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Overwintering, Host-Plant Selection, and Insecticide Susceptibility of *Systena frontalis* (Coleoptera: Chrysomelidae): A Major Insect Pest of Nursery Production Systems

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Abstract

Systena frontalis (F.) is a major insect pest of nursery production systems in the Midwest and Northeastern regions of the United States with the adults feeding on plant leaves, which reduces salability. However, there is conflicting information on overwintering, and no information on host-plant selection or insecticide susceptibility of *S. frontalis* adults. Therefore, we conducted a series of experiments under greenhouse, laboratory, and field conditions from 2015 to 2019. The overwintering experiment was isolated in a greenhouse to assess adult emergence from growing medium of containerized plants collected from a wholesale nursery. We found that *S. frontalis* overwinters in growing medium based on adults captured on yellow sticky cards and the presence of adults on new plant growth. Host-plant selection experiments were conducted at the wholesale nursery and under laboratory conditions to determine feeding selection based on *S. frontalis* adult feeding damage on whole plants using a foliar damage ranking scale for different cultivars of *Itea virginica* L., *Hydrangea paniculata* Siebold, *Weigela florida* (Bunge), and *Cornus sericea* L., plants. We found that *S. frontalis* adults exhibited no preference for the leaves of the plant species or cultivars tested in the field or laboratory. Insecticide efficacy experiments were conducted under field and laboratory conditions. In the field experiments, the insecticides acetamiprid, dinotefuran, and *Isaria fumosorosea* (Wize) (Hypocreales: Clavicipitaceae) provided better protection of plants from *S. frontalis* adult feeding than the untreated check. In the laboratory experiments, the acetamiprid and pyrethrins with canola oil treatments provided the highest percent *S. frontalis* adult mortality.

Key words: efficacy, feeding preference, ornamental, redheaded flea beetle, survival

Systena frontalis (F.), commonly referred to as the redheaded flea beetle, is a major insect pest of containerized nursery production systems in the Midwest and Northeastern regions of the United States. Redheaded flea beetle adults feed on the foliage of a broad range of ornamental plants grown in nursery production systems with *Cornus* spp., *Hydrangea* spp., *Itea* spp., and *Weigela* spp., highly susceptible to adult feeding (Cloyd and Herrick 2018a). Adults cause damage when feeding on the foliage of ornamental plants, which can reduce aesthetic quality and salability, resulting in a substantial economic loss. Economic assessments of redheaded flea beetle adult feeding damage have resulted in losses of $483,871 or 11% of the overall sale of plant material per year at Loma Vista Nursery (Ottawa, KS; T. Minter, Loma Vista Nursery, personal communication). Studies have evaluated the potential of redheaded flea beetle adults and larvae to feed on corn, *Zea mays* L. (Peters and Barton 1969, Jacques and Peters 1971). However, there is a general lack of information associated with the biology and origin of the redheaded flea beetle. For instance, there are extension-related publications, indicating that the redheaded flea beetle is native to the United States (Van Meter and Johnson 2014, Lauderdale 2017), but there is no scientific data to verify whether the redheaded flea beetle is actually native or a non-native (invasive) species.

The life cycle of the redheaded flea beetle includes an egg, larva, pupa, and adult stage. Eggs are oblong, approximately 1 mm long, and creamy white. Larvae are 5–10 mm in length, creamy white, and have a brown head capsule (Cloyd and Herrick 2018a). There are three larval instars with larvae residing in the growing medium/soil. The larvae feed on plant roots, although the extent of plant damage is not known. There is minimal information available associated with the pupal stage (Cloyd and Herrick 2018a,b). Adult females are generally larger than males. The adults are 5 mm long and shiny black with a red head. They possess an enlarged hind femur, which allows them to jump like a flea, hence the common name (Cloyd and Herrick 2018a). The jumping behavior of adults helps them escape from external stimuli, such as spray applications of insecticides, which can influence the efficacy of insecticide applications (R. Cloyd, personal observation).

Redheaded flea beetle adults feed on the upper and lower leaf surfaces, resulting in necrotic leaf spotting and/or holes in leaves. Feeding damage can vary depending on the plant species fed upon (N. J. Herrick and R. A. Cloyd, personal observation). There is conflicting information on overwintering, and no information on host-plant selection or insecticide susceptibility of redheaded flea beetle adults. Therefore, the objectives of the following study involved a multiple approach to improve management of the redheaded flea beetle, which included 1) determine if the redheaded flea beetle overwinters in plastic containers with growing medium and plants grown under nursery conditions, 2) assess if there are differences in host-plant selection by adults on ornamental species and cultivars under nursery and laboratory conditions, 3) determine the effectiveness of various insecticides in preventing damage to plant foliage by adults under nursery conditions, and 4) ascertain adult survival and efficacy of insecticides on field-collected populations of redheaded flea beetle adults under laboratory conditions.

Materials and Methods

The following study consisted of a series of experiments conducted from 2015 through 2019 under greenhouse, laboratory, and field conditions to obtain quantitative information on overwintering, host-plant selection, and insecticide susceptibility of redheaded flea beetle, *Systena frontalis*, adults.

Overwintering Experiment (Greenhouse)

This experiment was designed to visually observe if the redheaded flea beetle overwinters in plastic containers with plants containing growing medium (pine bark, sand, gypsum, pelletized lime, and Harrell's 18-4-8 controlled-release fertilizer) grown under nursery conditions. Plants grown in 9.5-liter plastic containers were obtained from Loma Vista Nursery (a 125 ha wholesale, container production operation of ornamental plants) prior to adult redheaded flea beetle activity in the field (before June; T. Minter, personal communication). Ten plastic containers of *Hydrangea paniculata* 'Vanilla-Strawberry' and 20 plastic containers of *Itea virginica* 'Little Henry' were obtained from the nursery. The aboveground plant portions were removed at the growing medium surface and the plastic containers were isolated in a research greenhouse at Kansas State University (Manhattan, KS). The environmental conditions inside the greenhouse during the experiment were 22–24°C, 50–60% relative humidity, and natural daylight.

Four bamboo stakes were inserted into the growing medium on opposite sides of each plastic container. Yellow sticky cards (12.5 × 7.5 cm) were attached to the bamboo stakes just above the growing medium surface using clothespins. The plastic containers were irrigated with approximately 1 liter of tap water every two days. New plant growth (leaves) served as a food source for any emerging redheaded flea beetle adults. The yellow sticky cards and new plant growth were inspected daily for one month to determine whether redheaded flea beetle adults emerged from the growing medium in the plastic containers. The presence of redheaded flea beetle adults on the new plant growth or yellow sticky cards would indicate that overwintering occurred in the growing medium of the plastic containers. Conversely, the absence of redheaded flea beetle adults on the new growth or yellow sticky cards would indicate that no overwintering occurred in the growing medium of the plastic containers.

Host-Plant Selection Experiments (Field)

Host-plant selection experiments were conducted at Loma Vista Nursery over the duration of adult redheaded flea beetle activity (June through September; T. Minter, personal communication). The experiments were conducted in 2015 and 2017–2019 to determine whether there were differences in host-plant selection by redheaded flea beetle adults based on foliar feeding damage. In each year, two plots were established; each consisting of 25–40 plants representing different plant species and/or cultivars grown at the nursery in 9.5 liter or 18.9 liter plastic containers. Plants were randomly positioned within each plot. Plot areas were 20.2 m^2 (4.5 × 4.5 m) for 25 plants and 34.1 m^2 (6.7 × 5.1 m) for 40 plants, with approximately 0.6 m between individual plastic containers and five replicates per plant species and/or cultivar per plot. Plants were pruned, watered, and fertilized during each experiment based on standard nursery production practices. The experiments were set up as a completely randomized design. The genus, species, and cultivars tested each year are listed in Table 1.

Plant damage estimates were conducted weekly or biweekly (depending on weather) and based on direct visual observations of the foliage of whole plants. The plant damage estimates were conducted from 7 to 20 wk, beginning when redheaded flea beetle adults were initially active (June) and concluding when redheaded

Table 1. Genus, species, and cultivars tested in 2015 and 2017–2019 to determine the potential differences in host-plant selection by *Systena frontalis* adults based on foliar feeding damage rankings to plants located at Loma Vista Nursery (Ottawa, KS)

Year	Genus	Species	Cultivar
2015	*Weigela*	*florida*	Fine Wine
			Minuet
			Red Prince
			Spilled Wine
			Wine and Roses
2017	*Hydrangea*	*paniculata*	Bobo
			Lime Light
			Little Quick Fire
			Vanilla-Strawberry
	Itea	*virginica*	Little Henry
	Weigela	*florida*	Fine Wine
			Minuet
2018	*Hydrangea*	*paniculata*	Bobo
			Lime Light
			Little Quick Fire
			Vanilla-Strawberry
	Itea	*virginica*	Little Henry
	Weigela	*florida*	Fine Wine
			Minuet
2019	*Cornus*	*sericea*	Kelseyi
	Hydrangea	*paniculata*	Bobo
			Lime Light
			Little Quick Fire
			Vanilla-Strawberry
	Itea	*virginica*	Little Henry
	Weigela	*florida*	Fine Wine
			Wine and Roses

flea beetle adult activity subsided (September). We used a foliar plant damage ranking scale, based on adult feeding, from 0 to 10, where 0 = 0% leaf damage, 1 = >0–10% 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.

The ranked data were analyzed, based on the level of foliar plant damage caused by redheaded flea beetle adult feeding associated with each cultivar at the end of the growing season, using PROC GLIMMIX at $\alpha = 0.05$ (SAS Institute 2012). Individual treatment means were separated using Tukey's honestly significant difference test when the analysis of variance (ANOVA) indicated a significant main effect. The analysis of the ranked data (i.e., categorical/ordinal data) using parametric statistics avoided a type I error (Larrabee et al. 2014).

Host-Plant Selection Experiments (Laboratory)

Two laboratory experiments were conducted to determine whether there were any differences in host-plant selection by field-collected redheaded flea beetle adults. The experiments were conducted in the Kansas State University, Horticultural and Plant Protection Laboratory, in the Department of Entomology (Manhattan, KS). Ten redheaded flea beetle adults were collected on 3 July 2018 for the first experiment and on 13 July 2018 for the second experiment from plots with *I. virginica* plants at Loma Vista Nursery. Adults were collected into 9-dram (33 ml) plastic vials using an aspirator. The vials contained a 1-cm section of moistened cotton-wick (Fisher Scientific, Pittsburgh, PA). In addition, 10 fully expanded leaves of similar age and size from designated plants were collected from the field and placed into 3.8-liter Ziploc plastic re-sealable bags (SC Johnson, Racine, WI).

In the first host-plant selection experiment, leaves from *I. virginica* 'Little Henry', *Hydrangea paniculata* 'Vanilla-Strawberry', *H. paniculata* 'Little Quick Fire', and *Weigela florida* 'Fine Wine' were used. These cultivars were selected based on availability. None of the plants that leaves were collected from were treated with any pesticides. The second experiment was performed similar to the first experiment; however, leaves from *H. paniculata* 'Lime Light', *H. paniculata* 'Bobo', *H. paniculata* 'Little Quick Fire', and *W. florida* 'Spilled Wine' were used based on availability.

Redheaded flea beetle adults and plant leaves were transported to Manhattan, KS, where adults were starved for 24 h at 21–23°C, 50–60% relative humidity, and under constant light. Leaves were placed into a refrigerator set at 7°C, 38% relative humidity, and under constant darkness. Prior to use in the experiment, leaves were removed from the refrigerator and allowed to acclimate to room temperature (21–23°C) for 1 h. Afterward, multiple-choice tests were conducted to simulate groups of plants that would be simultaneously available for feeding under field conditions by randomly placing one leaf from each of the four cultivars on opposing sides of a 14-cm plastic Petri dish with a lid. After leaf placement, one redheaded flea beetle adult was released into the center of the Petri dish and the lid was replaced. There were 10 replications per cultivar. After 24 h, the amount of leaf material consumed was assessed by placing a transparent section of graph paper, containing 4 mm^2 squares, over each leaf and estimating the total mm^2 of leaf material consumed, which was similar to the method performed by Herrick et al. (2012). The data were normalized using a Log_{10+1} transformation and analyzed using ANOVA (PROC GLM, $\alpha = 0.05$; SAS Institute 2012).

Table 2. Year, treatment/active ingredient, trade name, label rate (per 378 liter), application rate (per 3.7 liter), and manufacturer associated with determining the effect of various insecticides in preventing foliar plant damage caused by *Systena frontalis* adults under field conditions

Year	Treatment/active ingredient	Trade name	Label rate (378 liter)	Application rate (3.7 liter)	Manufacturer
2016	Acetamiprid	TriStar	12.0 oz	3.4 g	Cleary Chemicals, LLC, Dayton, NJ
	Bacillus thuringiensis subsp. *galleriae* (Strain SDS-502)	BeetleGONE	0.25–1.5 lbs	10.0 g	Phyllom BioProducts Corp., Oakland, CA
	Dinotefuran	Safari	8.0 oz	2.2 g	Valent USA Corp., Walnut Creek, CA
	Isaria fumosorosea (Apopka Strain 97)	Preferal	1.0 lb	4.5 g	SePro Corp., Carmel, IN
	Tolfenpyrad	Hachi-Hachi	21.0 fl oz	6.2 ml	SePro Corp., Carmel, IN
2017	Beta-cyfluthrin	Tempo SC Ultra	11.8 fl oz	3.5 ml	Bayer Environmental Science, Cary, NC
	Chlorantraniliprole + polyether-polymethylsiloxane-copolymer	Acelepryn + Capsil	8.0 + 6.0 fl oz	2.4 + 1.8 ml	Syngenta Crop Protection, Inc., Greensboro, NC + Aquatrols, Paulsboro, NJ
	Cyantraniliprole	Mainspring	8.0 fl oz	2.4 ml	Syngenta Crop Protection, Inc., Greensboro, NC
	Cyantraniliprole + polyether-polymethylsiloxane-copolymer	Mainspring + Capsil	8.0 + 6.0 fl oz	2.4 + 1.8 ml	Syngenta Crop Protection, Inc., Greensboro, NC + Aquatrols, Paulsboro, NJ
	Cyclaniliprole	Sarisa	16.4–27 fl oz	22.7 ml	OHP, Inc., Bluffton, SC
	Polyether-polymethylsiloxane-copolymer	Capsil	6.0 fl oz	1.8 ml	Aquatrols, Paulsboro, NJ
	Tetraniliprole	BCS-CL73507 SC	16.8 fl oz	3.5 ml	Bayer Environmental Science, Cary, NC

Insecticide Efficacy Experiments (Field)

From June through October of 2016 and 2017, field experiments were conducted to evaluate the effect of various insecticides in preventing foliar plant damage caused by redheaded flea beetle adults under nursery conditions when adults were active (June through September). The insecticides (treatments) tested are presented in Table 2. In 2016, two plots were set up approximately 15.2 m apart, with 60 *I. virginica* 'Little Henry' plants randomly assigned within each plot, and 0.3 m between individual plants. One plot was 2 × 5 plastic containers (approximately 0.8 × 2.4 m [width × length]) and designated for the untreated control plants, while the treatment plants were set up as a 5 × 10 plastic container plot (approximately 0.8 × 5.0 m [width × length]). Plants were in 18.9-liter plastic containers and pruned, watered, and fertilized the same for each experiment based on standard production practices. Plants were 45.5–55.8 cm in height when sprayed with the designated insecticide treatments. In 2016, there were five insecticide treatments (Table 2), and an untreated check, with 10 replications per treatment. In 2017, a similar experiment was conducted; however, 40 *I. virginica* 'Little Henry' plants were used based on availability. There were four insecticide treatments, two insecticide and surfactant combination treatments, one surfactant treatment, and a water control treatment (Table 2) with five replications per treatment.

Both experiments were set up as a completely randomized design. The treatments were applied weekly using 8-liter plastic poly sprayers (H. D. Hudson Manufacturing Comp., Lowell, MI) with about 120 ml of spray solution applied to each plant, which was a sufficient volume to cover all plant parts (leaves and stem) and the growing medium surface. Weekly or biweekly estimates (depending on weather) of redheaded flea beetle adult feeding damage to the foliage of each plant were assessed using the same ranking scale as described previously.

The ranked data were analyzed, based on the level of plant damage caused by redheaded flea beetle adult feeding at the end of the experiments, using PROC GLIMMIX at $\alpha = 0.05$ (SAS Institute 2012). Individual treatment means were separated using Tukey's honestly significant difference test when ANOVA indicated a significant main effect. The analysis of the ranked data (i.e., categorical/ordinal data) using parametric statistics avoided a type I error (Larrabee et al. 2014).

Survival and Insecticide Efficacy Experiments (Laboratory)

The following laboratory experiments were conducted in 2019 and evaluated survival and efficacy of insecticides on field-collected populations of redheaded flea beetle adults. Redheaded flea beetle adults were collected on 1 and 8 October 2019 from containerized *H. paniculata* 'Little Quick Fire' plants at Loma Vista Nursery. The collected adults were transported to the Horticultural Entomology and Plant Protection Laboratory in the Department of Entomology at Kansas State University and maintained on leaves of *I. virginica* 'Little Henry' at 21–23°C, 50–60% relative humidity, and under constant light. Specimens of redheaded flea beetle adults used in the experiments are deposited as voucher number 258 in the Kansas State University Museum of Entomological and Prairie Arthropod Research (Manhattan, KS). There were three experiments conducted in glass Petri dishes (100 × 15 mm), lined with a 9-cm piece of P8 Fisherbrand filter paper (Fisher Scientific, Pittsburgh, PA).

The experiment to determine survival of field-collected redheaded flea beetle adults in the laboratory was set up as a completely randomized design and was performed to assess the length of time future experiments should be conducted to obtain reliable estimates of survival, inclusive of natural mortality, of field-collected redheaded flea beetle adults. This was important because the age of the field-collected individuals was unknown.

There were two treatments with 10 replications per treatment. The first treatment consisted of 10 Petri dishes. Each Petri dish contained one redheaded flea beetle adult and a *H. paniculata* 'Little Quick Fire' leaf as a food source. The second treatment also included 10 Petri dishes, each containing one redheaded flea beetle adult, but no leaf was provided. Assessments of adult survival were conducted every 24 h for 120 h. Percent redheaded flea beetle adult survival was calculated by dividing the number of live 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 ANOVA (PROC GLM, $\alpha = 0.05$) with treatment or exposure type (with a leaf and without a leaf) as the main effects. Treatment means were separated using Fisher's least significant difference test when ANOVA indicated a significant main effect (SAS Institute 2012).

The first laboratory experiment to evaluate the efficacy of insecticides (based on mortality) on field-collected populations of redheaded flea beetle adults included three insecticide treatments: cyantraniliprole (Mainspring: Syngenta Crop Protection, LLC, Greensboro, NC), dinotefuran (Safari: Valent U.S.A. Corp., Walnut Creek, CA), and acetamiprid (TriStar: Cleary Chemical Corp., Dayton, NJ) prepared in 500 ml of tap water. There were four treatments, including a water control, with five replications per treatment. The insecticide treatments and application rates were as follows: cyantraniliprole (Mainspring) at 8 fl oz/100 gallons (0.31 ml/500 ml), dinotefuran (Safari) at 8 oz/100 gallons (0.29 g/500 ml), and acetamiprid (TriStar) at 12 oz/100 gallons (0.44 g/500 ml).

The second laboratory experiment to evaluate the efficacy of insecticides on field-collected populations of redheaded flea beetle adults included two insecticide treatments: cyclaniliprole (Sarisa: OHP Inc., Bluffton, SC) and pyrethrins with canola oil (Pycana: OHP Inc., Bluffton, SC) prepared in 500 ml of tap water. There were five treatments, including a water control, with five replications per treatment. The insecticide treatments and application rates were as follows: cyclaniliprole (Sarisa) at 16.4 fl oz/100 gallons (0.64 ml/500 ml), cyclaniliprole (Sarisa) at 22 fl oz/100 gallons (0.85 ml/500 ml), cyclaniliprole (Sarisa) at 27 fl oz/100 gallons (1.05 ml/500 ml), and pyrethrins with canola oil (Pycana) at 18.9 ml/946 ml (9.98 ml/500 ml)

Both insecticide efficacy experiments were set up as a completely randomized design with one group provided with a *W. florida* 'Fine Wine' (first experiment) or 'Wine and Roses' (second experiment) leaf (to simulate exposure to the treatments through ingestion) and a second group without a leaf (to simulate contact exposure to the treatments). For the group without the leaf, a sterile, 1-ml plastic syringe (BD: Becton, Dickinson and Company, Franklin Lakes, NJ) was used to dispense a 1-ml aliquot of solution associated with each treatment onto the filter paper, ensuring that the solution was evenly distributed over the entire filter paper. For the group with a *W. florida* 'Fine Wine' or 'Wine and Roses' leaf, individual leaves were immersed for five seconds in the appropriate treatment solution and then air-dried for 15 min before placing on top of the filter paper in each Petri dish. One redheaded flea beetle adult (starved for 24 h) was randomly selected from the collected individuals and transferred into each Petri dish using an aspirator and a 9-dram (33 ml) plastic vial. The Petri dishes were then covered with a lid and maintained in the laboratory at 21–23°C, 50–60% relative humidity, and under constant light for 72 h. The number of dead redheaded flea beetle adults was recorded 24, 48, and 72 h to determine mortality of redheaded flea beetle adults after exposure to the insecticide treatments.

Percent 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 ANOVA (PROC GLM, $\alpha = 0.05$) with treatment or exposure type (leaf dip or filter paper application) as the main effects. Treatment means were separated using Fisher's least significant difference test when ANOVA indicated a significant main effect (SAS Institute 2012).

Results

Overwintering Experiment (Greenhouse)

Based on our observations, no redheaded flea beetle adults were collected from the plastic containers associated with *H. paniculata* 'Vanilla-Strawberry' plants. However, 10 redheaded flea beetle adults were collected from the plastic containers of *I. virginica* 'Little Henry' plants. Five adults were captured on the yellow sticky cards, and five adults were collected from new plant growth. Therefore, we determined that redheaded flea beetle overwinters in the growing medium.

Host-Plant Selection Experiments (Field and Laboratory)

In 2015, there was no significant difference ($P > 0.05$) in the level of plant damage caused by redheaded flea beetle adults feeding on the leaves of the *W. florida* cultivars tested (Table 1) under nursery conditions. However, in 2017, 2018, and 2019, there were significant differences (2017: $F = 4.11$; df = 6, 54; $P = 0.0018$; 2018: $F = 8.6$; df = 6, 54; $P < 0.0001$; 2019: $F = 3.4$; df = 7, 63; $P = 0.0039$) in the level of plant damage caused by redheaded flea beetle adults feeding on the leaves of the species and cultivars tested under nursery conditions (Table 3). Nonetheless, despite significant differences in the rank of plant damage caused by redheaded flea beetle adults, there was no apparent preference for any specific cultivar in a given year (Table 3).

Furthermore, in the first and second laboratory experiments designed to assess host-plant selection by field-collected redheaded flea beetle adults, there was no significant difference ($P > 0.05$) in feeding by redheaded flea beetle adults on leaves of the plant species and cultivars tested.

Insecticide Efficacy Experiments (Field)

There was a significant difference in the rank of foliar plant feeding damage caused by redheaded flea beetle adults on *I. virginica* 'Little Henry' plants treated with weekly or biweekly spray applications of the insecticides in 2016 ($F = 3.94$; df = 5, 45; $P = 0.0048$) and 2017 ($F = 2.74$; df = 7, 28; $P = 0.027$; Table 4). In 2016, the acetamiprid at 3.4 g/3.7 liter, dinotefuran at 2.2 g/3.7 liter, and *Isaria fumosorosea* Apopka Strain 97 at 4.5 g/3.7 liter treatments significantly reduced foliar plant feeding damage by redheaded flea beetle adults compared with the untreated check. However, in 2017, none of the insecticide treatments ranked were significantly different ($P > 0.05$) from the water control (Table 4).

Survival and Insecticide Efficacy Experiments (Laboratory)

In the survival experiment, there was a significant effect of treatment (with a leaf or without a leaf as a food source) on survival of field-collected redheaded flea beetle adults ($F = 4.54$; df = 1, 24; $P = 0.035$) and a significant effect of time on survival of redheaded flea beetle adults (24, 48, 72, 96, 120, 144, 168, or 192 h [$F = 38.09$; df = 7, 24; $P < 0.0001$]), so the data were pooled within treatment and time because there was no significant two-way interaction ($P > 0.05$) between treatment and time (hours). Field-collected redheaded flea beetle adults survived significantly longer when provided with a *H. paniculata* 'Little Quick Fire' leaf as a food source (62.5 ± 5.5% [mean ± SEM]; $n = 20$) compared with no leaf provided (52.5 ± 5.6%; $n = 20$). Furthermore, survival of field-collected redheaded flea beetle adults significantly decreased after 96 h and was significantly lower at 120 h and longer, with or without a *H. paniculata* 'Little Quick Fire' leaf (Fig. 1). Moreover, survival was 95 ± 5.0% ($n = 20$) after 72 h, with or without a *H. paniculata* 'Little Quick Fire' leaf (Fig. 1). Therefore, the experiments that follow were not conducted any longer than 72 h from the date of collecting redheaded flea beetle adults in the field.

In the first experiment associated with insecticide efficacy on field-collected redheaded flea beetle adults (unknown sex and age), there was a significant difference in percent mortality between the leaf dip (40 ± 6.4%; $n = 60$) and filter paper (25 ± 5.6%; $F = 6.10$; df = 1,

Table 3. Mean foliar feeding damage ranking and corresponding percent foliar damage caused by *Systena frontalis* adults on four species and 10 cultivars of plants under field conditions at the end of 2017, 2018, and 2019 ($n = 10$)

Species	Cultivar	Mean foliar damage ranking and corresponding percent damage		
		2017	2018	2019
Cornus sericea	Kelseyi	—	—	0.0 (0%)b
Hydrangea paniculata	Bobo	1.0 (>0–10%)b	2.8 (11–20%)a	0.1 (>0–10%)ab
	Lime Light	1.0 (>0–10%)b	1.3 (>0–10%)c	0.3 (>0–10%)ab
	Little Lime	1.7 (>0–10%)a	—	—
	Little Quick Fire	1.0 (>0–10%)b	2.6 (11–20%)ab	0.3 (>0–10%)ab
	Vanilla-Strawberry	1.3 (>0–10%)ab	1.8 (>0–10%)bc	0.1 (>0–10%)ab
Itea virginica	Little Henry	1.3 (>0–10%)ab	1.8 (>0–10%)bc	0.6 (>0–10%)a
Weigela florida	Fine Wine	1.5 (>0–10%)ab	1.5 (>0–10%)c	0.0 (0%)b
	Minuet Dwarf	—	2.1 (11–20%)abc	—
	Wine and Roses	—	—	0.0 (0%)b

Means followed by the same letter within a year are not significantly different ($P > 0.05$) as determined by Tukey's honestly significant difference test. '—' indicates species not tested within a given year.

Table 4. Mean foliar feeding damage ranking and corresponding percent plant damage associated with *Systena frontalis* adults feeding on *Itea virginica* 'Little Henry' plants exposed to weekly spray applications of 10 insecticides under field conditions at the end of 2016 and 2017 (see Table 2 for application rates and manufacturer)

Year	Active ingredient	Trade name	*n*	Mean foliar damage ranking and corresponding percent plant damage
2016	Acetamiprid	TriStar	10	1.0 (>0–10%)b
	Bacillus thuringiensis subsp. *galleriae* (Strain SDS-502)	BeetleGONE	10	1.3 (>0–10%)ab
	Dinotefuran	Safari	10	1.0 (>0–10%)b
	Isaria fumosorosea (Apopka Strain 97)	Preferal	10	1.0 (>0–10%)b
	Tolfenpyrad	Hachi-Hachi	10	1.3 (>0–10%)ab
	Untreated check	—	10	1.5 (>0–10%)a
2017	Beta-cyfluthrin	Tempo SC Ultra	5	1.6 (>0–10%)b
	Chlorantraniliprole + polyether-polymethylsiloxane-copolymer	Acelepryn + Capsil	5	2.4 (11–20%)ab
	Cyantraniliprole	Mainspring	5	2.4 (11–20%)ab
	Cyantraniliprole + polyether-polymethylsiloxane-copolymer	Mainspring + Capsil	5	3.0 (21–30%)a
	Cyclaniliprole	Sarisa	5	2.4 (11–20%)ab
	Polyether-polymethylsiloxane-copolymer	Capsil	5	2.6 (11–20%)ab
	Tetraniliprole	BCS-CL73507 SC	5	2.0 (11–20%)ab
	Water control	—	5	2.0 (11–20%)ab

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

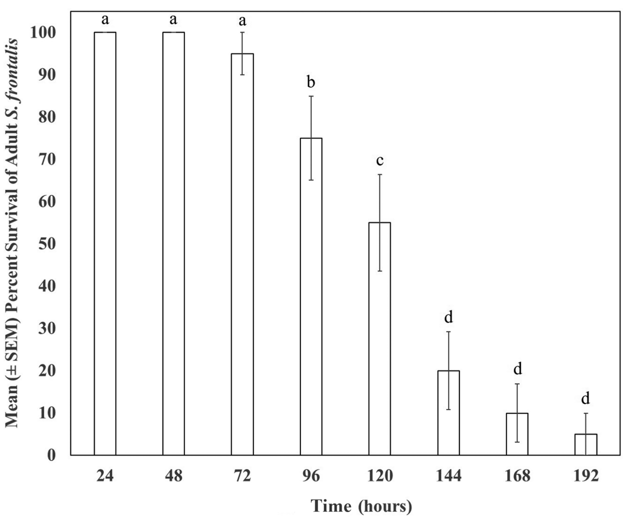

Fig. 1. Pooled mean (± SEM) percent survival of field-collected redheaded flea beetle, *Systena frontalis*, adults provided with a *Hydrangea paniculata* 'Little Quick Fire' leaf as a food source and no leaf as a food source (n = 20 within each time [hour] interval). Means followed by the same letter are not significantly different ($P > 0.05$) as determined by Fisher's least significant difference test. Vertical bars represent the standard error of the mean (SEM).

27; P = 0.015) applications. There was also a significant effect across the exposure durations (i.e., 24, 48, or 72 h) on percent redheaded flea beetle adult mortality where the highest percent mortality occurred after 72 h of exposure (50 ± 8.0%; n = 40), followed by 48 h of exposure (32.5 ± 7.5%), then 24 h of exposure (15 ± 5.7%; F = 11.07; df = 2, 27; $P < 0.0001$). Furthermore, there was a significant treatment × exposure duration interaction (F = 3.14; df = 6, 27; P = 0.0076), with the highest percent redheaded flea beetle adult mortality associated with the acetamiprid at 0.44 g/500 ml treatment after 48 h (90 ± 10%; n = 10). There was no significant ($P >$ 0.05) three-way interaction (i.e., treatment × application method × exposure duration).

Within the leaf dip applications, the acetamiprid at 0.44 g/500 ml treatment resulted in the highest percent redheaded flea beetle adult mortality, followed by dinotefuran at 0.29 g/500 ml and cyantraniliprole at 0.31 ml/500 ml (Fig. 2). Within the filter paper applications, the acetamiprid at 0.44 g/500 ml and dinotefuran at 0.29 g/500 ml treatments resulted in the highest percent redheaded flea beetle adult mortality, with the cyantraniliprole at 0.31 ml/500 ml treatment not significantly different from the water control (Fig. 2).

In the second experiment associated with insecticide efficacy on field-collected redheaded flea beetle adults, there was no significant difference ($P > 0.05$) between the leaf dip (41.3 ± 5.7%; n = 75) or filter paper (33.3 ± 5.5%) applications. However, there was a significant effect across the exposure durations on percent redheaded flea beetle adult mortality, where percent mortality increased as exposure to the treatments increased: 20 ± 8.2% (24 h of exposure), 36 ± 9.8% (48 h of exposure), and 44 ± 10.0% (72 h of exposure; F = 5.35; df = 2, 25; P = 0.0059; n = 25). There were no significant two- or three-way interactions ($P > 0.05$).

Exposure to the leaf dip applications resulted in the highest percent redheaded flea beetle adult mortality in the pyrethrins with canola oil at 9.98 ml/500 ml treatment, followed by cyclaniliprole at 1.05 ml/500 ml and cyclaniliprole at 0.64 ml/500 ml treatments, then cyclaniliprole at 0.85 ml/500 ml (Fig. 3). Exposure to the filter paper applications resulted in the highest percent redheaded flea beetle adult mortality in the pyrethrins with canola oil at 9.98 ml/500 ml treatment, followed by the cyclaniliprole at 0.85 ml/500 ml and cyclaniliprole at 0.64 ml/500 ml treatments. The cyclaniliprole at 1.05 ml/500 ml treatment had the lowest percent mortality across the treatments (Fig. 3).

Discussion

This is the first study associated with redheaded flea beetle, *S. frontalis*, adults to assess overwintering potential, host-plant selection, and insecticide susceptibility under greenhouse, laboratory, and field conditions. We determined, based on our observations, that redheaded

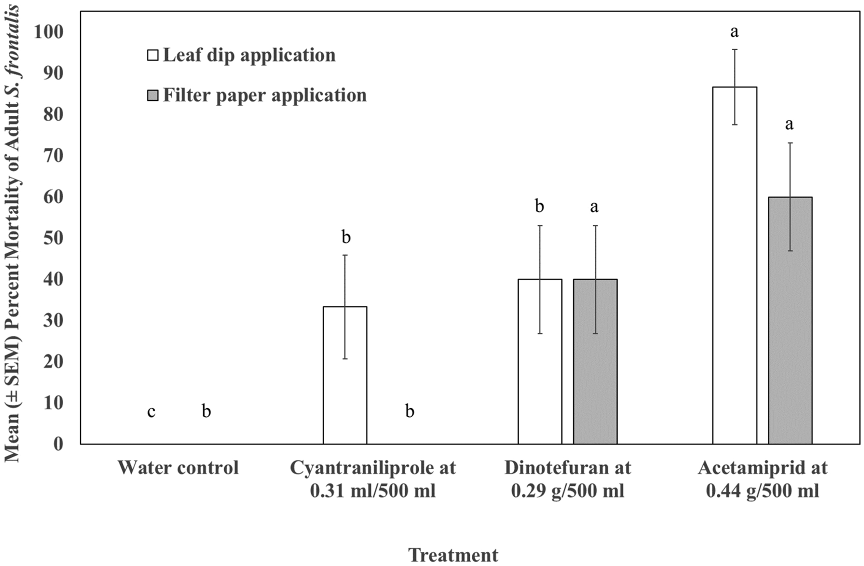

Fig. 2. Mean (± SEM) percent mortality of field-collected redheaded flea beetle, *Systena frontalis*, adults after exposure to leaf dip or filter paper applications associated with the following treatments: 1) water control, 2) cyantraniliprole (Mainspring) at 0.31 ml/500 ml, 3) dinotefuran (Safari) at 0.29 g/500 ml, and 4) acetamiprid (TriStar) at 0.44 g/500 ml after 24, 48, and 72 h (*n* = 5 within each treatment and an exposure type [leaf dip or filter paper application]). Means followed by the same letter within an exposure type are not significantly different (*P* > 0.05) as determined by Fisher's least significant difference test. Vertical bars represent the standard error of the mean (SEM).

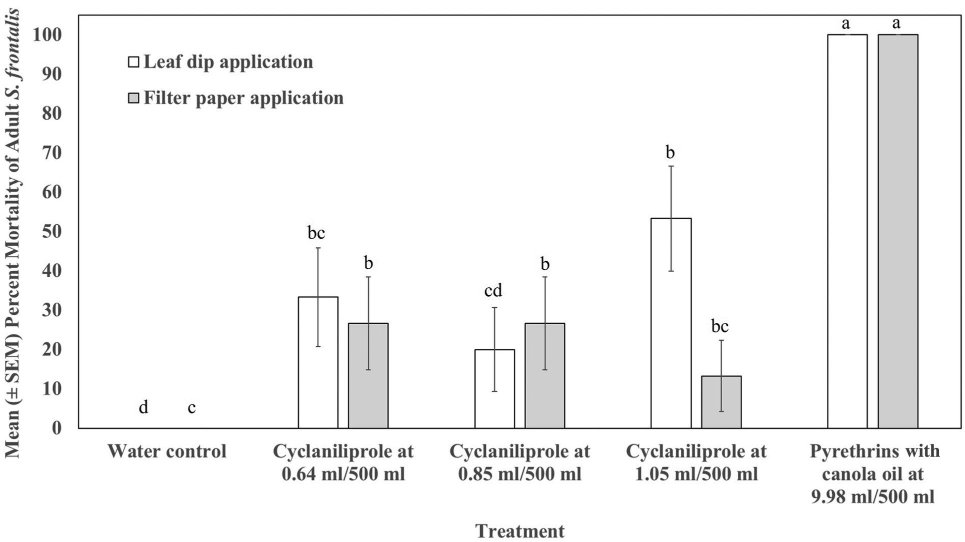

Fig. 3. Mean (± SEM) percent mortality of field-collected redheaded flea beetle, *Systena frontalis*, adults after exposure to leaf dip or filter paper applications associated with the following treatments: 1) water control, 2) cyclaniliprole (Sarisa) at 0.64 ml/500 ml, 3) cyclaniliprole (Sarisa) at 0.85 ml/500 ml, cyclaniliprole (Sarisa) at 1.05 ml/500 ml, and 4) pyrethrins with canola oil (Pycana) at 9.98 ml/500 ml after 24, 48, and 72 h (*n* = 5 within each treatment and an exposure type [leaf dip or filter paper application]). Means followed by the same letter within an exposure type are not significantly different (*P* > 0.05) as determined by Fisher's least significant difference test. Vertical bars represent the standard error of the mean (SEM).

flea beetle overwinters in containerized plants grown under nursery conditions. In the field experiments conducted under nursery conditions, we found no feeding preference by redheaded flea beetle adults associated with any of the plant species or cultivars tested, which is likely because redheaded flea beetle adults are generalist herbivores. However, it is worth noting that the greater foliar feeding damage to all plants in 2017 was related to higher redheaded flea beetle adult activity in 2017 than 2016 in the field. Furthermore, in both laboratory experiments affiliated with host-plant selection, there was no feeding preference by redheaded flea beetle adults among the species or cultivars tested. We also determined that laboratory experiments using field-collected redheaded flea beetle adults should not be conducted longer than 72 h from the date of collection due to the high percentage (>22%) of natural mortality after 72 h.

Insecticides used to protect plants from redheaded flea beetle adult feeding damage must be applied regularly (i.e., weekly) when adults are active. However, weekly applications may be cost-prohibitive with total labor involved in spraying insecticides to protect plants from redheaded flea beetle adult damage accounting for as much as 160 h a year (T. Minter, Loma Vista Nursery, personal communication). In our observations associated with the field experiments, we noticed that new leaves were fed upon more than older leaves (N. J. Herrick and R. A. Cloyd, personal observation), which has been reported with *Altica litigata* Fall (Coleoptera: Chrysomelidae) feeding on crape myrtle (*Lagerstroemia* spp.) cultivars (Cabrera et al. 2008). Therefore, thorough coverage of new leaf growth is mandatory to protect plants from redheaded flea beetle adult feeding damage (Tipping et al. 2003, Martini et al. 2012). In addition to thorough coverage of plant foliage, applications must be directed at the growing medium as adults will fall onto the growing medium surface or jump-off of plants when disturbed (N. J. Herrick and R. A. Cloyd, personal observation).

The insecticides acetamiprid, dinotefuran, and *Isaria fumosorosea* Apopka Strain 97 in the 2016 insecticide efficacy experiment were significantly different from the untreated check, but they were not significantly different from the other insecticide treatments. Therefore, none of the insecticides tested in our study provided adequate protection of foliage from redheaded flea beetle adult feeding based on the general percent plant damage ranking of ≤20%. The insecticide applications were made weekly or biweekly, which are not labor, time, or cost efficient for large nursery operations. Under laboratory conditions, the insecticides we tested did cause adult mortality, but this is likely because adult behavior (i.e., jumping) was restricted in the Petri dishes, which prevented the adults from escaping exposure from the insecticides.

The economic impact of redheaded flea beetle adults has been determined by Loma Vista Nursery (Ottawa, KS) where adult feeding damage can result in a $483,871 loss in the sale of plant material per year, which is 11% of overall sales at the nursery (T. Minter, Loma Vista Nursery, personal communication). In addition, there are costs associated with labor in pruning plants damaged by redheaded flea beetle adults, which is estimated to be as much as 60 h per week. When attempting to suppress redheaded flea beetle adult populations, insecticide applications primarily protect plants from feeding damage as opposed to directly killing adults because of the difficultly in contacting adults with insecticide sprays, which is due to their sensitivity to external stimuli and behavior (i.e., jumping-off plants or falling onto the growing medium surface; R. Cloyd, personal observation).

Our study provides quantitative information on overwintering potential, host-plant selection, and insecticide susceptibility of redheaded flea beetle, *S. frontalis*, adults, which helps to understand some basic biology of this insect pest. Although insecticide sprays may not result in high mortality of redheaded flea beetle adults, these spray applications are necessary to protect plants from adult feeding damage to ensure salability. Furthermore, there are currently no alternative management strategies. Finally, additional studies should be conducted to further our understanding of the basic biology of the redheaded flea beetle and determine if applying systemic insecticides to the soil or growing medium is a cost-effective option in managing adult and larval populations under field conditions.

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