell et al. 1994, Lin et al. 2020, Trevizan et al. 2005). Acephate has a water solubility of 790,000 ppm (79 g/L at 20°C) (Lewis et al. 2016). Hence, this systemic insecticide moves rapidly throughout the plant. Systemic insecticides with high water solubility are quickly translocated throughout plants, reaching plant tissues such as leaves and stems where insect pests feed (Burt et al. 1965, Cloyd et al. 2011, Ferreira and Seiber 1981, Reynolds and Metcalf 1962, Schuster and Morris 2002). Cloyd and Herrick (2023) found that plants treated with acephate were protected from redheaded flea beetle adult feeding damage 7 DAA. However, in the current study, acephate did not protect plants from redheaded flea beetle adult feeding damage 25 DAA. Nonetheless, acephate protected plants from feeding damage 15 DAA. Therefore, acephate, when applied as a drench at 0.85 g/946 ml, does not protect the leaves of *I. virginica* 'Little Henry' plants from redheaded flea beetle adult feeding between 15 and 25 DAA. Consequently, the ability of acephate to protect plants from redheaded flea beetle adult feeding damage diminishes between 15 and 25 DAA. Although there is a cost difference among the systemic insecticide products, with acephate less expensive ($0.05 per g) than dinotefuran ($0.47 per g) and thiamethoxam ($0.68 per g) (Hummert International 2023 Commercial Catalog, Earth City, MO), the cost difference may be offset by the increased labor involved in reapplying acephate during the growing season.

In conclusion, our study demonstrates that the systemic insecticides dinotefuran and thiamethoxam can protect plants from redheaded flea beetle adult feeding damage for 45 DAA, resulting in long-term protection during the growing season. The 45-d residual activity may allow plants to be sold and shipped from the nursery operation before protection from redheaded flea beetle adult feeding declines later in the growing season.

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