IMPROVING INTEGRATED PEST MANAGEMENT STRATEGIES FOR THE REDHEADED FLEA BEETLE (COLEOPTERA: CHRYSOMELIDAE) IN ORNAMENTAL NURSERIES

by

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(Under the Direction of Shimat V. Joseph)

ABSTRACT

Redheaded flea beetle, *Systena frontalis* (F.) (Coleoptera: Chrysomelidae), is a foliage-feeding pest in ornamental container nurseries. In 2021 and 2022, three experiments were conducted to develop pest management tactics for *S. frontalis* in nurseries. Results show that high densities of *S. frontalis* larvae overwinter in potting media of plant containers as a high number of adults consistently emerged from the plant containers. As nonchemical management tactic, the overhang fence barrier reduced *S. frontalis* damage on panicle hydrangea foliage regardless of insecticide impregnation. Of 13 insecticides tested, adult *S. frontalis* survival and incidence and severity of feeding damage were reduced when exposed to fresh 7 d field-aged residues of tetraniliprole, and cyclaniliprole.

INDEX WORDS: Ornamental nurseries, potting media, barrier fence, residual activity, insecticides

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Systena frontalis (F.) (Coleoptera: Chrysomelidae) is a serious insect pest species widespread in the central and eastern United States. The common names (not approved by ESA) of *S. frontalis*, including redheaded flea beetle, cranberry beetle, and blueberry flea beetle, are testimonies of the species, polyphagy and economic impacts in multiple crop systems (Herrick and Cloyd 2020, Joseph et al. 2021). This paper is a review of the biology and current management approaches against *S. frontalis* in ornamental plant nurseries in the U.S. Information gathered from cranberry and blueberry production systems are included where they are appropriate and supplementary to the discussion.

Description of life stages

Adults are 3.0 to 6.25 mm long, with an oval, shiny, metallic black body and a head with a faint reddish tinge (Mahr 2005; Fig. 1. 1). The serrated antennae emerge below the eyes, and each is approximately half the body length (Joseph and Hudson 2020). Similar to other flea beetles, femora on hind legs of *S. frontalis* are enlarged, allowing adults to jump (Mahr 2005, MCE 2020).

Adults and larvae of several foliage-feeding beetle species may damage ornamental plants in nurseries and landscapes. Some prevalent species in the eastern U.S. are black vine weevil [*Otiorhynchus sulcatus* (F.); Curculionidae], cranberry rootworm [*Rhabdopterus picipes* (Olivier); Chrysomelidae], elm leaf beetle [*Xanthogaleruca luteola* (Müller); Chrysomelidae], Fuller rose beetle (*Naupactus cervinus* Boheman; Curculionidae), imported willow leaf beetle

[*Plagiodera versicolora* (Laicharting); Chrysomelidae], Japanese beetle (*Popillia japonica* Newman; Scarabaeidae), rose chafer [*Maacrodactylus subspinosus* (F.); Curculionidae], strawberry rootworm (*Paria fragariae* Wilcox; Chrysomelidae), viburnum leaf beetle [*Pyrrhalta viburni* (Paykull); Chrysomelidae], and flea beetles (such as *Altica litigata* Fall and *S. frontalis*; Chrysomelidae) (Johnson and Lyon 1988, Mizzell et al. 2011, Braman et al. 2015). Adult is the life stage that presents the most distinguishing characteristics for species identification among foliage-feeding beetles. Flea beetles can be distinguished easily from other prevalent foliage-feeding beetle species by their enlarged femora on the hind legs.

Systena spp. can be distinguished from *Altica* spp. by closed procoxal cavities (Arnett et al. 2002), which is observable under a microscope. Distinguishing the two genera in the field can be challenging. Both genera are generally shiny and metallic black, blue or green. In general, *S. frontalis* is larger (3.5-5.3 mm vs. 3.4-3.6 mm), darker in color (black vs. dark blue or greenish blue), and with pronotum slightly narrower (one-third wider than long vs. two-fifth wider than long), sides of elytra less convex, and antennae lighter in color (distal flagellomeres dark brown vs. brownish black for the entire length) than *A. litigata* (Ciegler 2007). The most distinguishing characteristic of adult *S. frontalis* is a head that is tinged red (hence, the species epithet that means “with a marked frons”). Some individuals may have only lightly tinged heads, which makes the heads appear almost completely black (Chong, pers. obs.).

Mature female *S. frontalis* deposit eggs singly in or on soil or substrate surface (Mahr 2005). Eggs are oval, pale-yellow, and 0.7-0.9 mm in diameter. A larva is 5-10 mm long, with its body cylindrical, pale yellow and translucent, and head capsule brown (Fig. 1. 2). The dorsum of the last larval abdominal segment is armed with an upward, fleshy projection with hairs (setae) (Mahr 2005, Dudek 2011, MCE 2020; Fig. 1. 2).

Biology

Few biological data and observations are available from ornamental plant system; therefore, we include information from other crop systems in this review to help us better understand this pest. *S. frontalis* phenology in various crop systems in the U.S. is illustrated in Fig. 1. 3.

S. frontalis overwinters as eggs in growing media of potted plants in nurseries (Herrick and Cloyd 2020, RA unpublished data). The soil-dwelling *S. frontalis* larvae feed on plant roots (Peters and Barton 1969, Averill and Sylvia 1998, Mahr 2005). When exposed to light, the larvae move deeper into the root ball (Lauderdale 2017). The larvae develop through three instars before pupating in the soil (Mahr 2005). Adults are active on the foliage of containerized plants in the nurseries of the southeastern U.S. from May to October (Joseph and Hudson 2020), which may represent three generations (Lauderdale 2017). In North Carolina, *S. frontalis* generations overlap by mid-summer as adult, egg and larval stages are found simultaneously (Lauderdale 2017).

In the northern region, such as Wisconsin, eggs are found on soil beds of cranberry plants from mid-June to mid-July, August to September, and in some years, in November (Jaffe et al. 2021). Larvae are active in the soil from mid-June to early August. Both larvae and eggs are detected at 15–30 cm from the soil surface and are spread across the cranberry beds (Jaffe et al. 2021). In cranberry system, *S. frontalis* adults are active from mid-July to October in Wisconsin (Jaffe et al. 2021) and from late June to mid-September in Michigan nurseries (Dudek 2011).

Host plant, damage, and economic impact

S. frontalis feeding damage is reported on more than 50 plant species, including ornamental plants, vegetables, fruits, legumes, cereal crops, and weeds (Table 1. 1). Plant hosts affected by

S. frontalis adult feeding include rose (*Rosa* spp.), panicle hydrangea (*Hydrangea paniculata* Siebold), Virginia sweetspire (*Itea virginica* L.), forsythia (*Forsythia* × *intermedia* Zabel), anise-tree (*Illiucium* spp.), azalea (*Rhododendron* spp.), crape myrtle (*Lagerstroemia* spp.), dogwood (*Cornus* spp.), weigela [*Weigela florida* (Bunge) A.DC.], and wax myrtle [*Morella cerifera* (L.) Small]. In addition, *S. frontalis* infests weeds that are often found in and around the nurseries, such as jewelweed (*Impatiens capensis* Meerb.), lambsquarter (*Chenopodium album* L.), pigweed (*Amaranthus* spp.), smartweed (*Polygonum* spp.), Canadian thistle [*Cirsium arvense* (L.) Scop.], clover (*Trifolium* spp.), common burdock (*Arctium* spp.), and velvetleaf (*Abutilon theophrasti* Medik.) (Lauderdale 2017, Joseph and Hudson 2020).

While *S. frontalis* adults did not demonstrate feeding preference among plant species or cultivars of Virginia sweet spire, panicle hydrangea, Weigela, and red twig dogwood (*Cornus sericea* L.) in the field and laboratory experiments (Herrick and Cloyd 2020), growers reported a noticeable preference for hydrangea, Virginia sweetspire, weigela, hollies (*Ilex* spp.), rose and azalea in nurseries (Joseph et al. 2021). There is a clear preference for some species within a genus. For example, five to six times more damage was observed on *H. paniculata* than on *Hydrangea serrata* (Thunb.) Ser. or *Hydrangea macrophylla* (Thunb.) Ser. (Kunkel 2021). The exact mechanism of host preference by *S. frontalis* is unknown. Proposed mechanisms include the presence of waxiness (Kunkel 2021), leaf toughness (Kunkel 2021), and production /maintenance practices, such as placement of new stock or liners near older, *S. frontalis*-infested stock plants (Joseph et al. 2021). Understanding the underlying factors and mechanisms for *S. frontalis* preference and susceptibility or resistance to feeding would help improve *S. frontalis* management in ornamental nurseries by focusing monitoring and management on the most susceptible or preferred species or cultivars.

Adult *S. frontalis* prefers to feed on developing new leaves than older mature leaves (Cloyd and Herrick 2018b, Jaffe et al. 2021) as younger foliage is easier to chew than older foliage. Adults initially remove the epidermal layers on adaxial and abaxial leaf surfaces (Joseph and Hudson 2020; Figs. 1. 1 & 1. 4A). The damage appears as shot holes once feeding punctures both surfaces (Joseph and Hudson 2020; Fig. 1. 4A and B). Leaves are skeletonized as the shot holes expand and coalesce until only the midrib and veins remain (Lauderdale 2017). Adults also deposit black fecal material on the leaves while feeding (Cloyd and Herrick 2018a; Fig. 1. 1A [blue arrow]). Larvae feed on the roots of container plants, although the impact of larval feeding on plant health is unknown.

Foliage damage caused by adults is the main cause of the reduced aesthetic value of ornamental plants grown in nurseries. The marketability of plants can be impacted after only 2 days of feeding, and severely defoliated plants are not salable (Joseph et al. 2021). In addition to a loss of aesthetic value and sale, *S. frontalis* causes economic losses by increasing the labor and opportunity costs in the nurseries. Plants damaged by adult feeding are not dead. With extensive pruning that encourages re-flush of foliage, growers can reinvigorate the plants or mask the damage, thus making the previously damaged plants marketable. However, extensive pruning is labor intensive and holding the pruned plants for reflushing takes up valuable growing space that could otherwise be used to grow more plants. The additional pruning, maintenance and opportunity costs reduce at least 10% of the regular market value as the plants are aged and overgrown in the containers (Joseph et al. 2021). *S. frontalis* management costs on those unsold damaged plants, such as pesticides, labor, and equipment costs, to be ready for next market window are estimated to be USD$1,637 per ha per year (Joseph et al. 2021). Similarly, Herrick and Cloyd (2020) indicated that *S. frontalis* adult feeding damage causes an estimated loss of

USD$483,871 in plant sales annually, accounting for 11% of total sales in a specific nursery in Kansas. The additional labor time for pruning damaged plants is estimated at 60 h per week, which adds to the cost (Herrick and Cloyd 2020).

Management

Monitoring

Monitoring eggs and larvae, although critical for understanding the population dynamic of *S. frontalis,* can be challenging because these below-ground life stages are difficult to detect visually (Peters and Barton 1969, Averill and Sylvia 1998, Mahr 2005). Management of the egg and larval stages may be effective if the size of the population on the root system can be estimated through monitoring (Jaffe et al. 2021). Larvae move deeper into the root balls when the potting medium is dry, which makes their detection more difficult; therefore, the potting medium should be wet with irrigation before examining the root balls for the larvae (Lauderdale 2017). Assessing the larval stages and developmental time can help determine the application timing of insecticide to the media to target larvae and the foliage before adult emergence (Waller 2021).

Regular and systematic scouting for adults on the susceptible hosts, such as hydrangea or rose, is important (Lauderdale 2017, Joseph and Hudson 2020). In cranberry, adult beetles can be collected using a sweep net, vigorous shaking, or drop-clothing (Dudek 2011). However, these tactics may not be effectively implemented on containerized ornamental plants as they may cause cosmetic damage. Moreover, sweep netting can take more time to do than visual sampling.

Most nursery growers rely on routine visual inspection for adults and their damage to the susceptible plants (Joseph et al. 2021). Detection of adults may not be the most effective monitoring strategy because damage may have already been done by the time adults are detected

(Joseph et al. 2021). Yellow sticky cards deployed on the canopies also were considered for *S. frontalis* monitoring. However, it might not be an effective monitor tool for adults because the beetles are not attracted to sticky cards (Maltais and Ouellette 2000, ACES 2020, SVJ unpublished data). Most growers opt for monitoring ornamental plants and weeds for *S. frontalis* damage, starting in early to mid-May, and making insecticide applications as soon as damage is detected to prevent additional damage.

In ornamental nurseries, the tolerance to *S. frontalis* infestation is very low because moderate to severe damage to the leaves would affect the marketability of the plant. However, the treatment threshold based on the degree of damage or consumer acceptability has not been identified. Similarly, the economic threshold for *S. frontalis* densities or damage has not been developed in cranberry because the occurrence of adults can be unpredictable on the cranberry beds (Jaffe et al. 2021). However, captures of 15 or more adults per sweep netting are tentatively set as the benchmark for pest management decisions in cranberry (MCE 2020).

Plant phenological indicators and degree-day models may be used to predict *S. frontalis* activity and to prompt the initiation of frequent scouting before refining insecticide application timing. On the eastern shore of Virginia, larvae became active when azalea, wild cherry (*Prunus serotina* Ehrh), and Virginia sweetspire (*Itea virginica* L.) were in bloom (Kunkel and Colon. 2012). In Delaware and Maryland, the larval activity of *S. frontalis* was observed when black locust (*Robinia pseudoacacia* L.) and Chinese fringetree (*Chionanthus retusus* L.) were in bloom (Kunkel and Colon. 2012). In North Carolina, first-generation larvae became active between 250 and 480 GDD_{50} (Growing Degree Day with a base temperature of 10°C or 50°F and start date of 1 January), whereas adults were first observed between 590 and 785 GDD_{50}, or when *Magnolia grandiflora* L. and *Ilex verticillata* L. were in bloom (Lauderdale 2017). In New Jersey, first-generation larvae were first observed between 242 and 600 GDD_{50}, and the appearance of the first-generation adults was noted between 517 and 1028 GDD_{50} (Waller 2021).

Cultural and biological control

Adult *S. frontalis* feeds on various weed species in ornamental plant nurseries. Although the value of these weed species to adult survival and reproductive capacity and larval development and survival is unknown, the presence of weeds in and around a nursery can pose a risk to the ornamental crop by serving as hosts or refuges. Removal of volunteer plant species, including weeds, may reduce *S. frontalis* densities and damage on ornamental plants, although little information is available on the dispersal behavior of adults from weeds or volunteer hosts to the ornamental crop (Kunkel 2021).

Containers infested with eggs and larvae can be sold and transported to nurseries and garden centers in various parts of the country, thus contributing to the dispersal of *S. frontalis* (Kunkel 2021). Proper quarantine practices, i.e., temporarily placing and maintaining in-coming plants in spatially isolated receiving areas before integrating them with the rest of the nursery stock, can help reduce the dispersal risk posed by containerized plants infested by *S. frontalis* (Joseph and Hudson 2020). Similarly, isolating the new liners developed within the nursery from the nursery stock with a history of *S. frontalis* infestation breaks the chain of re-infestation to new liners. In the cranberry system, trap crops and physical barriers, such as row covers or thick mulch, could effectively reduce the movement of *S. frontalis* adults (Guédot and Henschell 2015).

Biological control tactics, such as using entomopathogenic nematodes, effectively prevent the emergence of *S. frontalis* adults (Jaffe et al. 2021). Application of *Oscheius onirici* Torini (Nematoda: Rhabditidae) and *Heterorhabditis georgiana* Nguyen (Rhabditida:

Heterorhabditidae), two nematode species native to Wisconsin, in commercial cranberry marshes suppressed larval abundance (Ye et al. 2018, Foye and Steffan 2019). Entomopathogenic fungi, such as *Beauveria bassiana* Bals. -Criv. and *Metarhizium anisopliae* Metschn, also suppressed adult emergence from potting media (Joseph and Hudson 2020). These entomopathogens could be used as an alternative to insecticides in ornamental plant nurseries. There is little information on arthropod natural enemies of *S. frontalis* (Kunkel 2021).

Chemical control

About 89% of surveyed ornamental plant growers use foliar sprays of insecticides to protect plants from *S. frontalis* adult attacks (Joseph et al. 2021). However, some growers target *S. frontalis* larvae (47%) or both larvae and adults (48%) as their management plan (Joseph et al. 2021). The survey did not gauge the growers' perception of targeting which of these life stages yields the most reduction in plant damage. While adults cause the most visible damage and, therefore, are the target for management, successful management will likely require the management of both the larvae (to reduce the number of adults) and adults (to reduce damage) (Herrick and Cloyd 2020).

Neonicotinoids, followed by carbaryl, pyrethroids, organophosphates, and diamides, are the most widely used insecticides against adults on ornamental plants (Joseph et al. 2021). These insecticides are applied to plants as a foliar spray to prevent or stop foliar damage by adults. Some growers incorporate insecticides into the potting media or apply insecticides as media drench or granular application to the potting media to reduce larval abundance (ACES 2020). While consumers demand neonicotinoid-free plant materials (Rihn and Khachatryan 2016, Wei et al. 2020) due to the implication of insecticides as a factor contributing to pollinator decline (Blacquière et al. 2012), a recent survey showed that most nursery growers have no reservations on using neonicotinoids to manage *S. frontalis* (Joseph et al. 2021). Despite the number of available products, most growers (54%) indicated that they do not have adequate insecticide options for *S. frontalis* management (Joseph et al. 2021). This report of a lack of options may be the perception of poor residual efficacies of the available products.

Despite its economic impact, few studies comparing the efficacies of insecticides have been published or are made publicly available. A series of 15 experiments conducted between 2012 and 2021 identified acetamiprid, clothianidin + bifenthrin, cyclaniliprole, and pyrethroids (bifenthrin, lambda-cyhalothrin, and tau-fluvalinate) as the insecticides that had provided the most consistent suppression of adult abundance or severity of foliar damage (Palmer and Vea 2022). Other products, such as chlorantraniliprole, cyantraniliprole, imidacloprid + bifenthrin, spinosad, sulfoxaflor + spinetoram, thiamethoxam, and tolfenpyrad, were able to suppress adult density or damage but inconsistently (Palmer and Vea 2022). Data from these experiments suggested that no product can provide long-term protection of foliage from adult feeding damage with just one application. The newly expanded leaves are not protected by the insecticides and appear more prone to *S. frontalis* adult feeding than the older foliage (Herrick and Cloyd 2020). Additionally, residues of these insecticides are either insufficient to repel adults or degrade too quickly under the full sun. These shortcomings necessitate complete coverage of the entire canopy and repeated applications to prevent damage to the foliage (Lauderdale 2017, 2020, ACES 2020, Joseph and Hudson 2020). Currently, repeated insecticide applications at weekly intervals is recommended for a longer-term residual suppression of adult feeding damage below the assumed threshold (i.e., < 10% foliar damage) (ACES 2020, Lauderdale 2021).

Herrick and Cloyd (2020) showed that *S. frontalis* adult feeding damage on foliage was reduced when insecticides were applied to both the foliage and the potting medium, hinting at the importance of managing both the larval and adult populations. Drench or granular applications of acephate, acetamiprid, azadirachtin, clothianidin, clothianidin + bifenthrin, chlorpyrifos, cyantraniliprole, dinotefuran, flupyradifurone, imidacloprid, imidacloprid + bifenthrin, pyriproxyfen, sulfoxaflor + spinetoram, thiamethoxam, *Isaria fumosorosea* (an entomopathogenic fungus) and *Steinernema carpocapsae* (a nematode) at egg hatch or larval activity achieved a significant reduction of larval densities in potting media (Lauderdale 2021a, b). When targeting larvae, one application can provide 60 to 90 days of larval and adult suppression and protect foliage below the assumed treatment threshold (Lauderdale 2021a). In some cases, one application against larvae may be sufficient to protect the plants for the growing season. Similarly, when imidacloprid is soil-incorporated or top-dressed in April, adequate control was observed for the entire season, especially when the *S. frontalis* densities were low to moderate (Lauderdale 2021b and c). However, additional foliar applications may be needed to protect the plants from late-season adult damage.

The development of chemical control programs against *S. frontalis* in ornamental plant production systems is still in its infancy. The timely application of insecticides necessitates a better understanding of *S. frontalis* biology, distribution, behavior, and ecology, as well as the development of a more accurate and effective monitoring system that makes use of more *S. frontalis*-targeted monitoring tools and (degree-day and plant phenological) predictive models in plant nurseries. When insecticides are repeatedly applied, it is critical to rotate active ingredients with distinctly different modes of action (IRAC 2022) to prevent the development of pesticide resistance and limit the resurgence of other pests, such as spider mites (Lauderdale 2017, Waller 2021). Guidelines on pesticide rotation and managing multiple pests would be crucial for the adoption and successful implementation of *S. frontalis* management program. The translocation of systemic insecticides to the nectar and pollen of ornamental plants and the risk of systemic insecticide treatment on pollinators visiting the flowering plants warrant further examination. Additionally, more research is warranted to improve insecticide screening and delivery strategies to extend residual activity of insecticide, minimize application frequency and management cost, and increase the profitability of container plants in ornamental nurseries.

Future directions

All aspects of *S. frontalis* management system, not just chemical control, require additional research, development, and improvement. A survey was developed to identify and capture current research and education needs on *S. frontalis* management in ornamental plant nurseries. Researchers and Extension personnel from Cornell University, University of Delaware, University of Maryland, Virginia Polytechnic Institute and State University, North Carolina State University, Clemson University, University of Tennessee, University of Georgia, Auburn University, Louisiana State University, University of Florida, and Texas A&M University contributed to the development of the questionnaire and the distribution of the survey. The respondents ranked the pre-populated research and Extension needs (listed in Tables 1. 3 and 1. 4) as 1 (very important), 2 (important), 3 (somewhat important), 4 (slightly important), and 5 (not important).

The survey was converted into an online survey tool developed by Qualtrics (Provo, Utah, U.S.) under subscription purchased by the University of Georgia and then distributed by green industry associations in the eastern US to their members, including wholesale and retail nurseries, retail garden centers, and landscape installation and maintenance companies. Invitations to participate in the survey were distributed to additional green industry members and allies via emails, newsletters, and Extension communications from the participating institutions and organizations representing the green industry. The newsletters are often distributed beyond state lines and reach a broad audience. Survey responses received via Qualtrics between 24 June and 2 September 2020 were included in this analysis. The mean and standard deviation of responses was calculated for each research or Extension need.

The research or Extension needs are ranked and presented in Tables 1. 3 and 1. 4. This survey clearly identifies the research and Extension efforts stakeholders considered important to advancing the management of *S. frontalis* and the operation and profitability of their businesses. Research and Extension priorities identified in this survey will form the foundation and justification for guiding future research and Extension efforts against *S. frontalis*.

The top-ten research needs are related to the biology and management of *S. frontalis* (Table 1. 3). The top-ranked pest management needs to be focused on chemical management (e.g., insecticide efficacy, delivery methods, and residual activity), alternative control options (e.g., repellents), and the compatibility of control options with current cultural practices (e.g., irrigation). Survey respondents identified the importance of management against both adult and larval stages. Related to management is the economic research that needs to understand the costs and benefits of each treatment option. The top-ranked biological research needs to focus on enhancing the understanding of the life cycle, overwintering biology, and dispersal behavior of *S. frontalis* as influenced by the environment and its hosts.

Survey respondents identified the development of guidelines for the management of *S. frontalis*, including biological control and trapping, and understanding consumer preference or perception as the top Extension priorities (Table 1. 4). Respondents were clear in their preference to receive information through digital media (videos, blogs, social media, e-newsletter, etc.; Table 1. 4), but they did not rank the development of an information clearinghouse or tracking map as the top Extension priority.

Research Objectives

The research objectives were to determine:

Objective 1: whether the potting media serves as a potential source for overwintering *S. frontalis* infestation in the ornamental nursery. The underlying hypothesis is that potting media of plant containers could be a potential overwintering site of *S. frontalis,* but this was not systematically determined. Therefore, this study will help determine whether adults attacking container nursery plants emerge from the plant potting media or nearby vegetation.

Objective 2: the effects of fence barriers on the incidence and damage of *S. frontalis* adults in a container nursery. The underlying hypothesis is that a physical barrier and an overhang function as fences can reduce the influx of incoming *S. frontalis* on to plants.

Objective 3: the residual activity of common and potential insecticides against adult *S. frontalis* under laboratory conditions. The hypothesis is that the effectiveness of insecticides varies with age of insecticide residue.

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Table 1. 1. Host plants susceptible to *S. frontalis* adult infestation.

Common name	Species	Production system	Reference
Glossy abelia	*Abelia* spp.	N	e
Pigweed*	*Amaranthus* spp.	N	d
Common burdock*	*Arctium minus*	N	d
Sugar beet	*Beta vulgaris*	V	b
Beggar-ticks*	*Bidens frondosa*	V	b
Cabbage	*Brassica oleracea*	V	b
Turnip	*Brassica rapa*	V	b
Butterfly bush	*Buddleja* spp.	N	e
Beautyberry	*Callicarpa* spp.	N	e
Buttonbush	*Cephalanthus occidentalis*	N	e
Lambsquarter*	*Chenopodium album*	N	d
Canadian thistle*	*Cirsium arvense*	N	e
Tickseed	*Coreopsis* spp.	N	e
Dogwood	*Cornus* spp.	N	d, e
Chrysanthemum	*Dendranthema* spp.	N	b, d
Ivy tree	*Distylium* spp.	N	e
Joe-pye weed*	*Eutrochium* spp.	O	c
Forsythia	*Forsythiac x intermedia*	N	d, e
Strawberry	*Fragaria grandiflora*	O	b
Soybeans	*Glycine soya*	L	b
Sunflower	*Helianthus annuus*	S	b
China rose	*Hibiscus* spp.	N	e
Big leaf hydrangea	*Hydrangea macrophylla*	N	f
Panicle hydrangea	*Hydrangea paniculata*	N	d, e, f
Mountain hydrangea	*Hydrangea serrata*	N	f
Japanese holly	*Ilex crenata*	N	d, e
Jewelweed*	*Impatiens biflora*	O	c, d
Jewelweed*	*Impatiens capensis*	N	d
Sweet potato	*Ipomoea batatas*	V	b
Virginia sweet spire	*Itea virginica*	N	d, e
Crepe myrtle	*Lagerstroemia* spp.	N	d, e
Alfalfa	*Medicago sativa*	P	c
Wax myrtle	*Myrica cerifera*	N	e
Fragrant olive	*Osmanthus fragrans*	N	d, e
Common ninebark	*Physocarpus* spp.	N	e
Smartweed*	*Polygonum* spp	O	c, d
Pear	*Pyrus communis*	O	b
Azalea	*Rhododendron* spp.	N	d, e
Rose	*Rosa* spp.	N	d, e
Black-eyed Susan	*Rudbeckia* spp.	N	e
Common sage	*Salvia* spp.	N	d, e
Whorled stonecrop	*Sedum* spp.	N	d, e
Hardhack*	*Spirea tomentosa*	O	c, d

Marsh St. Johnswort*	*Triadenum virginicum*	O	c
Clover*	*Trifolium* spp.	N	d
Highbush blueberry	*Vaccinium corymbosus*	O	c
Cranberry	*Vaccinium macrocarpon*	O†	b, c, g
Ironweed*	*Vernonia* spp.	N	e
Common snowball	*Viburnum* spp.	N	e
Grapes	*Vitis* spp.	O	b
Weigela	*Weigela florida*	N	d, e
Corn	*Zea mays*	C	a
Zinnia	*Zinnia* spp.	N	d

*, weeds; †, tree fruits, vine, and small fruits. The abbreviations: N, ornamental nursery; O, fruit orchards; P, pasture; V, vegetable farm; C, cereal; S, oil seeds; and L, legume farm.

a, Jacques et al. 1971; b, Maltais and Ouellette 2000; c, Mahr 2005; d, Lauderdale 2017; e, Joseph et al. 2021; f, Kunkel 2021; and g, Jaffe et al. 2021.

Table 1. 2. Insecticide class, the active ingredient, trade name, application method, and host plants associated with determining the efficacy of insecticides against adults of *S. frontalis* under field and laboratory conditions.

Insecticide class	Active ingredient	Trade name	Rate per ha[a]	Efficacy	System	Application method	Reference
Neonicotinoid	dinotefuran	Venom	292.2 mL	+++	Cranberry	Foliar	1
Neonicotinoid	thiamethoxam	Actara	292.2 mL	+++	Cranberry	Foliar	1
Neonicotinoid	Acetamiprid	Assail	292.2 mL	+++	Cranberry	Foliar	1
Neonicotinoid	clothianidin	Belay	292.2 mL	+++	Cranberry	Foliar	1
Neonicotinoid	clothianidin	Belay	876.9 mL	-	Cranberry	Drench (pre-bloom)	1
Neonicotinoid	clothianidin	Belay	876.9 mL	++	Cranberry	Drench (post-bloom)	1
Neonicotinoid	acetamiprid	Assail	876.9 mL	-	Cranberry	Drench (pre-bloom)	1
Neonicotinoid	dinotefuran	Safari	NM	+++	Ornamentals	Foliar	2
Neonicotinoid	thiamethoxam	Flagship	NM	++	Ornamentals	Foliar	2
Neonicotinoid	dinotefuran	Safari	NM	+++	Ornamentals	Drench	2
Neonicotinoid	imidacloprid + fertilizer	Discus	NM	++	Ornamentals	Drench	2
Neonicotinoid	imidacloprid	Marathon 1G	29.6 g per 13.6 L container	+++	Ornamentals	Top dressing	5
Neonicotinoid	imidacloprid	Mallet 0.5G	2.02 kg per m^3	+++	Ornamentals	Soil incorporated	6
Neonicotinoid	acetamiprid	TriStar	NM	++	Ornamentals	Foliar	3
Neonicotinoid	thiamethoxam	Flagship	226.8 g per 454.6 L	+++	Ornamentals	Foliar	4
Diamide	cyantranilipole	Mainspring	NM	+++	Ornamentals	Foliar	2
Diamide	cyantranilipole	Mainspring	354.9 mL per 454.6 L	++	Ornamentals	Foliar	4
Diamide	chlorantraniliprole	Altacor	219.1 mL	+++	Cranberry	Foliar	1

Diamide	chlorantraniliprole	Altacor	328.9 mL	-	Cranberry	Drench (pre-bloom)	1
Pyrethroid	bifenthrin	Talstar	NM	++	Ornamental weed	Foliar	2
Pyrethroid	lambda-cyhalothrin	Scimitar	NM	++	Ornamentals	Foliar	2
Pyrethroid	cyfluthrin	Tempo	NM	++	Ornamentals	Foliar	3
	azadirachtin	Azadirachtin	NM	+++	Ornamentals	Drench	2
Bacillus thuringiensis	*Bacillus thuringiensis*	Beetlegone	7257.5 g per 454.6 L	-	Ornamentals	Foliar	4
Sulfoximine	sulfoxaflor	Closer	416.4 mL	++	Cranberry	Foliar	1
Sulfoximine + Spinosyn	sulfoxaflor + spinetoram	XXpire	103.5 mL per 454.6 L	-	Ornamentals	Foliar	4
Organophosphate	chlorpyrifos	Lorsban	709.8 mL	++	Cranberry	Foliar	1
Organophosphate	phosphorothioate	Diazinon	946.4 mL	+++	Cranberry	Foliar	1
Organophosphate	phosmet	Imidan	453.0 g	+++	Cranberry	Foliar	1
Organophosphate	acephate	Orthene	317.5 g per 1.1 L	++	Cranberry	Foliar	1
Carbamate	carbaryl	Sevin	317.5 g per 1.1 L	++	Cranberry	Foliar	1
Diacylhydrazine	tebufenozde	Confirm	1028.9 mL	-	Cranberry	Foliar	1
Spinosyn	spinetoram	Delegate	437.7 mL	++	Cranberry	Foliar	1
Benzoylureas	novaluron	Rimon	876.9 mL	++	Cranberry	Foliar	1
Diacylhydrazine	methoxyfenozide	Intrepid	1169.0 mL	-	Cranberry	Foliar	1

[1]Guédot and Henschell 2015, [2]Kunkel 2016, [3]Cloyd and Herrick 2018a, [4]Kunkel 2021, [5]Lauderdale, D. 2021b, [6]Lauderdale, D. 2021c.

[a]calculated for ha otherwise specified. The symbols: -, Not effective; ++, moderately effective; +++, highly effective, and NM, not mentioned based on published articles.

Table 1. 3. Research priorities

Overall Rank	Research Rank	Research Question	Mean	Std Dev	n	Research Area
1	1	Evaluate the efficacy and residual activity of insecticide against adults and larvae.	1.33	0.9	24	Management
2	2	Quantify the difference among insecticide application methods against adults and larvae.	1.38	0.9	24	Management
3	3	Understand the life cycle of RHFB, which includes the number of generations, the activity time of adults and larvae, survival of each life stage, reproductive capability, etc.	1.67	1.07	24	Biology
4	4	Evaluate the potential of improving residual efficacy of insecticides with protectants, extenders or other adjuvants.	1.73	0.91	22	Management
5	5	Identify the location and life stage in which RHFB overwinter.	1.79	1.19	24	Biology
7	6	Understand how environmental factors, such as temperature, rainfall, and wind, influence the development, survival, and reproduction of RHFB.	1.88	1.2	24	Biology
8	7	Identify factor(s) that triggers adult flight or dispersal.	1.88	1.33	24	Biology
9	8	Determine if insecticide efficacy against larvae may be influenced by irrigation frequency or amount.	1.88	1.01	24	Management
10	9	Evaluate existing repellents against adults, such as kaolin clay.	1.92	1.19	24	Management
11	10	Identify the most susceptible life stage for each biological control agent.	1.92	1.35	24	Management

12	11	Identify the biotic (such as host plant and insect physiology) and abiotic factors (such as temperature and rainfall) that trigger the activity timing of adults and larvae.	2	1.19	24	Management
13	12	Identify the biotic (such as host plant and insect physiology) and abiotic factors (such as temperature and rainfall) that trigger reproduction.	2	0.98	23	Management
14	13	Determine if the majority of adults dispersed from the fields into the nursery or originated from larvae developing in the medium of the containerized plants.	2	1.22	24	Management
15	14	Evaluate the efficacy of each biological control agent in a field production setting.	2	1.35	24	Management
16	15	Develop a state or regional degree-day model for RHFB.	2.04	1.27	24	Biology
18	16	Identify predators or parasitoids for controlling RHFB.	2.04	1.34	24	Management
19	17	Identify characteristics that make a plant susceptible or resistant.	2.08	1.38	24	Management
20	18	Determine if potting medium (type, composition, etc.) influence larval survival and development.	2.08	1.32	24	Management
21	19	Determine if water management reduces RHFB abundance and damage.	2.08	1.08	24	Management
22	20	Develop new trapping or monitoring methods, such as pheromone, light, or visual traps.	2.08	1.32	24	Monitoring
23	21	Determine a treatment threshold.	2.13	1.51	24	Monitoring
24	22	Determine if RHFB are attracted to plant volatile, and identify these plant volatiles.	2.13	1.05	24	Monitoring
25	23	Develop a plant volatile-based lure for monitoring or mass trapping.	2.13	1.33	24	Monitoring

26	24	Evaluate existing, commercially available lures and traps for monitoring.	2.13	1.3	24	Monitoring
27	25	Quantify the cost-benefit ratio of each treatment option.	2.13	1.2	24	Economics
28	26	Identify the biotic (host plant and insect physiology) and abiotic factors (such as temperature and rainfall) that trigger overwintering.	2.17	1.24	23	Biology
29	27	Quantify the impact of adult feeding on plant growth, appearance, and marketability.	2.17	1.46	24	Economics
30	28	Identify spatial and temporal patterns in the appearance of adults or the severity of the damage.	2.17	1.14	24	Biology
32	29	Understand how host plant species influence the development, survival, and reproduction of RHFB.	2.21	1.08	24	Biology
33	30	Quantify the impact of larval feeding on plant growth, appearance, and marketability.	2.21	1.5	24	Management
34	31	Determine if plant spacing influences the severity of the damage.	2.21	1.32	24	Management
35	32	Determine the accuracy of predictive models (degree-day or plant phenology indicator) on the regional scale, and identify the factor(s) that can reduce/improve the model accuracy.	2.21	1.15	24	Management
36	33	Quantify the impact of potting medium (type, composition, etc.) on insecticide efficacy.	2.21	1.22	24	Management
37	34	Determine if economic considerations influence the adoption of treatment options.	2.21	1.29	24	Economics
38	35	Identify the major host species in the field if the majority of adults originated from the surrounding fields.	2.25	1.36	24	Biology
39	36	Determine if soil fertility affects RHFB abundance and damage.	2.25	1.16	24	Management

42	37	Identify factor(s) contributing to the spatial pattern in adult activity and damage, if there is one.	2.29	0.98	24	Biology
43	38	Understand how microclimate within a nursery can influence the accuracy of a degree-day model for RHFB.	2.29	1.21	24	Biology
44	39	Evaluate the efficacy of rotating crops within the nursery in reducing RHFB population/damage or improving control.	2.29	1.34	24	Management
45	40	Identify commercial and non-commercially available entomopathogenic nematodes and fungi for controlling RHFB.	2.29	1.46	24	Management
46	41	Conduct risk analysis on spatial and temporal patterns, and develop a predictive risk model.	2.33	1.14	24	Biology
47	42	Determine the relative susceptibility of plant species.	2.38	1.35	24	Biology
48	43	Develop a plant phenological indicator model for RHFB.	2.38	1.28	24	Biology
49	44	Quantify the economic value of RHFB-susceptible plant species on a state, regional and national level.	2.38	1.41	24	Economics
52	45	Determine if RHFB populations on different crop species (such as nursery crops, cranberry, soybean, and potato) represent different species or biotypes.	2.54	1.41	24	Biology
53	46	Evaluate the potential of using a physical barrier (such as screen, fence, or guard) in reducing EHFB abundance and damage.	3	1.47	24	Management

Table 1. 4. Extension priorities

Overall rank	Extension rank	Research Question	Mean	Std Dev	n
6	1	How important is digital media (videos, blogs, social media, e-newsletter, etc.) as your source of information?	1.87	0.95	23
17	2	How important is print media (bulletins, fact sheets, magazines, etc.) as your source of information?	2.04	0.93	24
31	3	Develop guidelines for using biological control against RHFB.	2.17	1.37	23
40	4	Develop guidelines on the deployment method of various traps when the traps become available.	2.25	1.36	24
41	5	Determine if economic considerations influence consumer acceptance or the perceived value of a crop.	2.25	1.33	24
50	6	Develop a website or clearinghouse for RHFB resources and information.	2.43	1.21	23
51	7	Develop a web-based reporting and tracking system (such as EDD Maps) on the county level.	2.5	1.29	24

Fig. 1. 1. *S. frontalis* adult on leaves of rose (*Rosa* sp.). The black arrows show the fresh feeding injury, red arrows show the old feeding injury, and blue arrows show fecal matter. Photo credit: Shimat V. Joseph, University of Georgia.

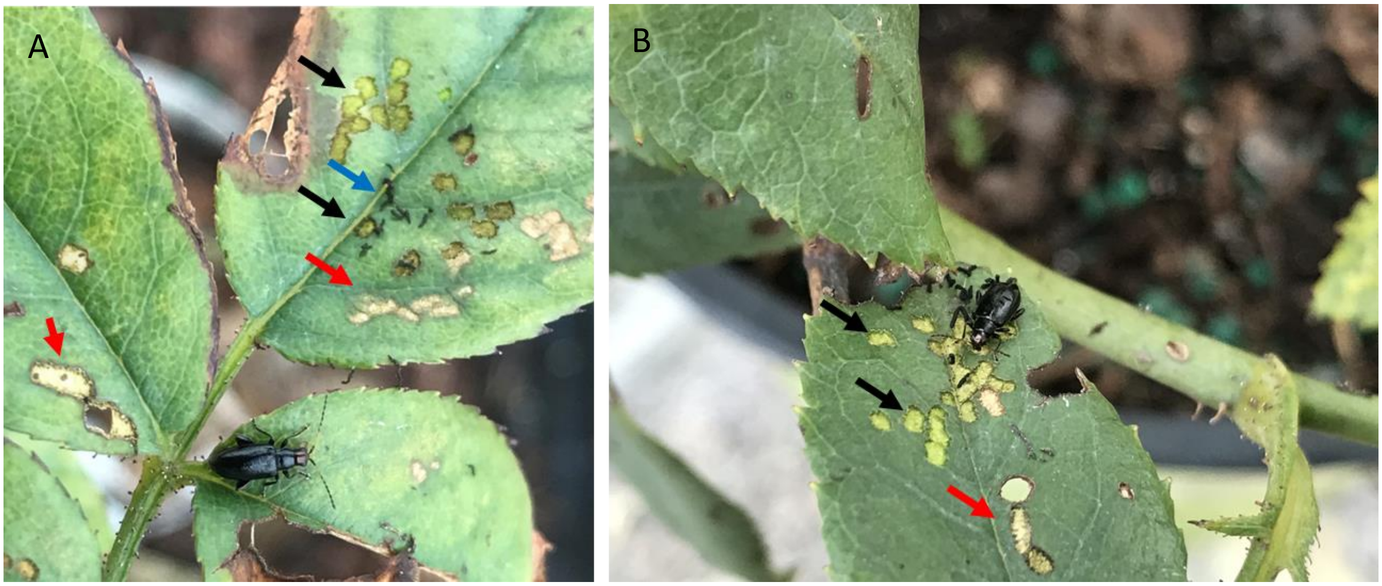

A
B

Fig. 1. 2. Larva of *S. frontalis* on the (A) root of *Weigela* sp. with three pairs of legs (white arrow), head capsule (red arrow), and last segment on the rear end of the larva is oriented upward (orange arrow). and (B) larva near ruler (in inches). Photo credit: (A) D.K.B. Cheung http://www.dkbdigitaldesigns.com/clm/content/*systena-frontalis*-12 and (B) Danny Lauderdale, North Carolina Cooperative Extension.

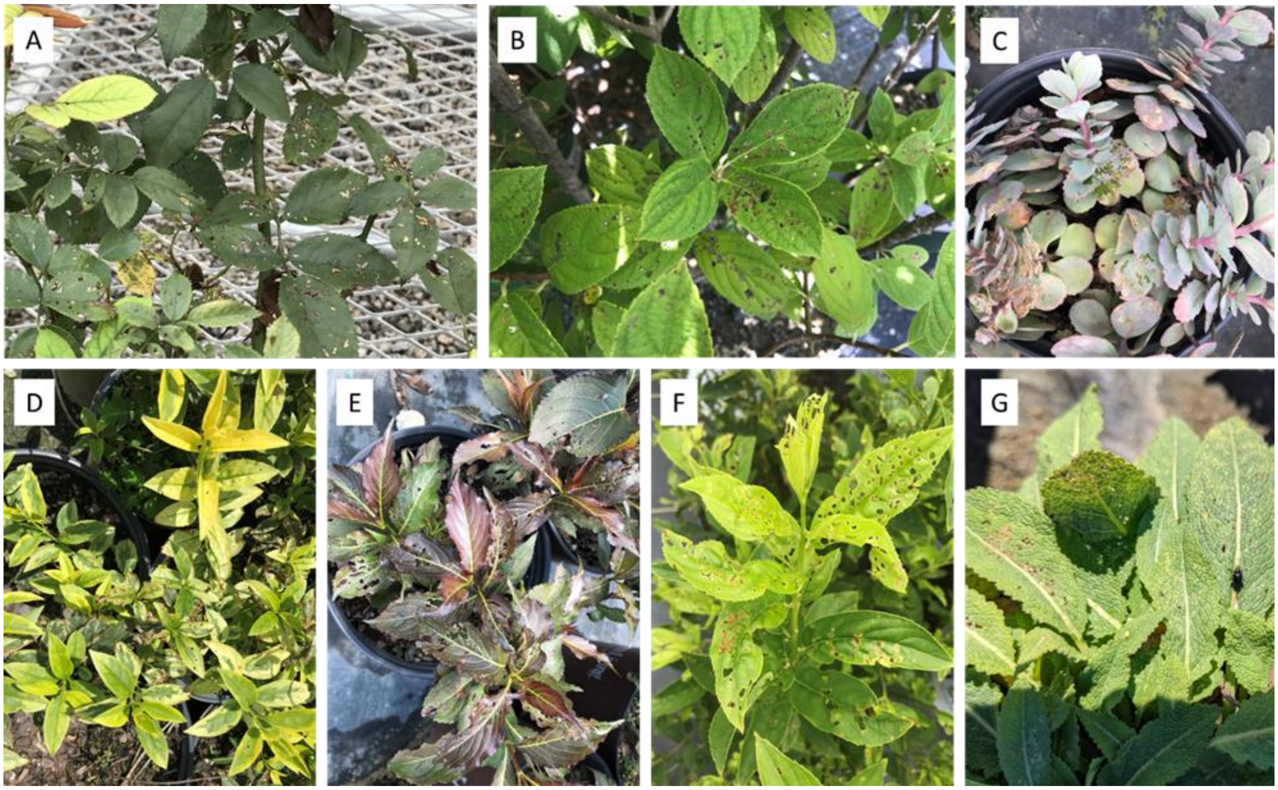

A
B
1/8
1/4
3/8
1/2

Fig. 1. 3. Phenology of *S. frontalis* in the eastern and midwestern U.S.

State	System	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Reference
North Dakota	Soybean and Corn	Overwintering eggs	Overwintering eggs	Overwintering eggs	Overwintering eggs	Overwintering eggs	Larvae	Larvae and adults	Adults	Adults			Overwintering eggs	Beauzay and Knodel 2021
Maine	Cranberry	Overwintering eggs	Overwintering eggs	Overwintering eggs	Overwintering eggs	Eggs and Larvae	Larvae	Larvae and adults	Larvae and adults	Adults			Overwintering eggs	MCE 2020
Wisconsin	Cranberry	Overwintering eggs	Overwintering eggs	Larvae	Larvae	Larvae	Eggs and Larvae	Eggs, larvae and adults	Eggs, larvae and adults	Eggs and adults	Eggs and adults		Overwintering eggs	Jaffe et al. 2021
Michigan	Ornamental Nursery						Adults	Adults	Adults	Adults				Dudek 2011
Connecticut	Ornamental Nursery	Overwintering eggs	Overwintering eggs	Larvae	Larvae	Larvae	Larvae and adults	Adults	Adults	Adults	Adults		Overwintering eggs	Hiskes 2013
New Jersey	Ornamental Nursery	Overwintering eggs	Overwintering eggs	Larvae	Larvae	Larvae	Adults	Adults	Adults	Adults			Overwintering eggs	Rettke 2013
Kansas	Ornamental Nursery	Overwintering eggs	Overwintering eggs				Adults	Adults	Adults	Adults	Adults	Adults	Overwintering eggs	Herrick and Cloyd 2020; Cloyd and Herrick 2018a
Georgia	Ornamental Nursery	Overwintering eggs	Overwintering eggs		Eggs and Larvae	Eggs, larvae and adults	Eggs, larvae and adults	Eggs, larvae and adults	Adults	Adults	Adults		Overwintering eggs	Joseph and Hudson 2020
Alabama	Ornamental Nursery				Adults	Adults	Adults	Adults	Adults	Adults	Adults			ACES 2020

Adults
Larvae
Overwintering eggs
Eggs and Larvae
Eggs, larvae and adults
Eggs and adults
Larvae and adults

Fig. 1. 4. Feeding damage caused by the adult *S. frontalis* on leaves of (A) rose [*Rosa* spp.], (B) hydrangea [*Hydrangea paniculata*], (C) whorled stonecrop [*Sedum* spp.], (D) Weigela [*Weigela florida*], (E) Weigela [*Weigela florida*], (F) Virginia sweet spire [*Itea virginica*], and (G) salvia [*Salvia* spp.]. The holes on the leaves are the feeding damage making the plants unmarketable. Photo credit: (A-E) Shimat V. Joseph, University of Georgia, (F) Danny Lauderdale, North Carolina Cooperative Extension, and (G) Brian Kunkel, University of Delaware.


A
B
C
D
E
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G

CHAPTER 2

EVALUATION OF POTTING MEDIA AS A POTENTIAL SOURCE FOR OVERWINTERING REDHEADED FLEA BEETLE (COLEOPTERA: CHRYSOMELIDAE) INFESTATION IN ORNAMENTAL NURSERIES

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Abstract

Systena frontalis (F.) (Coleoptera: Chrysomelidae) is a serious insect pest of ornamental plants in container nurseries in the central and eastern USA. Adults of *S. frontalis* feed on the leaves and cause numerous shot holes on young and mature foliage, which are not marketed. In spring, *S. frontalis* adults were observed on many host plants in nurseries. The potting media of plant containers could be a potential overwintering site of *S. frontalis*, but this is not systematically determined. Thus, the study aimed to determine if potting media of containers serve as a potential overwintering site for immatures of *S. frontalis* in nurseries. Experiments were conducted on panicle hydrangea (*Hydrangea paniculata* Siebold) in Georgia, North Carolina, and Virginia nurseries in 2021 and 2022. The treatments were: 1) canopy caged, 2) whole plant caged, and 3) noncaged hydrangea plants. The adult densities and feeding damage were recorded. Overall, the numbers of adult *S. frontalis* found on the foliage were significantly greater for the fully caged and noncaged treatments than for the caged canopy treatment. The incidence and severity of *S. frontalis* feeding damage were significantly greater for the fully caged and noncaged treatments than for the caged canopy treatment. This suggests that high numbers of *S. frontalis* adults consistently emerged from the potting media of the plant container overwintered in the nurseries. Because plant containers can harbor large numbers of *S. frontalis* during winter, control measures targeting overwintering immature populations in potting media may reduce adult damage in spring.

Key words Redheaded flea beetle, container nursery, panicle hydrangea, potting media

Systena frontalis (Fabricius) (Coleoptera: Chrysomelidae) is a serious insect pest of many ornamental container plants in nurseries of the eastern and central USA (Lauderdale 2017, ACES 2020, Herrick and Cloyd 2020, Joseph et al. 2021). *S. frontalis* is referred to as redheaded flea beetle, cranberry beetle, or blueberry flea beetle. In 2020, the ornamental crops sold were valued at $4.8 billion USD in the USA (NASS 2021). The ornamental production industry, including floriculture, nursery, and specialty ornamental crops from the top 10 states, represents more than two-thirds of total nursery crop sales $13.8 billion USD (NASS 2020). North Carolina and Georgia states were placed sixth and ninth, respectively, among the top 10 ornamental plant-producing states (NASS 2020). In Georgia, the ornamental horticulture industry, including container and field nurseries, was ranked the fifth largest agricultural commodity and was collectively valued at $260.5 million USD (Wolfe and Stubbs 2019). *S. frontalis* adults attack more than 50 ornamental plants, including roses (*Rosa* spp.) and panicle hydrangeas (*Hydrangea paniculata* Siebold), Virginia sweetspire (*Itea virginica* L.), forsythia (*Forsythia* × *intermedia*), anise-tree (*Illiucium* spp.), azalea (*Rhododendron* spp.), crape myrtle (*Lagerstroemia* spp.), dogwood (*Cornus* spp.), weigela (*Weigela florida* Bunge), and wax myrtle (*Morella cerifera* L.) mostly in container nurseries (Lauderdale 2017, Joseph et al. 2021). In addition to ornamental container nurseries, *S. frontalis* has been observed feeding on various row and specialty crops, including berries, vegetables, cereals, oilseeds, and many weeds (Maltais and Ouellette 2000, Lauderdaule 2017, ACES 2020, Joseph et al. 2021).

Adult *S. frontalis* oviposits beneath the surface of soil or substrate in potting medium (Joseph and Hudson 2020, Herrick and Cloyd 2020) and overwinters as eggs (Joseph and Hudson 2020). In early spring, the eggs hatch, and larvae develop inside the growing medium, feeding on roots. The larvae molt through three instars before pupating in the soil (Mahr 2005). The larval feeding was rarely reported to cause economic plant injury in the nursery (Joseph and Hudson 2020). The adults emerge out of the soil and feed on the foliage. *S. frontalis* adult feeding causes economic damage, although the role of larval feeding on plant health and marketability has not been evaluated.

S. frontalis adults cause plant damage by initially feeding on the epidermal cell layers on adaxial and abaxial leaf surfaces, and the damage later develops into numerous shot holes (Joseph and Hudson 2020). Adult *S. frontalis* prefer to feed on newly developing leaves than mature old leaves (Cloyd and Herrick 2018, Jaffe et al. 2021). With extensive feeding, the leaves appear skeletonized, and container plants with noticeable foliar damage are not salable. Severely affected container plants that were not sold are extensively pruned for re-flush and re-growth (Joseph et al. 2021). As these affected plants remain in the nursery for an extended period until the next market window, additional management costs, such as pesticides, fertilizer, irrigation, equipment, and labor costs, were approximately estimated at $1,637 USD per ha for a year (Joseph et al. 2021). These additional maintenance costs account for about 10% of the current market value (Joseph et al. 2021). Thus, the crop loss due to *S. frontalis* in a container nursery is determined by how many plants are affected and not sold at any given time.

Although *S. frontalis* adults have been reported on commercial crops in the USA since the late 1800s (Chittenden 1902, Peters and Barton 1969, Maltais and Ouellette 2000), it recently emerged as a serious pest in the nurseries (Lauderdale 2021). After overwintering *S. frontalis* adults are observed on plant foliage from early to mid-May in container nurseries in the eastern USA (SVJ unpublished data). It is unclear where the bulk of the *S. frontalis* populations overwinter or originate and are later observed on the container plants in the spring. In the eastern

USA, the landscapes around the nurseries are composed of wood lots (such as pines and hardwood trees), pasture, row crops (such as *Zea mays* L. and *Glycine max* L.), residential gardens and lawns, and unutilized public lands with general grassy- and broad-leaved weeds. In the nursery, many plant species are grown in containers at any given time. It is unclear if *S. frontalis* utilizes host plants outside the nurseries or merely colonizes within the plant containers in the nursery. Previously, *S. frontalis* adults were recovered from the plant containers (Herrick and Cloyd 2020). However, a direct comparison of the proportion of the size of *S. frontalis* population and damage from adults emerging from the containers and those observed on the plant foliage in the nursery was not studied. Thus, the objective of the study was to determine if potting media of containers serve as a potential overwintering site for immatures of *S. frontalis* in nurseries and compare it with the field population. This information will help develop more precise management options, such as drenching, top dressing, or soil incorporating insecticides and strategies that reduce the emergence of *S. frontalis* adults from the containers and their damage.

Materials and Methods

Study sites. Experiments were conducted in Georgia (GA), North Carolina (NC), and Virginia (VA) nurseries in 2021 and 2022 (Table 2. 1). In Georgia, the nurseries were located in McDuffie and Fulton counties in 2021, whereas in 2022, the nursery in McDuffie County was part of the study. In NC, the nursery was located in Cumberland County in both years. In VA, the nursery located in Isle of Wight County was part of the study in 2021, whereas, in 2022, a nursery in Virginia Beach was selected for this study. All the selected nurseries have had persistent problems with *S. frontalis* and suffered a serious crop loss in the past. The details of the size of the nurseries and the landscapes surrounding the nurseries are outlined in Table 2. 1.

Rose spp., *Itea virginica*, *Lagerstroemia* spp., *Hydrangea* spp., and *Wigelia* spp. were the host plants within a 10 m radius where the experiments were conducted.

Plant. In GA, NC, and VA, one-year-old 'Lime Light' panicle hydrangea container plants (*H. paniculata*) were used in the experiment in both years, except for GA site 1 in 2021, cultivar 'Lime Light Punch' was used. In all sites, 11.4 L plastic containers were used in both years of the experiments, except at one VA nursery in 2022, 18.9 L containers were used. Panicle hydrangea is susceptible to *S. frontalis* adult attack and feeding damage (Herrick and Cloyd 2020, Joseph et al. 2021). The year before the experiments (in 2020 and 2021), the panicle hydrangea plants were potted and maintained under a standard growing regime. The plants were irrigated at least once a day for the duration of the experiments. These container plants were kept in the nursery and were exposed to natural adult populations of *S. frontalis* for at least two months before the onset of winter. The container plants were overwintered in the nurseries and were used in the following spring.

Insect. *S. frontalis* adults naturally occur in the selected container nurseries as adults are often observed feeding on the foliage. The assumption was that *S. frontalis* adults oviposited a sufficient number of eggs into the potting media of these plant containers before winter. The eggs of *S. frontalis* typically overwinter in the soil (Joseph and Hudson 2020, Jaffe et al. 2021), and they hatch when the soil temperatures rise above 15 °C in the late winter. By early spring, larvae develop inside the potting media, molt through later larval stages, pupate, and adults emerge by early to mid-May in GA, and NC. In VA, adults emerge beginning mid to late May. Experiments were conducted on the emergence of F1 adults originating from the overwintering eggs. During the spring, panicle hydrangea plants break winter dormancy in April as new foliage is formed. In GA, experiments were set up in the third week of April before the emergence of *S.*

frontalis adults from the potting media. In NC and VA, the experiments were set up by mid-May in both years. The foliage of panicle hydrangea plants had no damage from *S. frontalis* adult feeding before the experiments were initiated. *S. frontalis* individuals were at late larval stages or pupae in the soil or potting media when the experiments were set up in the nurseries.

Experimental design. The experiment was conducted inside the nursery in both years and in all three states. Container panicle hydrangea plants that were previously naturally exposed to *S. frontalis* adults were used in the experiments. Three treatments were included, and they were: 1) canopy caged, 2) completely caged, and 3) noncaged plants. For the first treatment, the canopy of the hydrangea plants was wrapped with a fabric mesh (No-see-um nylon netting, BioQuip, Rancho Dominguez, CA) to prevent access of *S. frontalis* adults to the foliage. The rectangular-sized mesh (0.7 m × 0.6 m) was wrapped and secured on the plant canopy using medium-sized binder clips (32 mm) from the crown to the top of the canopy (Fig. 2.1A). The plants used for the completely caged treatment were placed within 47.5 × 47.5 × 93.0 cm (Width: Depth: Height) cages (BugDorm, BugDorm-4E4590 Insect Rearing Cage, https://shop.bugdorm.com/index.php). The mesh size aperture of the cages was 150 x 150 µm, allowing irrigation water into the potting media. The plants in the cages were completely isolated, and *S. frontalis* adults had no access to the foliage from outside (Fig. 2. 1B). For noncaged treatment, the container plants were cage-free with no physical barriers, and *S. frontalis* adults found in the nurseries could freely access the foliage (Fig. 1. 1C). In the nurseries, the treatments were arranged in a randomized complete block design at all sites in both years. The plant containers and blocks were maintained at 1 m spacing from each other. In GA, the treatments were replicated 10 times in both years. In NC, treatments were replicated 10 and 5 times in 2021 and 2022, respectively, whereas, in VA, the treatments were replicated 4 and 6 times. The individual container plant served as the experimental unit. In GA, the experiment was set up on 27 April and 4 May 2021 for sites 1 and 2, respectively. In 2022, the experiment was set up on 28 April in GA. The experiment was set up in NC on 12 May 2021 and 12 May 2022. In VA, it was set up on 12 May 2021 and 13 May 2022, respectively.

Evaluation. To quantify the number of *S. frontalis* adults on foliage, the number of adults was visually quantified for one minute per plant. For canopy caged treatment, the mesh sleeves wrapped around the canopy of the plants were opened completely before assessment. For the completely caged treatment, the cages were partially opened for assessment. In 2021, the numbers of *S. frontalis* adults on the foliage were also quantified on 18 and 24 May in GA site 1, and 19 and 25 May in GA site 2. In 2022, the numbers of *S. frontalis* adults were quantified on 17, 24, and 31 May in GA site 1. In 2021, the numbers of *S. frontalis* adults on the foliage were quantified on 19, 25 May, 1, 9, and 23 June in NC, and 26 May and 27 June in VA, whereas, in 2022, they were quantified on 18, 23 May, 1, 8, 14, 22 June and 6 July in NC, and 20, 27 May, 2, 10, 21 and 23 June in VA.

To determine the incidence and severity of feeding damage, the panicle hydrangea leaves were individually bagged from each plant (replicate) and transported to the entomology laboratories for evaluation. The incidence of *S. frontalis* damage was assessed by recording the number of leaves with at least one discrete *S. frontalis* feeding damage. Because *S. frontalis* adults feed on the epidermal layers, the affected areas are clearly visible as reddish-brown scoops or shot holes on the leaves. To determine the severity of *S. frontalis* feeding damage, the percentage of leaf area damaged by adult feeding was visually determined from each sampled leaf, and the proportion of severity of damage was determined. In GA, the incidence and severity of feeding damage on the panicle hydrangea foliage were evaluated after collecting 100 and 20 random fully-expanded leaves from each plant on 24 May 2021 and 31 May 2022, respectively, from Georgia sites. In NC and VA, only the numbers of *S. frontalis* adults on foliage and incidence of feeding damage were documented, while the severity of feeding damage was not evaluated. In NC and VA sites, 100 fully expanded leaves were randomly collected in both years. In NC, leaves were collected from each plant on 23 June 2021 and 6 July 2022, whereas in VA, they were collected on 27 June 2021 and 23 June 2022.

Statistical analyses. The statistical analyses for all data were conducted using SAS software (SAS Institute 2016). The numbers of adult *S. frontalis* collected until final sample dates were averaged by treatment and replication. The adult beetle data were subjected to one-way analysis of variance (ANOVA) using the generalized linear model using the PROC GLIMMIX procedure in SAS with log link function and distribution as negative binomial. The method used was laplace. The treatments and replications were fixed and random effects, respectively. Means and standard errors were calculated using PROC MEANS procedure, and separated by Tukey-Kramer test ($P < 0.05$).

The percentage of damaged leaves (any incidence of *S. frontalis* feeding damage) and severity of damage (%) caused by *S. frontalis* feeding on every leaf were arcsine square-root transformed. The transformed data were subjected to one-way ANOVA using the general linear model using the PROC GLM procedure in SAS. The treatments and replications were fixed and random effects, respectively. The normality of the residuals for all the sites and years was checked after examining the histograms using PROC UNIVARIATE procedure in SAS. Means and standard errors were calculated using PROC MEANS procedure and separated by Tukey HSD test ($P < 0.05$).

Results

Adult *S. frontalis*. In 2021, the numbers of adult *S. frontalis* were significantly greater for the fully caged and noncaged treatments than for canopy caged treatment at site 1 (Table 2. 2, Fig. 2. 2A) and site 2 (Table 2. 2, Fig. 2. 1B) in GA. There were no significant differences among treatments in NC site 3 (Table 2. 2, Fig. 2. 2C) and VA site 4 (Table 2. 2, Fig. 2. 2D). In 2022, the fully caged treatment had significantly greater numbers of *S. frontalis* adults than for noncaged treatment followed by canopy caged treatment in GA site 1 (Table 2. 2, Fig. 2. 2E). There were no significant differences among treatments in NC site 2 (Table 2. 2, Fig. 2. 2F) and VA site 3 (Table 2. 2, Fig. 2. 2G).

Incidence of *S. frontalis* feeding damage. In 2021, the percentage incidence of *S. frontalis* feeding damage was significantly greater for fully caged and noncaged treatments than for canopy caged treatment in GA site 1 (Table 2. 2, Fig. 2. 3A), 2 (Table 2. 2, Fig. 2. 3B) and in NC site 3 (Table 2. 2, Fig. 2. 3C). Noncaged treatment had a significantly greater incidence of *S. frontalis* feeding damage than for fully and canopy caged treatments at VA site 4 (Table 2. 2, Fig. 2. 3D).

In 2022, the percentage incidence of *S. frontalis* feeding damage was significantly greater for fully caged and noncaged treatments than for canopy caged treatment in GA site 1 (Table 2. 2, Fig. 2. 3E) and NC site 2 (Table 2. 2, Fig. 2. 3F). There were no significant differences among treatments in VA site 3 (Table 2. 2, Fig. 2. 3G).

Severity of *S. frontalis* feeding damage. In 2021, the severity of *S. frontalis* feeding damage was significantly greater for fully caged and noncaged treatments than for canopy caged treatment in site 1 (Table 2. 2, Fig. 2. 4A) and site 2 (Table 2. 2, Fig. 2. 4B) in GA. In 2022, the severity of *S. frontalis* feeding damage was significantly greater for fully caged treatment than for canopy caged and noncaged treatments (Table 2. 2, Fig. 2. 4C).

Discussion

We sought to determine if containers of panicle hydrangea maintained in nurseries over the growing season and grown from overwintering liners would serve as a source for *S. frontalis* in the following spring. The results show that high numbers of *S. frontalis* adults consistently emerge from the potting media of the panicle hydrangea containers maintained in the previous growing season and overwintered on site. This suggests that *S. frontalis* eggs or larvae can overwinter in plant containers and become a source for adult infestation on the hydrangea and other potentially other plants in the spring. However, the results did not determine what proportion of *S. frontalis* population utilized potting media as they could overwinter and develop on plants outside the nurseries and then migrate into the container plants in the nurseries. This is the first replicated study conducted in multiple nurseries in three southeastern US states showing the potting mixture of the containerized ornamentals can serve as a source for *S. frontalis* adults. Moreover, this result is consistent with previous work, where *S. frontalis* adults were collected from containers in the greenhouse (Herrick and Cloyd 2020). Thus, overwhelming densities of *S. frontalis* overwinter in containers as eggs, and the eggs hatch when the temperature gradually increases during late winter.

Nursery growers in the eastern states mainly use foliar insecticide sprays to combat *S. frontalis* damage, which has shown limited or inconsistent success (Joseph et al. 2021). For *S. frontalis* adult control, neonicotinoids are the most extensively used insecticides by nursery growers (Joseph et al. 2021). Because insecticides mostly, neonicotinoids have been linked to pollinator decline (Blacquière et al. 2012), and consumers demand neonicotinoid-free plant materials from nurseries (Rihn and Khachatryan 2016, Wei et al. 2020). Thus, some nursery growers avoid using neonicotinoids (Joseph et al. 2021) for *S. frontalis* control but are left with limited alternative options. The results from the current study suggest that growers could target eggs, developing larval stages, and pupae in the potting media, as high numbers of eggs and immature stages colonize the potting media and adults emerge from the media. As alternative options, such as drench application, soil incorporation, and top dressing of insecticides and entomopathogenic nematodes and fungi, are other potential methods of control. However, more research is warranted on the drench application method for managing soil-borne stages. These approaches could reduce the dependence on neonicotinoids and other insecticides currently applied as foliar sprays.

In summary, the experiments conducted over two years and three nurseries conclusively show that the potting media of plant containers is a source of *S. frontalis* adult problems in the nurseries. More research is warranted to determine the efficacy of insecticides against immature stages of *S. frontalis* in potting media. This tactic will reduce the need for additional foliar sprays for *S. frontalis* control. In addition, the timing of insecticide drench into the containers to target the developing larvae could be improved as precise use of insecticide or other agents, such as entomopathogenic nematodes and fungi, will reduce the costs involved in scouting, insecticide material, labor, and equipment. These precise non spray tactics will reduce the burden on the environment by preventing water contamination, nontarget exposure, especially to beneficial arthropods, such as predators, parasitoids, and pollinators, and unintended exposure of insecticides on applicators. Thus, the current research will help reduce the need for the excessive number of foliar insecticide applications and the amounts used for *S. frontalis* control in the nurseries.

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Table 2. 1. The characteristics of nursery sites in GA, NC, and VA.

Year	State	County	Site	Nursery type	Nursery area (ha)	Landscape characters adjacent to the nursery
2021						
	GA	Fulton	1	Retail	2.9	Pasture, retail nursery sales, residential
	GA	McDuffie	2	Wholesale	11.4	Wood lot and nursery
	NC	Cumberland	3	Wholesale	43.5	Wood lot and nursery
	VA	Isle of Wight	4	Wholesale	180.0	Pastures, wood lots, row crop fields
2022						
	GA	McDuffie	1	Wholesale	11.4	Wood lot and nursery
	NC	Cumberland	2	Wholesale	43.5	Wood lot and nursery
	VA	Virginia Beach[a]	3	Wholesale / Research	1.5	Wood lot, industrial area, housing

[a] Independent city (not County)

Table 2. 2. Analysis of variance of the number of *S. frontalis* adults, incidence (%), and severity (%) of *S. frontalis* feeding damage per plant in four nurseries in GA, NC, and VA. Experiments were conducted in 2021 and 2022.

2021					2022				
State	Variable	*F*	df	*P*	State	Variable	*F*	df	*P*
GA					GA				
Site 1	Beetle[a]	10.1	2, 18	0.001	Site 1	Beetle	10.6	2, 18	0.001
	Incidence[b]	18.6	2, 27	< 0.001		Incidence	34.8	2, 15	< 0.001
	Severity[c]	32.6	2, 18	< 0.001		Severity	14.8	2, 15	< 0.001
Site 2	Beetle	9.8	2, 16	0.002		-	-	-	-
	Incidence	57.3	2, 26	< 0.001		-	-	-	-
	Severity	61.1	2, 16	< 0.001		-	-	-	-
NC					NC				
Site 3	Beetle	0.0	2, 18	0.993	Site 2	Beetle	0.2	2, 8	0.859
	Incidence	22.3	2, 17	< 0.001		Incidence	16.5	2, 4	0.001
VA					VA				
Site 4	Beetle	2.2	2, 6	0.197	Site 3	Beetle[a]	1.7	2, 10	0.227
	Incidence	64.8	2, 6	< 0.001		Incidence	3.0	2, 5	0.093

[a] number of *S. frontalis* adults observed per plant; [b] incidence of *S. frontalis* damage (%) per plant; [c] severity of *S. frontalis* feeding damage (%) per plant.

Fig. 2. 1. Panicle hydrangea two-year old liner plants with caging treatments: (A) canopy caged, (B) fully caged, and (C) non-caged.


A
B
C
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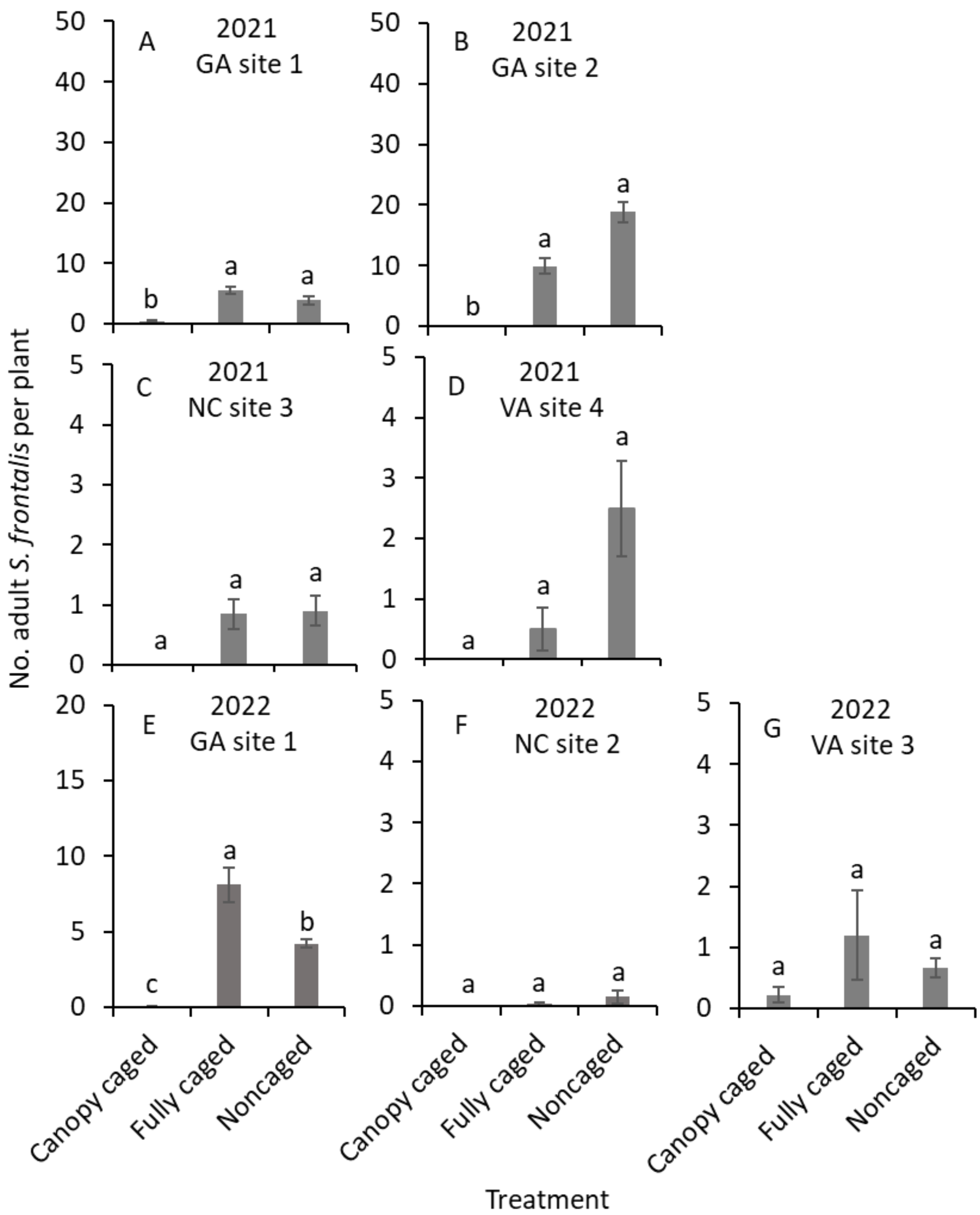
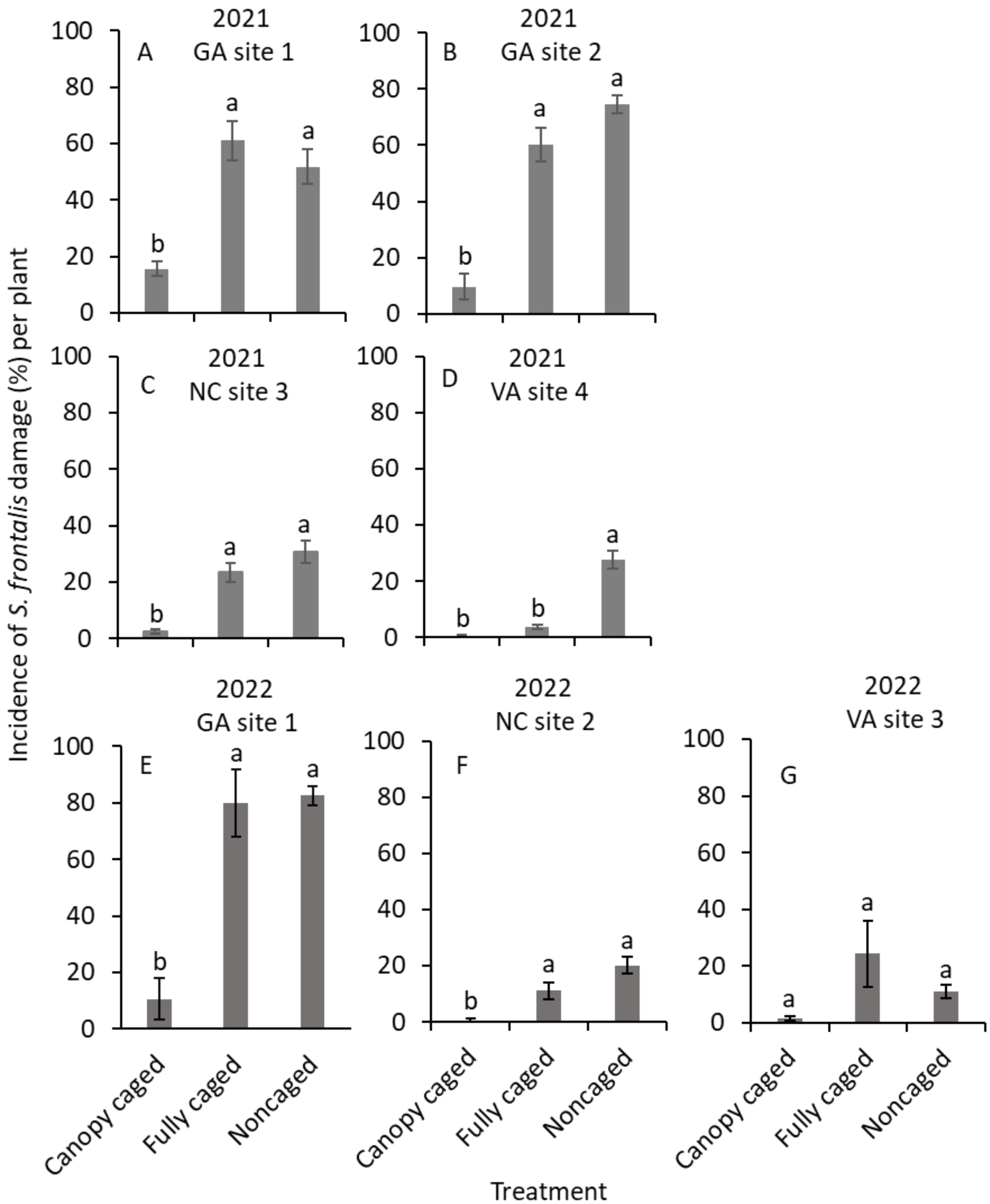
Fig. 2. 2. Mean (±SE) *S. frontalis* adult densities (expressed as number of adult beetles per plant) found on canopy caged, fully caged, or non-caged panicle hydrangea plants grown in nurseries in Georgia (GA), North Carolina (NC), and Virginia (VA) in 2021 and 2022: (A) site 1 (GA, (B) site 2 (GA), (C) site 3 (NC), (D) site 4 (VA) in 2021, and (E) site 1 (GA), (F) site 2 (NC) and (G) site 3 (VA) in 2022. Bars with the same letters within a figure are not significantly different at (α = 0.05) using Tukey-Kramer Test.



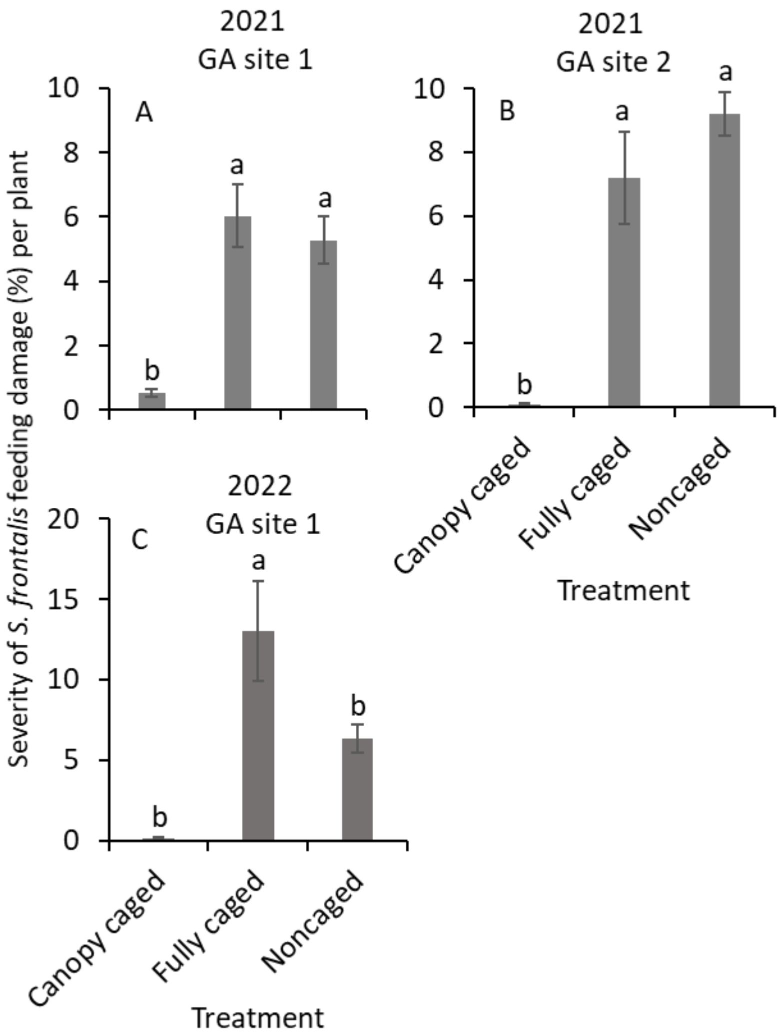
A
2021
GA site 1
B
2021
GA site 2
C
2021
NC site 3
D
2021
VA site 4
E
2022
GA site 1
F
2022
NC site 2
G
2022
VA site 3
No. adult S. frontalis per plant
Canopy caged
Fully caged
Noncaged
Treatment

Fig. 2. 3. Mean (±SE) percentage incidence of *S. frontalis* feeding damage found on canopy caged, fully caged, or non-caged foliage of panicle hydrangea plants grown in nurseries in Georgia (GA), North Carolina (NC), and Virginia (VA) in 2021 and 2022: (A) site 1 (GA), (B) 2 (GA), (C) 3 (NC), (D) 4 (VA) in 2021 and (E) site 1 (GA), (F) 2 (NC) and (G) 3 (VA) in 2022. Bars with the same letters within a figure are not significantly different at ($\alpha = 0.05$) using Tukey-Kramer Test.



Incidence of S. frontalis damage (%) per plant
2021
A
GA site 1
2021
B
GA site 2
2021
C
NC site 3
2021
D
VA site 4
2022
GA site 1
E
2022
NC site 2
F
2022
VA site 3
G
Canopy caged
Fully caged
Noncaged
Treatment

Fig. 2. 4. Mean (±SE) severity of *S. frontalis* feeding damage found on canopy caged, fully caged, or non-caged foliage of panicle hydrangea plants grown in nurseries in Georgia (GA): (A) site 1 (GA), (B) 2 (GA) in 2021, and (C) site 1 (GA) in 2022. Bars with the same letters within a figure are not significantly different at ($\alpha = 0.05$) using Tukey-Kramer Test.


2021
GA site 1
A
2021
GA site 2
B
2022
GA site 1
C
Severity of S. frontalis feeding damage (%) per plant
Canopy caged
Fully caged
Noncaged
Treatment
a
b

CHAPTER 3

EFFECTS OF FENCE BARRIER ON INCIDENCE AND DAMAGE OF REDHEADED FLEA BEETLE (COLEOPTERA: CHRYSOMELIDAE) ADULTS IN CONTAINER NURSERIES

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Abstract *Systena frontalis* (F.) (Coleoptera: Chrysomelidae) is an important pest of many container ornamental plants in the central and eastern USA. Adult *S. frontalis* cause feeding damage on leaves, and affected plants are not marketed. *S. frontalis* adults are currently managed using insecticides, especially neonicotinoids, and growers are seeking alternative options as the customers demand neonicotinoid-free plants after concerns over nontarget exposure to pollinators. As an alternative management option, barrier fences were investigated to protect an ornamental nursery crop from invading insect pest in a nursery setting. However, the utility of barrier fences for invading *S. frontalis* adults is unknown. Thus, the objective was to determine the effect of overhang barrier fence with and without insecticide impregnation on *S. frontalis* adult densities and their feeding damage on nursery-grown panicle hydrangea. In 2021 and 2022, a 150 cm tall, exclusion, overhang fence study was conducted in a container nursery in Georgia, USA. The treatments were: 1) deltamethrin-impregnated netting enclosed barrier, 2) nontreated netting enclosed barrier, and 3) no barrier. Four plant containers were placed in the experimental plot's center. Both barrier treatments reduced the incidence and severity of adult feeding damage on the panicle hydrangea than no barrier treatment, regardless of deltamethrin-impregnation. The numbers of *S. frontalis* adults were not consistently lower for netting barrier treatments than for no barrier treatment. The results suggest that the exclusion or inclusion overhang barrier fence can protect plants from invading adult *S. frontalis*.

Key words: Panicle hydrangea, redheaded flea beetle, container nursery, netting, deltamethrin, overhang

Systena frontalis (F.) (Coleoptera: Chrysomelidae) is a serious insect pest of many container ornamental plants in the central and eastern USA (Lauderdale 2017, ACES 2020, Herrick and Cloyd 2020, Joseph et al. 2021). In 2020, the ornamental horticulture industry had a farmgate value of ~$1.2 billion USD, where 19.7% of it was contributions from container nurseries in GA, USA (Kane 2022). The marketing of container plants relies on high standards of plant quality and aesthetic appeal. Adults of *S. frontalis*, however, feed on plant foliage which causes numerous shot holes, and severely affected plants often have many skeletonized leaves. The plants with *S. frontalis* feeding damage are rarely marketed (Joseph et al. 2021, Lauderdale 2021a). The container growers often incurred losses as management inputs to protect the plants from the *S. frontalis* feeding and maintaining the plants for an extended period when they could not deliver the plants during specific market windows due to *S. frontalis* feeding damage (Joseph et al. 2021). Off more than 50 ornamental plant species attacked, *S. frontalis* caused severe damage to panicle hydrangea (*Hydrangea paniculata* Siebold)

Adult *S. frontalis* populations are typically managed using insecticides, such as neonicotinoids (such as dinotefuran, clothianidin, and thiamethoxam), acephate, carbaryl, and bifenthrin (Joseph et al. 2021). Among insecticides, neonicotinoids are used by most growers for *S. frontalis* management (Joseph et al. 2021, Lauderdale 2021b). Because neonicotinoids have been implicated in harming nontargets, such as pollinators and beneficial organisms (Blacquière et al. 2012, Calvo-Agudo et al. 2019), and some customers demand neonicotinoid-free products, nursery producers are seeking alternative efficacious insecticides (Joseph et al. 2021), delivery strategies and alternate control options to meet the market demands.

As alternative control options to insecticides against arthropod pests, protecting the managed crops by physical exclusion techniques from the invading pest population were examined in various agroecosystems. In cranberry, *Vaccinium macrocarpon* Aiton, row covers physically excluded *S. frontalis* adults from the plants (Guédot and Henschell 2015). Similarly, exclusion barrier fences were tested successfully against many pests in vegetable and row crop systems. For example, incidence and damage from invading cabbage maggot, *Delia radicum* (L.), tiger fly, *Coenosia tigrina* (F.), and the carrot rust fly, *Psila rosae* (F) have proved effective in protecting crops, such as radish [*Raphanus sativus* (L.)], rutabaga [*Brassica napus* (L.)], and carrot [*Daucus carota* (L.)] using exclusion barrier fences constructed around the crop fields (Vernon and Mackenzie 1998, Päts and Vernon 1999, Vernon and McGregor 1999, Bomford et al. 2000). The exclusion barrier fences were build using metal frames and fabric mesh screen excluded the invading pest adults in both small (Vernon and Mackenzie 1998) and large-scale field trials (Vernon and McGregor 1999). Bomford et al. (2000) suggested that an exclusion fence with collection overhangs on the top can be more effective than without an overhang in excluding flying insect pests. However, little is known about the efficacy of physical barrier fences in protecting plants from *S. frontalis* adults in ornamental container nurseries. Thus, the objective was to determine the effects of overhang fence barriers with and without insecticide-impregnated mesh screens on the incidence of invading *S. frontalis* adults as well as the incidence and severity of *S. frontalis* feeding damage in an ornamental nursery.

Materials and Methods

Study site. The experiments were conducted in a 330-ha wholesale nursery in McDuffie County, GA, in 2021 and 2022. The experimental site was selected because the nursery has a history of persistent *S. frontalis* problems and has suffered serious crop losses in the past. Wood lots and nursery crops surrounded the experimental site. Ornamental plants, such as crape myrtle (*Lagerstroemia indica* L.), China rose (*Hibiscus rosa-sinensis* L.), panicle hydrangea

(*Hydrangea paniculata* Siebold), and rose (*Rosa* spp.) were present within a 10-m radius of the experimental site. Adults of *S. frontalis* and their feeding damage have been regularly observed on these hosts (Lauderdale 2017). The experiments were conducted from 7 June to 28 June in 2021 and 10 May to 19 July in 2022 as adult *S. frontalis* population from immature overwintering stages were observed from mid-May to late July in GA nurseries (Joseph and Hudson 2020).

Plants and insects. Experiments were conducted using 11.4 L, 2-year-old, 'Lime Light' panicle hydrangea container-grown plants. The plant canopy height of the container plants was ~70 cm. Panicle hydrangea is a high-value ornamental flowering plant and is extremely vulnerable to *S. frontalis* adult feeding and damage (Herrick and Cloyd 2020, Joseph et al. 2021). Liners of panicle hydrangea were potted using standard nursery media composed of composted bark and sand and maintained in the nursery during summer, and those container plants were used in spring the following year. Plants were maintained in an area of the nursery where *S. frontalis* populations and their damage were not observed. Plants were irrigated on a standard overhead irrigation schedule twice per day for 30 mins. Plants were top dressed at 7.59 kg per m^2 with slow-release fertilizer per plant (Osmocote Pro, 18: 9: 10 [N:P: K], Summerville, SC). The container plants were maintained in the nursery for the rest of the summer and winter and were moved to the experimental site in April of the following year (2021 and 2022). Although *S. frontalis* adults or their feeding damage were not observed on the selected plants where plants were maintained, the surface of the potting media of all containers was covered with a 0.65 m × 0.65 m fabric mesh (no-see-um nylon netting, BioQuip, Rancho Dominguez, CA) using 91.4 cm plastic zip ties (Malco Products Inc., Barberton, OH) and 32 mm binder clips. To secure the fabric mesh, a zip tie was wrapped around the fabric mesh around the containers, and binder clips were placed along the circular lip or edge of the plastic container and on the stem in the crown area of the plant. This physical barrier in the surface of the potting media prevented any emergence of adult *S. frontalis* if infested. The netting material on the potting media surface allowed the irrigation water to pass through.

Fence design. Custom-built fences consisted of wooden posts and no-see-um fabric mesh netting; eight 3.8 × 1.9 × 180 cm (depth × width × height) posts were deployed on a leveled ground with the bottom 30 cm buried into the ground (Fig. 3. 1A). These wooden posts were erected on a 365 × 365 cm plot with three posts on each side. Insect netting was attached along the outside of the upright wooden posts (Fig. 3. 1A). The enclosed fence barrier was 150 cm tall. On top of each wooden post, a 3.8 × 1.9 × 53 cm (width × breadth × length) wooden piece was attached using a 23 cm metal clamp facing the outward direction (Fig. 3. 1). The clamps were screwed into the wooden post. The same fabric screen used on the side of the fence was attached to the wooden pieces (Fig. 3. 1), forming a mesh overhang sloping downward at 45 ° and facing outward. The fabric mesh screens were attached to the wooden posts, and overhang pieces using heavy-duty staples were shot 20-30 cm apart on the exterior of each wooden post. The wooden overhang functioned as a collection device restricting the movement of incoming adults of *S. frontalis* over the fence barrier (Bomford et al. 2000).

Experimental design. There were three treatments: (1) fence barrier with deltamethrin-impregnated mesh, (2) fence barrier with nontreated mesh, and (3) no fence barrier. The treatments were replicated four times in a randomized complete block design. Each treatment and block were 2 m apart from each other. The experiment unit was 365 × 365 cm (13.3 m^2) enclosed fenced barrier plot (Fig. 3. 1B) or open plot. Four 11.4 L panicle hydrangea container plants (as described in the previous section) were placed inside each plot area. The insecticidal barrier treatment was 92 cm wide black-colored polyethylene fabric mesh netting (PermaNet® screens, Vestergaard S.A., Place St. Francois, Lausanne, Switzerland). The mesh size of the insecticide-impregnated mesh was 32 holes per cm^2. The insecticide impregnated on the polyethylene screen was 0.4% w/w deltamethrin. Deltamethrin-impregnated fabric mesh netting is assumed to be lethal to insect pests upon contact (Arthurs 1997, Arthur et al. 2018). The insecticide-impregnated netting was wrapped around the wooden frame with a 15 cm overlap.

For nontreated barrier treatment, the no-see-um fabric mesh netting was used. It was 150 cm wide and was wrapped around the wooden posts (Fig. 3. 1B). The overlapped area around the fence was secured using large safety pins. The bottom portion of the screen was in contact with the ground with no gaps. The overhang structure was built to trap and prevent adult *S. frontalis* from flying over the fence, as well as to improve the effectiveness of the barriers.

No barrier treatment was essentially the control as there was no fence barrier to restrict the movement of *S. frontalis* adults. The open plot was 365 × 365 cm (13.3 m^2), so the dispersing *S. frontalis* adults could freely access the four panicle hydrangea container plants. The experiments were initiated when the container plants were installed inside the enclosed fence area or open plots on 7 June 2021 and 10 May 2022.

Evaluation. To determine the treatment effects, the numbers of *S. frontalis* adults and the incidence and severity of *S. frontalis* adult feeding damage on the hydrangea foliage in each treatment were quantified. A 2 m high ladder was used to access the container plants inside the fenced area for evaluation as to preserve the integrity of the fence structure. Numbers of *S. frontalis* adults on the foliage and incidence and severity of feeding damage on the panicle hydrangea foliage were evaluated on 14, 21, and 28 June in 2021 and 17, 24, 31 May, 7, 28 June, and 19 July in 2022. Once the integrity of the fence structure was compromised, the experiment was concluded. In 2021, the experiment was concluded after three weeks because a storm damaged the structure of some of the fences.

To determine the incidence of *S. frontalis* adults, the numbers of adults settled on the foliage were visually counted for five mins on four plants (per replication). To determine the incidence and severity of feeding damage on panicle hydrangea foliage, 20 random leaves from each plant were nondestructively evaluated; thus, 80 random leaves were evaluated per treatment. To avoid re-evaluating the same leaves on subsequent sampling dates, evaluated leaves were marked using a permanent marker pen. Incidence of *S. frontalis* damage was recorded when at least one distinct *S. frontalis* feeding damage spot or scooped surface was observed. Percentages of total damaged leaves were calculated to determine the incidence of feeding damage per plant and averaged to get a value for each replication. The severity of *S. frontalis* feeding damage was assessed by determining the percentage of leaf area damaged by adult feeding. This information from 80 leaves was averaged to get a value on the severity from each replication.

Statistical analyses. SAS software was used to conduct statistical analyses on all of the data (SAS Institute 2016). The numbers of adult *S. frontalis* data were log-transformed and subjected to a one-way analysis of variance (ANOVA) using the PROC GLIMMIX procedure with log link function and distribution as negative binomial. The method was Laplace. The Tukey-Kramer test ($P < 0.05$) was used to separate the means. Means and standard errors were calculated using the PROC MEANS procedure in SAS.

The percentages of incidence and severity of damage were arcsine square-root transformed and subjected to one-way ANOVA using the general linear model PROC GLM procedure. The treatment and replication were fixed and random effects in the model. The means were separated using Tukey HSD Test (*P* < 0.05). The means and standard errors were calculated using the PROC MEANS procedure.

Results

Adult *S. frontalis.* In 2021, there were no significant differences in the numbers of adult *S. frontalis* among treatments at 7 (*F* = 1.9; df = 2, 6; *P* = 0.219; Fig. 3. 2A), 14 (*F* = 1.5; df = 2, 6; *P* = 0.301; Fig. 3. 2B) and 21 days after set up (DAS) (*F* = 1.1; df = 2, 6; *P* = 0.402; Fig. 3. 2C). In 2022, the numbers of *S. frontalis* adults were significantly lower for the insecticidal barrier and the nontreated barrier treatments than for no barrier treatment at 7 (*F* = 9.6; df = 2, 6; *P* = 0.014; Fig. 3. 2D), 21 (*F* = 5.5; df = 2, 6; *P* = 0.044; Fig. 3. 2F), and 49 DAS (*F* = 10.5; df = 2, 6; *P* = 0.011; Fig. 3. 2H). For the remaining observation dates, there were no significant differences among treatments as at 14 (*F* = 3.7; df = 2, 6; *P* = 0.090; Fig. 3. 2E), 28 (*F* = 1.6; df = 2, 6; *P* = 0.282; Fig. 3. 2G), and 70 DAS (*F* = 0.0; df = 2, 6; *P* = 0.963; Fig. 3. 2I).

Incidence of *S. frontalis* feeding damage. In 2021, the percentage incidence of *S. frontalis* feeding damage was significantly lower for insecticidal barrier and the nontreated barrier treatments than for no barrier treatment at 7 (*F* = 35.1; df = 2, 3; *P* = 0.001; Fig. 3. 3A), and 14 (*F* = 11.1; df = 2, 3; *P* = 0.009; Fig. 3. 3B). At 21 DAS, incidence of *S. frontalis* feeding damage for the nontreated barrier was significantly lower than for no barrier treatment. However, no significant differences were found between insecticidal barrier and no barrier, as well as between insecticidal barrier and the nontreated barrier (*F* = 8.3; df = 2, 3; *P* = 0.019; Fig. 3. 3C). In 2022, the percentage incidence of *S. frontalis* feeding damage was significantly lower for insecticidal and the nontreated barrier treatments than for no barrier treatment at 7 (*F* = 17.3; df = 2, 3; *P* = 0.003; Fig. 3. 3D), 14 (*F* = 64.3; df = 2, 3; *P* < 0.001; Fig. 3. 3E), 21 (*F* = 92.5; df = 2, 3; *P* < 0.001; Fig. 3. 3F), 28 (*F* = 29.3; df = 2, 3; *P* = 0.001; Fig. 3. 3G), and 49 DAS (*F* = 24.8; df = 2, 3; *P* = 0.001; Fig. 3. 3H). At 70 DAS, the incidence of *S. frontalis* feeding damage for the nontreated barrier was significantly lower than for no barrier treatment. However, no significant differences were found between the insecticidal barrier and no barrier, as well as between the insecticidal barrier and the nontreated barrier (*F* = 14.9; df = 2, 3; *P* = 0.005; Fig. 3. 3I).

Severity of *S. frontalis* feeding damage. In 2021, severity of *S. frontalis* feeding damage was significantly lower for insecticidal and the nontreated treatments than for no barrier treatment at 7 DAS (*F* = 14.7; df = 2, 3; *P* = 0.005; Fig. 3. 4A). However, at 14 DAS, there were no significant differences among treatments (*F* = 1.8; df = 2, 3; *P* = 0.246; Fig. 3. 4B). At 21 DAS, the nontreated treatment was significantly lower than for the no barrier treatment (*F* = 6.4; df = 2, 3; *P* = 0.033; Fig. 3. 4C). There were no significant differences between insecticidal barrier and no barrier treatments as well as insecticidal and the nontreated barrier treatments. In 2022, severity of *S. frontalis* feeding damage was significantly lower for insecticidal and the nontreated barrier treatments than for no barrier treatment at 7 (*F* = 21.3; df = 2, 3; *P* < 0.002; Fig. 3. 4D), 14 (*F* = 72.3; df = 2, 3; *P* < 0.001; Fig. 3. 4E), 21 (*F* = 58.8; df = 2, 3; *P* < 0.001; Fig. 3.4F), 28 (*F* = 44.3; df = 2, 3; *P* < 0.001; Fig. 3. 4G), 49 (*F* = 26.8; df = 2, 3; *P* = 0.001; Fig. 3. 4H) and 70 DAS (*F* = 16.8; df = 2, 3; *P* = 0.004; Fig. 3. 4I).

Discussion

We sought to determine whether enclosed physical barriers with overhangs could protect container plants from adult *S. frontalis* attacks in nurseries. The results show that the fence barrier reduced the invasion of *S. frontalis* adults as the incidence and severity of feeding damage typically caused by *S. frontalis* adults were lower than on plants placed in open plots (Fig. 3. 3 and 4). This result is consistent with previous studies where plants within fenced plots (Pats and Vernon 1999) with overhangs (Bomford et al. 2000) reduced invading adults of *D. radicum* and

P. rosae than in the nonfenced control plots. This study proves that fence barriers with overhangs can be a potential management strategy to mitigate adult *S. frontalis* attacks on container plants in nurseries. Particularly, the data suggest that plants can be protected from *S. frontalis* adults using enclosed exclusion fences for up to 70 d and reduce crop loss. Secondly, nursery growers routinely purchase plant material from other suppliers in the region, and the incoming plant material could be a source for *S. frontalis* infestation. Because lack of adequate facilities to isolate the large numbers of incoming plants, they are often maintained along with existing plant stock in the nursery. Moreover, limited effective insecticide tools are available for the longer-term management of *S. frontalis* in nurseries (Joseph et al. 2021). The spread of *S. frontalis* adults into the remaining areas of the nurseries can be prevented by maintaining the newly arrived plants in inclusion enclosed fenced areas where *S. frontalis* adults emerging from the new containers can be confined within the fence.

The incidence and severity of *S. frontalis* adult feeding damage between deltamethrin-impregnated netting and nontreated netting fences were not different. This suggests that deltamethrin-impregnated barriers may not provide additional value to preventing adult *S. frontalis* damage on ornamental plants in container nurseries. Previously, objects treated with deltamethrin (0.05%), such as plywood, concrete, and tile panels, were proved to be highly toxic to stored product beetles, such as *Tribolium castaneum* (Herbst) and *Rhyzopertha dominica* (F.) (Arthur 1997). Further, deltamethrin (0.4% w/w) impregnated exclusion nettings caused 43% reduction of penetration damage from Western flower thrips, *Frankliniella occidentalis* (Pergande) as compared with nontreated nettings under laboratory and greenhouse conditions (Arthurs et al. 2018). Similarly, deltamethrin-impregnated mesh barriers reduced mosquitoes, *Anopheles* spp. and sand flies, *Phlebotominae* spp. population densities against the spread of malaria and leishmaniasis into human populations (Faiman et al. 2011). It is unclear if deltamethrin has any activity against *S. frontalis* adults, but previous studies show that lambda-cyhalothrin protected plants for up to 20 d after foliar application (Kunkel 2016). Thus, more research is warranted to determine if the deltamethrin-impregnated netting caused adult mortality through contact.

Although the percentage incidence and severity of adult *S. frontalis* feeding damage were lower on plants within deltamethrin-impregnated and nontreated barriers than on plants at no barrier areas, the *S. frontalis* adult densities were generally similar. The exact reasons for low adult densities are unclear, and it could be related to a function of the method used for data collection or the influence of abiotic factors affecting the activity of adults. The numbers of adult *S. frontalis* were visually counted as effective sampling tools, and monitoring traps are currently unavailable for *S. frontalis* adults. Studies show that information about pest densities obtained through human visual observations may be inaccurate and inconsistent (Zhong et al. 2018). Secondly, most observations on *S. frontalis* adult activity were conducted during mid-day (between 11 AM to 12 PM). The temperatures and relative humidity during data collection days were varied and could have affected the activity of *S. frontalis* adults and visual observations. Previously, Lobo et al. (1998) showed that fluctuations in abiotic factors, such as high temperatures, and variation in solar radiation, have implicated variations in the flying activity of many species of scarabaeids. Therefore, short-term fluctuations in weather could have affected and contributed to inconsistent adult *S. frontalis* activity on the plants in the current study.

The current study shows that the barrier fence with overhangs provides a promising non-chemical strategy to minimize adult *S. frontalis* attacks. Data also show that the use of nontreated netting alone provided a satisfactory reduction in *S. frontalis* adult feeding damage, as insecticide-impregnated netting did not provide an additional reduction in *S. frontalis* adult feeding damage. Although the current study could serve as a proof of concept, more research is warranted to determine adequate fence enclosure area to fence height ratio for effective *S. frontalis* control and reduction in feeding damage. Also, limited knowledge exists of the flight behavior of *S. frontalis* adults, especially how high the adults can fly. Overhangs were used in the fence design based on a previous study (Bomford et al. 2000). Additional research is needed to compare the efficacy of fences without overhangs, which will simplify the fence design and grower adoption if effective. Similarly, we did not evaluate the incidence of adult *S. frontalis* population beyond 70 d in 2022. Longer-term evaluation of the adult *S. frontalis* population and damage will help to determine if fence barriers could provide season-long protection. The data also suggest that although the incidence and severity of *S. frontalis* adult feeding damage on plants were lower in the fenced area than in no barrier, there was still some damage to the plants in the fenced area. Perhaps, this is caused by the adults trapped inside the fenced area. Besides that, the current study shows that this nonchemical strategy should be further refined and incorporated into integrated pest management programs.

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Fig. 3. 1. (A) Design of barrier fence with overhangs and an enclosed barrier fenced plot in the field (B). Fence components include: (a) overhang support wood, (b) upright wooden post, (c) mesh overhang screen, (d) mesh screen, and (e) clamp to attach overhang. Drawing created using BioRender.com.

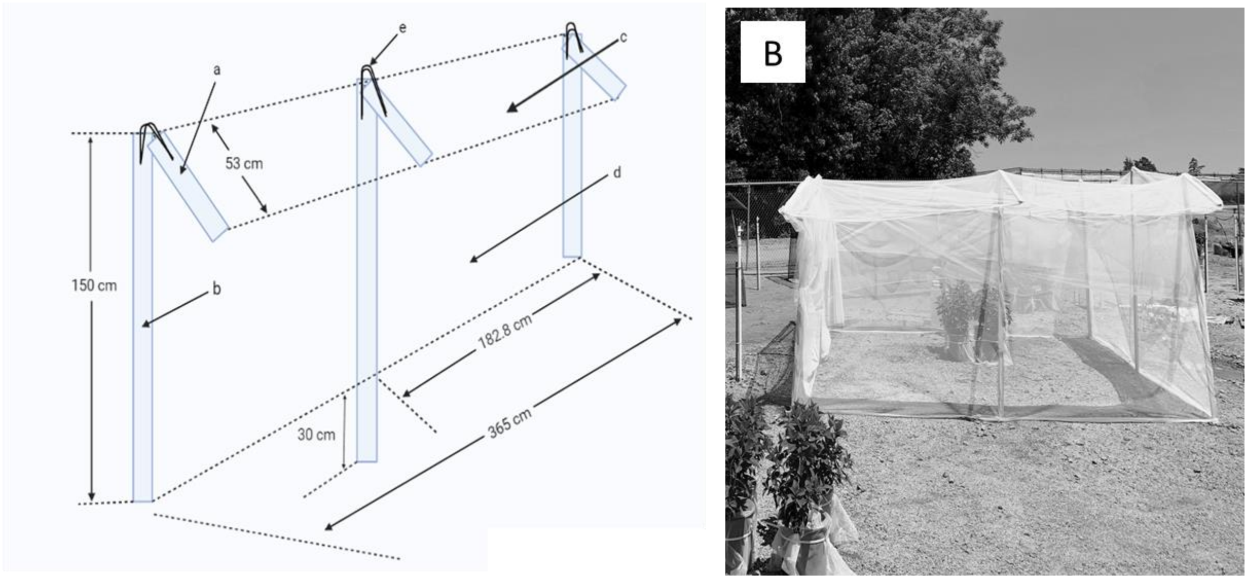
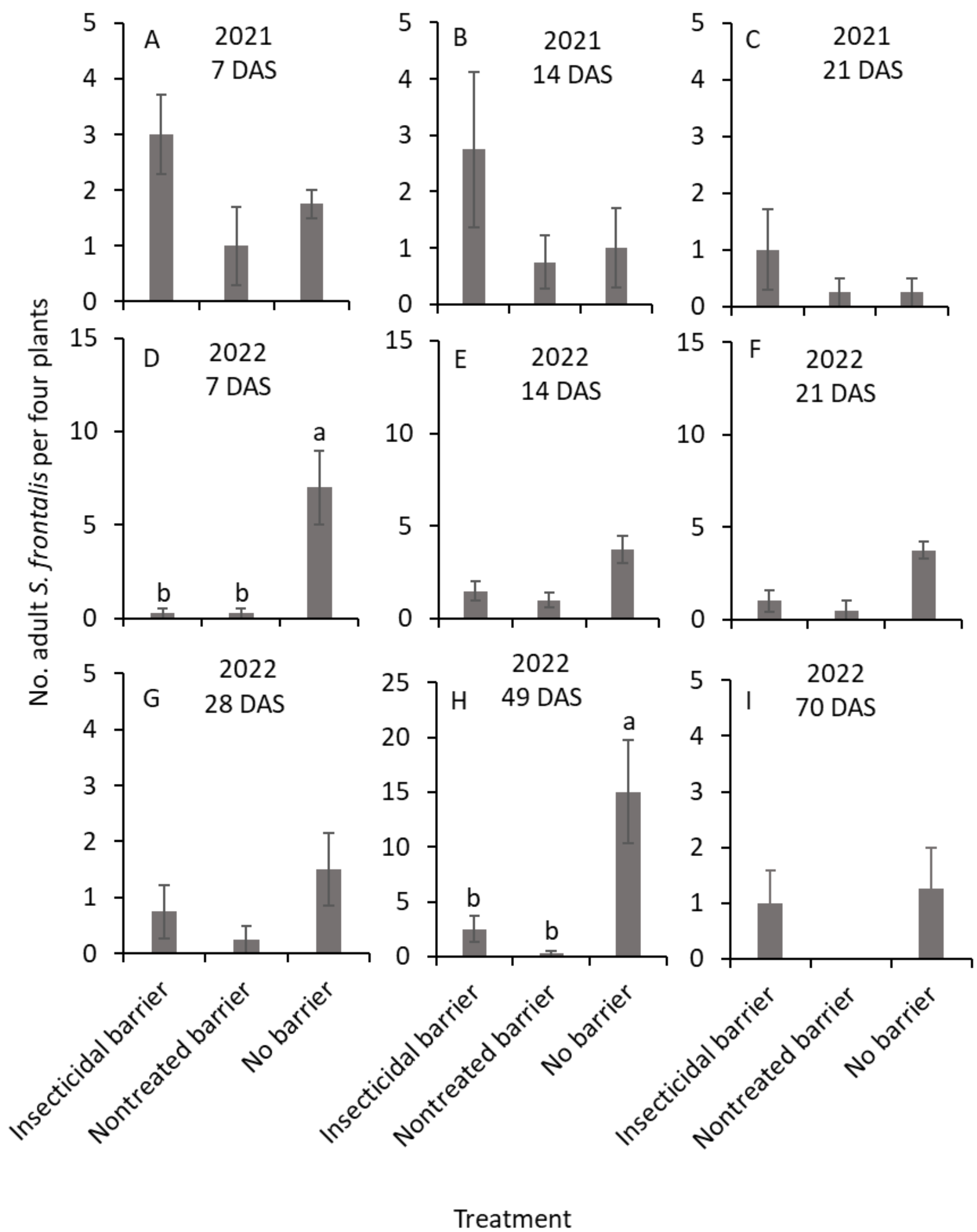

a
e
c
53 cm
d
150 cm
b
182.8 cm
30 cm
365 cm
B

Fig. 3. 2. Mean (±SE) *S. frontalis* adult densities per four plants after (A) 7, (B) 14, (C) 21 days after set up (DAS) in 2021, and (D) 7, (E) 14, (F) 21, (G) 28, (H) 49 and (I) 70 DAS in 2022. Bars with the same letters within a figure are not significantly different (Tukey-Kramer Test, $\alpha = 0.05$). Where no differences were observed among treatments, no letters are given.



No. adult S. frontalis per four plants
A
2021
7 DAS
B
2021
14 DAS
C
2021
21 DAS
D
2022
7 DAS
E
2022
14 DAS
F
2022
21 DAS
G
2022
28 DAS
H
2022
49 DAS
I
2022
70 DAS
a
b
Insecticidal barrier
Nontreated barrier
No barrier
Treatment

Fig. 3. 3. Mean (±SE) percentage incidence of *S. frontalis* feeding damage on foliage (A) 7, (B) 14, (C) 21 days after set up (DAS) in 2021, and (D) 7, (E) 14, (F) 21, (G) 28, (H) 49 and (I) 70 DAS in 2022. Bars with the same letters within a figure are not significantly different (Tukey's HSD Test, $\alpha = 0.05$).

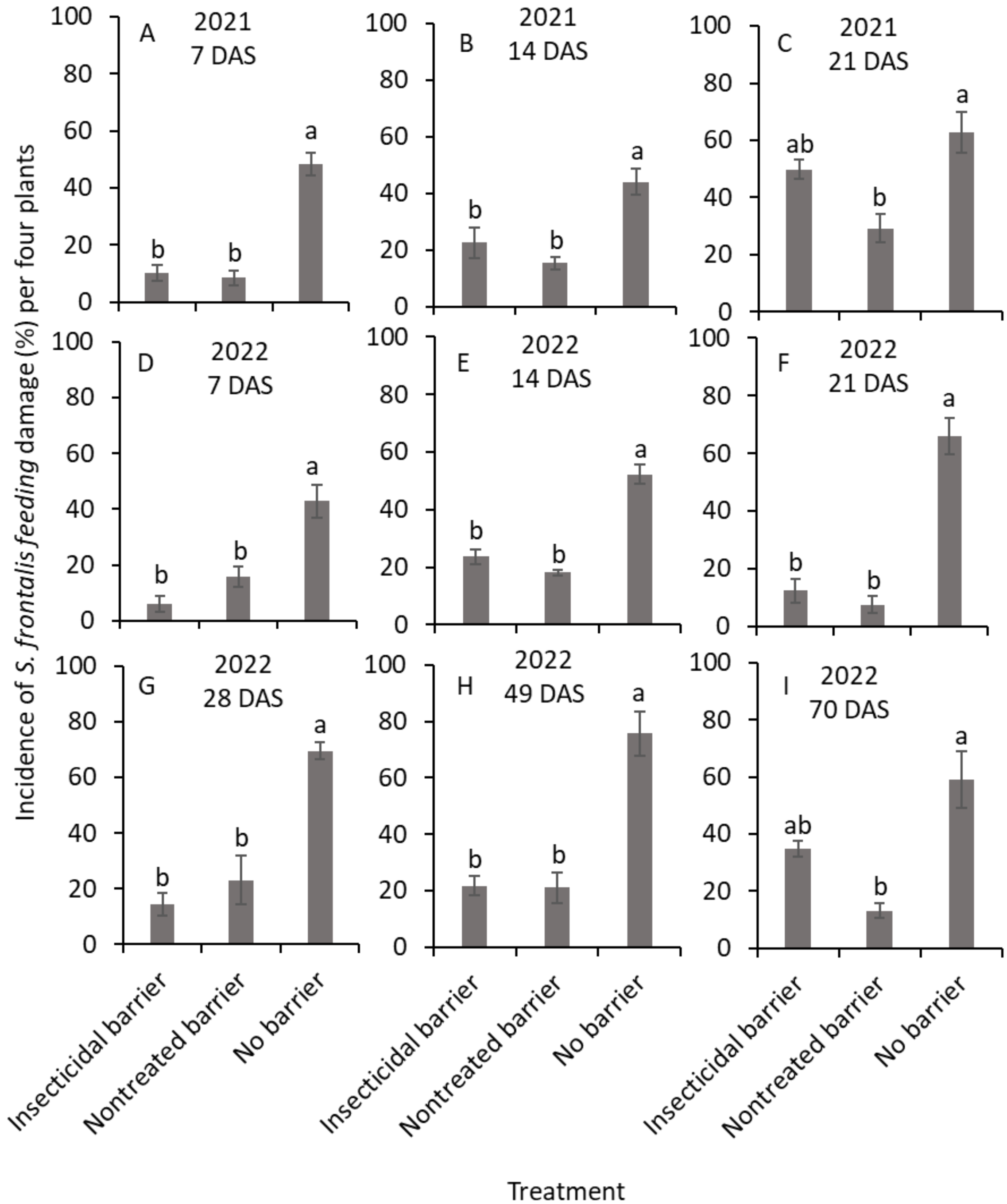
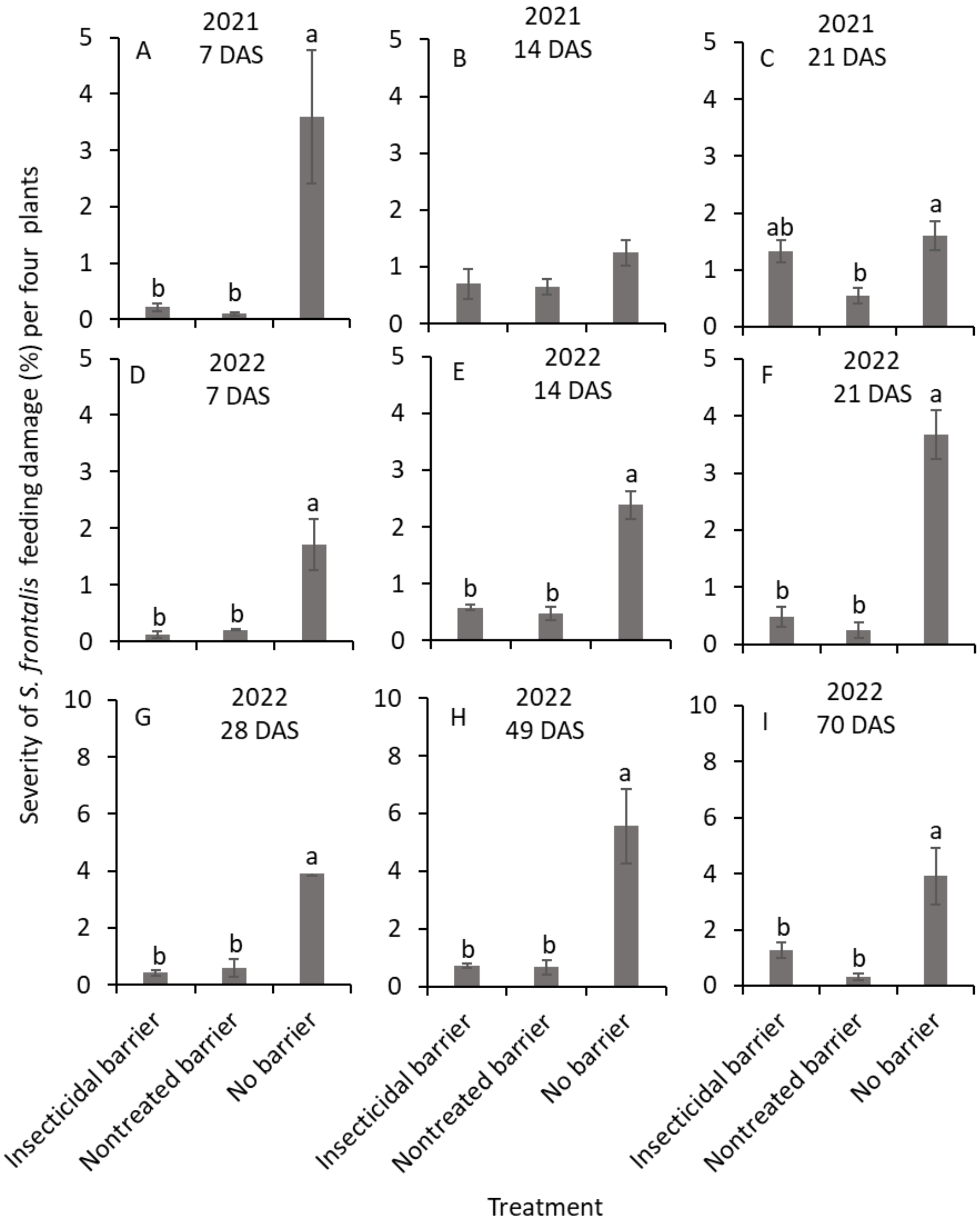

A
2021
7 DAS
B
2021
14 DAS
C
2021
21 DAS
D
2022
7 DAS
E
2022
14 DAS
F
2022
21 DAS
G
2022
28 DAS
H
2022
49 DAS
I
2022
70 DAS
Incidence of S. frontalis feeding damage (%) per four plants
Insecticidal barrier
Nontreated barrier
No barrier
Treatment

Fig. 3. 4. Mean (±SE) severity of *S. frontalis* feeding damage (%) on foliage (A) 7, (B) 14, (C) 21 days after set up (DAS) in 2021, and (D) 7, (E) 14, (F) 21, (G) 28, (H) 49 and (I) 70 DAS in 2022. Bars with the same letters within a figure are not significantly different (Tukey's HSD Test, $\alpha = 0.05$). Where no differences were observed among treatments, no letters are given.


2021
7 DAS
A
2021
14 DAS
B
2021
21 DAS
C
2022
7 DAS
D
2022
14 DAS
E
2022
21 DAS
F
2022
28 DAS
G
2022
49 DAS
H
2022
70 DAS
I
Severity of S. frontalis feeding damage (%) per four plants
Insecticidal barrier
Nontreated barrier
No barrier
Treatment

CHAPTER 4

RESIDUAL ACTIVITY OF INSECTICIDES AGAINST ADULT REDHEADED FLEA BEETLE (COLEOPTERA: CHRYSOMELIDAE) UNDER LABORATORY CONDITIONS

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Abstract *Systena frontalis* (F.) (Coleoptera: Chrysomelidae) is a serious insect pest in nursery production as it can damage > 50 plant species. Insecticides are an important management tool for *S. frontalis* adults to reduce economic losses. Because densities and activity *S. frontalis* adults are influenced by many biotic (e.g., adult emergence timing) and abiotic (e.g., fluctuating temperatures) factors in the nurseries, it is challenging to reliably determine the efficacy and residual activity of insecticides in the field conditions. Thus, the objective was to determine the residual activity of common and potential insecticides against adult *S. frontalis* in laboratory conditions. Field collected *S. frontalis* adults were exposed to fresh, and a week-old, field-aged residue of 13 insecticides applied on panicle hydrangea (*Hydrangea paniculata* Siebold) shoots. The beetle mortality, and percentages of incidence and severity (hydrangea leaf area damage) were quantified at 1, 3, and 7 d after exposing five adults per assay. The fresh residues of tetraniliprole, cyclanilirole, and sulfoxaflor + spinetoram were the most effective against *S. frontalis* adults, whereas only tetraniliprole and cyclaniliprole elicited evidence of efficacy when their residues were aged for a week. Based on the progress of damage severity after exposure, leaves with tetraniliprole residues did not develop any feeding damage when exposed to fresh or 7 d old residues. Severity of damage was significantly lower for cyclaniliprole, sulfoxaflor + spinetoram, and cyantraniliprole treatments than for the remaining treatments and also slowly developed on fresh residues but was only observed with cyclaniliprole on 7 d old residues.

Key words Redheaded flea beetle, insecticide, panicle hydrangea

Systena frontalis (F.) (Coleoptera: Chrysomelidae) has emerged as an economically important insect pest in ornamental container nurseries in the central and eastern USA (Lauderdale 2017, Herrick and Cloyd 2020, Joseph et al. 2021). *S. frontalis* is a polyphagous insect and can cause feeding damage to more than 50 ornamental plant species in nurseries (Joseph et al. 2021). Panicle hydrangea (*Hydrangea paniculata* Siebold [Hydrangeaceae]), Sweetspire (*Itea virginica* L. [Iteaceae]), Weigela (*Weigela* spp. [Caprifoliaceae]), roses (*Rosa* spp. [Rosacea]) and azalea (*Rhododendron* spp. [Ericaceae]) are the few highly susceptible plant species affected in the nurseries (Lauderdale 2017, Cloyd and Herrick 2018, Joseph et al. 2021). Adults of *S. frontalis* consume the newly emerging and mature leaves from both abaxial and adaxial surfaces, causing shot holes on the leaves (Joseph et al. 2021). The affected container plants are excluded from shipment, causing delays in fulfilling the orders and market demands. The damaged containers are heavily pruned and fertilized to generate fresh foliage to be sold in the later market window. Any delay in marketability causes additional maintenance costs, such as labor, agricultural inputs, and nursery space. In Georgia, the ornamental nursery industry is valued at more than $846 million USD, and 13.6% of that is field nurseries, including container nurseries (Georgia grown, 2022). Thus, it is important to manage *S. frontalis* and reduce the damage to container plants in the nurseries.

S. frontalis overwinters as eggs in the plant containers (Lauderdale 2017), and larvae feed on plant roots. However, there is no evidence of plant damage from larval feeding (Joseph and Hudson 2020). Larvae of *S. frontalis* pupate in the soil and the emerging adults feed on plant leaves. In the nurseries, *S. frontalis* adults are visually monitored (Joseph et al. 2021) and are utilized to determine management decisions (Lauderdale 2017).

Managing *S. frontalis* population has recently posed a serious challenge in nurseries (Kunkel 2016). To reduce the *S. frontalis* damage and minimize losses, insecticides are routinely used (ACES 2020, Joseph et al. 2021). Foliar sprays of neonicotinoids (mostly dinotefuran), carbamate (mostly carbaryl), pyrethroids (mostly bifenthrin), and organophosphates (mostly acephate) are applied at weekly to monthly schedules depending on adult density (Joseph et al. 2021, Lauderdale 2021c). The most effective insecticides against *S. frontalis* larvae and adults, thus far, are neonicotinoids (Lauderdale 2021c). Topdressing *I. virginica* plant containers with granular imidacloprid prevented damage from *S. frontalis* adults feeding based on low damage ratings (Lauderdale 2021b). Similarly, granular imidacloprid was effective in reducing damage from *S. frontalis* when incorporated in *I. virginica* at potting media (Lauderdale 2022). Foliar applications of cyantraniliprole, lambda-cyhalothrin and dinotefuran reduced damage on new foliage and adult feeding on forsythia (*Forsythia x intermedia* Zabel), salvia (*Salvia* spp.) and sedum (*Sedum* spp.) (Kunkel 2016). Furthermore, acephate and chlorpyrifos drench provided 100% *S. frontalis* larval control (Lauderdale 2021c).

Although many insecticides are registered, available for use, and can provide various levels of protection, the residual activity of these insecticides is poorly understood. Multiple insecticide sprays at shorter intervals were often recommended for longer-term residual activity (ACES 2020, Lauderdale 2021a). Under heavy adult *S. frontalis* densities, weekly or biweekly applications of foliar insecticides are required to keep plants marketable (< 10% damage) (Lauderdale 2021c). However, many insecticide labels limit the number of applications allowed yearly (for example, six applications for carbaryl) (Lauderdale 2021c). Clearly, there is a knowledge gap in our understanding of effective insecticide application timing and frequency to develop IPM strategies for the *S. frontalis*. Moreover, obtaining reliable management data through field studies alone is challenging because efficacy is usually tied to consistent and adequate *S. frontalis* densities, less variable abiotic conditions (such as temperature and relative humidity), and minimal disruption in the inventory of plant materials. However, the *S. frontalis* densities constantly fluctuate and are often unpredictable in the nurseries. Thus, we investigated the residual activity of the registered and potential insecticides under laboratory conditions against adults of *S. frontalis*.

Materials and Methods

Insects. *S. frontalis* adults were collected from *Sedum* spp., *Weigela* spp. and *H. paniculata* plants in the wholesale nursery in GA during the summer of 2021 and 2022. The adults were gently handpicked or sucked up using aspirators from the foliage. The field-collected *S. frontalis* adults were temporarily maintained on 11.4 L 'Lime Light' panicle hydrangea container plants. The plants were placed in 47.5 × 47.5 × 93.0 cm (width: depth: height) cages (BugDorm, BugDorm-4E4590 Insect Rearing Cage, https://shop.bugdorm.com/index.php) in a greenhouse. A new plant was replaced when 60% of the foliage was damaged. The caged plants were not treated with any pesticides. Field-collected *S. frontalis* adults were used for the assays within 24-72 h after introduction. These caged plants were maintained in the greenhouse under ~30 °C, 75 ± 5% relative humidity (RH), and irrigated every eight hours for five mins using overhead sprinklers. The species identification of adults was confirmed as *S. frontalis*, and voucher specimens were deposited in Natural History Museum in Athens, GA.

Plants. Panicle hydrangea 'Lime Light' plants were propagated from liners and were potted in 11.4 L containers using shredded pine bark potting media in a nursery located in McDuffie County, GA. After planting the liners, the container plants were top dressed with fertilizer (Osmocote Pro, 18: 9: 10 [N:P: K], Summerville, SC) at 7.59 kg per m^2. The plants were irrigated thrice per week for 20 mins. In October 2019, seven months before the laboratory experiments were initiated, these container plants were transported from the nursery to the University of Georgia, Griffin Campus, Griffin, GA, and maintained in a shade house (50:50, light and shade). Plants were kept in screened chambers in the screen house to prevent any *S. frontalis* infestation. To prevent adult emergence from these containers (in case of accidental infestation), the surface of the potting media was covered with no-see-um netting (No-see-um nylon netting, BioQuip, Rancho Dominguez, CA) using 91.4 cm plastic zip ties (Malco products Inc., Barberton, Ohio) and 32 mm binder clips to prevent the emergence of adult *S. frontalis* so that emerging *S. frontalis* adults are physically blocked. These nontreated plants were used for laboratory experiments.

Insecticide. Thirteen insecticides were used in the study. The details of the active ingredients, brand names, IRAC groups, manufacturers, and rates used in the experiments are listed in Table 4. 1. Of the 13 insecticides, all except tetraniliprole are registered on ornamentals in nurseries. The insecticide solutions were foliar applied on ~30 cm long terminals of panicle hydrangea using a CO_2-powered single-boom sprayer at 206.843 kPa. The tip used in the nozzle was TeeJet 8002VS (yellow-colored flat spray tip, TeeJet Technologies, Glendale Heights, Illinois, USA). The water volume used to prepare the insecticide solution was 373.9 L per ha. For the duration of the study, the plants were maintained in the screen house.

Experimental design. In 2021 and 2022, experiments were set up in the entomological laboratory at the University of Georgia, Griffin campus, Griffin, GA. Ten, insecticide-treated, ~30 cm long terminal shoots with eight leaves and no flowers, were removed from each container plant maintained in the screen house, and brought to the laboratory. The insecticide-treated shoots and a nontreated shoot served as treatments in the experiment. The insecticide treatments were replicated 10 times in a randomized complete block design (RCBD). The cut end of the terminals was inserted into 20 mL polypropylene cup (6 cm diam. wide and 7.1 cm long) filled with water through a 5 mm diameter hole on the lid of the cup (Fig. 4. 1). Because the cut end of the terminals was immersed in water, the leaves were maintained alive for 7 d. To expose the *S. frontalis* adults, assays were constructed using clear film (Grafix, Maple Heights, OH, USA) and no-see-um mesh. The details of the assay construction are described in Joseph et al. (2016), Joseph (2019), Joseph and Jespersen (2021). Rectangular sections of the film were rolled lengthwise to construct a cylinder. The fabric netting was attached on the top of the cylinder using tape (Fig. 4. 1). The cage was placed over the terminal in a cup. The cages were arranged in a RCBD and set up on the laboratory bench. After introducing five *S. frontalis* adults in each cage, the circular edge touching the laboratory bench was sealed using hot glue. The hot glue at the base prevents the escape of *S. frontalis* adults after introduction. This single tubular assay served as an experimental unit (replicate).

To determine the residual activity of insecticides, the terminals were collected at 0 and 7 d post- insecticide application. The plant terminals were exposed to *S. frontalis*, as described above. The experiment was repeated twice, in 2021 and in 2022, with five replications per insecticide and the control. Tetraniliprole treatment was added in 2022. In the analysis, data from both years was pooled. All ten replications were conducted with a nontreated treatment. Experiments were conducted at room temperature ~21 °C and ~45% RH and natural photoperiod.

Evaluation. Each experimental unit was evaluated at 1, 3, and 7 d post-exposure to insecticide-treated or nontreated panicle hydrangea terminals. The number of dead *S. frontalis* adults, and the incidence and severity of *S. frontalis* adult feeding damage were evaluated. The incidence of

S. frontalis damage was recorded if at least a feeding injury was noticed on a leaf. The percentages of damaged leaves were calculated. To assess the severity of damage caused by *S. frontalis* feeding, the percentage of leaf area damaged by adult feeding was recorded. All the leaves were individually assessed from each experimental unit. Subsequently, the percentage severity of damage was determined by averaging the rating from all the leaves per experimental unit.

Statistical Analyses. The statistical analyses for all experiments were conducted using SAS software (SAS 2016). The adult mortality data were log-transformed (ln [x +1]) to establish the homogeneity of variance and were subjected to two-way ANOVA in SAS using the general linear model PROC GLM procedure. The percentages of incidence and severity of damage by *S. frontalis* adults were arcsine square-root transformed and subjected to two-way ANOVA in SAS using the general linear model PROC GLM procedure. The effects of insecticide and exposure time and their interaction were analyzed on adult mortality as well as percentages of incidence and severity of the damage. The treatment (insecticide, exposure time, and interaction) and replication were fixed and random effects, respectively, in the model. Analyses were conducted for 0- and 7-day residues separately.

Because interactions were significantly different at $\alpha = 0.05$, one-way ANOVA was performed with insecticide and exposure time as treatments. The means were separated using Tukey HSD Test ($P < 0.05$). The means and standard errors were calculated using the PROC MEANS procedure in SAS. The number of dead beetles was log-transformed. Using the general linear model procedure (PROC GLM) in SAS, the transformed data were subjected to one-way ANOVA to determine beetle mortality for each treatment. The Tukey-Kramer test ($P < 0.05$) was used to separate the means. Means and standard errors were calculated using the PROC MEANS procedure in SAS.

Results

0-d old insecticidal residue. The insecticide exposure time and their interaction were significantly different for adult *S. frontalis* mortality as well as incidence and severity of feeding damage at 0 d old insecticide residue (Table 4. 2).

***Adult S. frontalis mortality*.** At 1 day after exposure (DAE), numbers of dead adult *S. frontalis* were significantly greater for tetraniliprole treatment than for the remaining treatments (Table 4. 3; Fig. 4. 2A). Adult mortality was significantly greater for cyclaniliprole followed by flupyradifurone treatment than for azadirachtin, bifenthrin, chlorantraniliprole, cyantraniliprole, flonicamid, imidacloprid, indoxacarb, imidacloprid, pyrifluquinazon, spirotetramat, sulfoxaflor + spinetoram, and nontreated treatments (Table 4. 3, Fig. 4. 2A). At 3 DAE, mortality of adults was significantly greater for tetraniliprole followed by cyclaniliprole, cyantraniliprole, flupyradifurone, imidacloprid, indoxacarb and sulfoxaflor + spinetoram than for azadirachtin, bifenthrin, chlorantraniliprole, flonicamid, pyrifluquinazon, spirotetramat and nontreated treatments (Table 4. 3, Fig. 4. 2A). At 7 DAE, numbers of dead adults were significantly greater for tetraniliprole, cyclaniliprole, sulfoxaflor + spinetoram, cyantraniliprole, imidacloprid, flupyradifurone, indoxacarb, pyrifluquinazon and bifenthrin treatments than for azadirachtin, chlorantraniliprole, flonicamid, spirotetramat and nontreated treatments (Table 4. 3, Fig. 4. 2A).

The adult *S. frontalis* mortality in tetraniliprole, flupyradifurone, imidacloprid, indoxacarb, pyrifluquinazon, and sulfoxaflor + spinetoram treatments was significantly lower at 1 DAE than at 3 and 7 DAE (Table 4. 4, Fig. 4. 2A). For bifenthrin, significantly lower numbers of dead *S. frontalis* observed at 1 and 3 DAE than at 7 DAE. For cyclaniliprole, numbers of dead

S. frontalis were significantly lower at 1 DAE followed by at 3 DAE, than at 7 DAE. For chlorantraniliprole and cyantraniliprole, significantly lower numbers of dead adults were observed at 1 DAE than at 7 DAE (Table 4. 4, Fig. 4. 2A). However, no significant difference between the 3 and 7 DAE, as well as between the 1 and 7 DAE was observed. There were no significant differences in the densities of dead adult *S. frontalis* among DAEs for azadirachtin, spirotetramat, flonicamid, and nontreated treatments (Table 4. 4, Fig. 4. 2A).

Incidence of S. frontalis feeding damage**.** The percentage incidence of *S. frontalis* damage was significantly lower for tetraniliprole than for any other treatments at 1 DAE (Table 4. 3, Fig. 4. 2B). Cyclaniliprole and imidacloprid treatments were significantly lower than for azadirachtin, bifenthrin, flonicamid, chlorantraniliprole, cyantraniliprole, indoxacarb, pyrifluquinazon, flonicamid, and nontreated treatments at 1 DAE (Table 4. 3, Fig. 4. 2B). At 3 DAE, significantly lower incidence of feeding damage was observed for cyclaniliprole, tetraniliprole, sulfoxaflor + spinetoram, imidacloprid, indoxacarb, cyantraniliprole, bifenthrin, spirotetramat and flupyradifurone treatments than for azadirachtin, chlorantraniliprole, pyrifluquinazon, flonicamid, and nontreated treatments (Table 4. 3, Fig. 4.2B). At 7 DAE, the percentage incidence of feeding damage was significantly lower for tetraniliprole, cyclaniliprole, sulfoxaflor + spinetoram, imidacloprid, flupyradifurone, and cyantraniliprole treatments than azadirachtin, bifenthrin, chlorantraniliprole, indoxacarb, pyrifluquinazon, spirotetramat, flonicamid, and nontreated treatments (Table 4. 3, Fig. 4.2B).

For azadirachtin, chlorantraniliprole, flupyradifurone, and imidacloprid, the percentage incidence of *S. frontalis* damage was significantly lower at 1 DAE than at 3 and 7 DAE (Table 4. 4, Fig. 4. 2B). For bifenthrin, cyantraniliprole, and indoxacarb, significantly lower incidence of damage was observed at 1 and 3 DAE than at 7 DAE. Incidence of damage was significantly lower at 1 DAE followed by at 3 DAE than at 7 DAE for pyrifluquinazon, spirotetramat and nontreated control treatments (Table 4. 4, Fig. 4. 2B). Significantly less incidence of damage was observed at 1 DAE than at 7 DAE for cyclaniliprole, sulfoxaflor + spinetoram and flonicamid treatments. Days after exposure to insecticides were not significantly different in the incidence of damage for tetraniliprole treatment (Table 4. 4, Fig. 4. 2B).

Severity of S. frontalis feeding damage. The severity of feeding damage was significantly lower for tetraniliprole and cyclaniliprole treatments than for azadirachtin, bifenthrin, chlorantraniliprole, cyantraniliprole, flonicamid, flupyradifurone, imidacloprid, indoxacarb, pyrifluquinazon, spirotetramat, sulfoxaflor + spinetoram and nontreated control treatments at 1 DAE (Table 4. 3, Fig. 4.2C). At 3 DAE, tetraniliprole, cyclaniliprole, cyantraniliprole, imidacloprid, and sulfoxaflor + spinetoram treatments had significantly less severe damage than for azadirachtin, bifenthrin, chlorantraniliprole, flonicamid, flupyradifurone, indoxacarb, pyrifluquinazon, spirotetramat and nontreated control treatments (Table 4. 3, Fig. 4.2C). At 7 DAE, the severity of damage was significantly lower for tetraniliprole, cyclaniliprole, sulfoxaflor + spinetoram treatments than for azadirachtin, bifenthrin, chlorantraniliprole, cyantraniliprole, flonicamid, flupyradifurone, imidacloprid, indoxacarb, pyrifluquinazon, spirotetramat and nontreated control treatments (Table 4. 3, Fig. 4. 2C).

For flupyradifurone, and flonicamid treatments, the severity of damage was significantly lower at 1 DAE than at 3 and 7 DAE (Table 4. 4, Fig. 4. 2C). The severity of *S. frontalis* feeding damage was significantly lower at 1 DAE than at 7 DAE for sulfoxaflor + spinetoram treatment. For bifenthrin, chlorantraniliprole, cyantraniliprole, and cyclaniliprole, significantly lower severity of damage was observed at 1 and 3 DAE than at 7 DAE. The severity of damage was significantly lower at 1 DAE followed by at 3 DAE than at 7 DAE for azadirachtin, indoxacarb, pyrifluquinazon, spirotetramat, and nontreated control treatments (Table 4. 4, Fig. 4. 2C). There was no significant difference on the severity of damage for tetraniliprole and imidacloprid treatments (Table 4. 4, Fig. 4. 2C).

7-d old insecticidal residue. The insecticide, exposure time, and their interaction were significantly different for all the adult *S. frontalis* mortality as well as incidence and severity of feeding damage at 7 d old insecticide residue except for the interaction between insecticide and exposure time for the adult mortality (Table 4. 2).

***Adult S. frontalis mortality*.** At 1 DAE, the densities of adult *S. frontalis* mortality were significantly greater for tetraniliprole treatment than for the remaining treatments at 1 DAE (Table 4. 3, Fig. 4. 3A). Significantly greater numbers of dead adults were observed for cyclaniliprole treatment than for azadirachtin, bifenthrin, chlorantraniliprole, cyantraniliprole, flonicamid, flupyradifurone, imidacloprid, indoxacarb, pyrifluquinazon, spirotetramat, sulfoxaflor + spinetoram and nontreated control treatments. At 3 DAE, the numbers of adults who survived on tetraniliprole treatment were significantly lower than the remaining treatments (Table 4. 3, Fig. 4. 3A). cyclaniliprole and sulfoxaflor + spinetoram treatments had significantly lower numbers of survived adults than azadirachtin, bifenthrin, chlorantraniliprole, cyantraniliprole, flonicamid, flupyradifurone, imidacloprid, indoxacarb, pyrifluquinazon, spirotetramat and nontreated control treatments. Similarly, at 7 DAE, the numbers of dead adults were significantly greater for the tetraniliprole treatment than for the remaining treatments (Table 4. 3, Fig. 4. 3A). Mortality of adults was significantly greater for the cyclaniliprole, cyantraniliprole, flupyradifurone and sulfoxaflor + spinetoram treatments than for azadirachtin, bifenthrin, chlorantraniliprole, flonicamid, imidacloprid, indoxacarb, pyrifluquinazon, spirotetramat and nontreated control treatment (Table 4. 3, Fig. 4. 3A).

For tetraniliprole, indoxacarb, sulfoxaflor + spinetoram treatments, the numbers of dead adults were significantly lower at 1 DAE than at 3 and 7 DAE (Table 4. 4, Fig. 4. 3A). For flupyradifurone, mortality of adults was significantly lower at 1 DAE followed by at 3 DAE than at 7 DAE. Significantly greater numbers of adults survived at 1 and 3 DAE than at 7 DAE for spirotetramat, whereas lower densities of adult mortality were observed at 1 DAE than at 7 DAE for cyantraniliprole and flonicamid treatments (Table 4. 4, Fig. 4. 3A). The survival of adults among DAEs was not significantly different for azadirachtin, bifenthrin, chlorantraniliprole, cyclaniliprole imidacloprid, pyrifluquinazon, and nontreated control treatments.

***Incidence of S. frontalis feeding damage*.** The percentage incidence of damage was significantly lower for tetraniliprole treatment at 1, 3, and 7 DAE than for the remaining treatments (Table 4. 3, Fig. 4. 3B). For chlorantraniliprole, the incidence of damage was lower at 1 DAE than at 3 and 7 DAE, whereas, for azadirachtin, cyclaniliprole, imidacloprid, indoxacarb, spirotetramat, and flonicamid treatments, the incidence of damage was lower at 1 and 3 DAE than at 7 DAE (Table 4. 4, Fig. 4. 3B). Significantly lower incidence of damage was observed at 1 DAE followed by at 3 DAE than 7 DAE for bifenthrin, cyantraniliprole, flupyradifurone, pyrifluquinazon, and nontreated control treatments, whereas the incidence of damage was significantly lower at 1 DAE than at 7 DAE for sulfoxaflor + spinetoram treatment. There was no significant difference among DAEs for tetraniliprole treatment (Table 4. 4, Fig. 4. 3B).

Severity of S. frontalis feeding damage. The severity of damage was significantly lower for tetraniliprole treatment than for the remaining treatments at 1 DAE (Table 4. 3, Fig. 4. 3C). At 3 DAE, significantly lower severe damage was observed for tetraniliprole treatment followed by cyclaniliprole than for remaining treatments. At 7 DAE, the severity of damage was significantly lower for tetraniliprole treatment followed by cyclaniliprole than for azadirachtin, bifenthrin, chlorantraniliprole, cyantraniliprole, flonicamid, flupyradifurone, imidacloprid, indoxacarb, pyrifluquinazone, spirotetramat, sulfoxaflor + spinetoram and nontreated control treatments (Table 4. 3, Fig. 4. 3C).

For azadirachtin, bifenthrin, cyantraniliprole, flupyradifurone, imidacloprid, indoxacarb, spirotetramat, and nontreated control treatments, the damage was significantly less severe at 1 DAE followed by at 3 DAE than at 7 DAE (Table 4. 4, Fig. 4. 3C). The severity of damage was significantly lower at 1 and 3 DAE than at 7 DAE for chlorantraniliprole, cyclaniliprole, pyrifluquinazon, sulfoxaflor + spinetoram and flonicamid treatments (Table 4. 4, Fig. 4. 3C). There was no significant difference in the severity of damage for tetraniliprole treatment.

Discussion

Of the 13 insecticides evaluated, fresh residues of tetraniliprole (Tetrino 2022), cyclaniliprole (Sarisa 2022), and sulfoxaflor + spinetoram (XXpire 2022) were the most effective against *S. frontalis* adults, whereas only tetraniliprole and cyclaniliprole showed evidence of efficacy when their residues were aged for a week. Previously, the residual activity of foliar-applied cyclaniliprole and sulfoxaflor + spinetoram was inconsistent as *S. frontalis* feeding damage relative to nontreated varied from 7 to 49 d as population density and number of foliar applications potentially caused the variability (Lauderdale 2021c). In other studies, cyclaniliprole and tetraniliprole applications did not reduce foliage feeding damage from *S. frontalis* adults on nursery-grown *Itea virginica* (Herrick and Cloyd 2020, Kunkel 2021). These suggest that there is inconsistency in efficacy data in field studies because of variable *S. frontalis* adult densities and age of residues. In contrast under controlled conditions percentage of *S. frontalis* adult mortality was greater than nontreated when exposed to cyclaniliprole treated *H. paniculata* ‘Little Quick Fire’ leaf and filter paper (Herrick and Cloyd 2020), which is consistent with current research.

Thus, the results from the current study show that tetraniliprole, cyclaniliprole, and sulfoxaflor + spinetoram are effective options for *S. frontalis* adult management under controlled conditions.

The effectiveness of tetraniliprole, cyclaniliprole, and sulfoxaflor + spinetoram against foliage-feeding insect pests has also been documented in other cropping systems. In a cranberry (*Vaccinium macrocarpon* Ait.) nursery, foliar application of cyclaniliprole reduced *S. frontalis* adults for up to 7 d post- application during spring (Gue´dot and Perry 2016a), whereas fall application of cyclaniliprole effectively reduced *S. frontalis* adult densities for up to 21 d post-application (Gue´dot and Perry 2016b). The foliar applications of spinetoram + sulfoxaflor effectively reduced leaf damage from grapevine flea beetle, *Scelodonta strigicollis* Motschulsky attack on grapevine, *Vitis vinifera* cv. Muscat (Srinivasan et al. 2019). Mortality of adult Japanese beetles, *Popillia japonica* (Newman) (Coleoptera: Scarabaeidae) was greater on cyclaniliprole-treated smartweed, *Polygonum pensylvanicum* (L.) leaves than on nontreated at 2 d in Petri dish assay (Nottingham et al. 2015). Tetraniliprole reduced larvae densities of defoliators, such as *Helicoverpa armigera* Hubner (Lepidoptera: Noctuidae) and *Cydia ptychora* Meyrick (Lepidoptera: Tortricidae) on soybean, *Glycine max* (L.) Merril (Kambrekar et al. 2017). Srinivasan and Kalyanasundaram (2019) reported that spray applications of spinetoram + sulfoxaflor reduced okra leaf hopper, *Amrasca biguttula biguttula* (Ishida) leaf damage on okra, *Abelmoschus esculentus* (L.). These suggest that tetraniliprole, cyclaniliprole, and sulfoxaflor + spinetoram are effective in reducing feeding damage and pest densities in various cropping systems.

Cyclaniliprole and tetraniliprole are grouped in the diamide class of insecticides, and they are Ryanodine receptor (Ryr) modulators that act on the nerves and muscles of insects (IRAC 2022). The binding of these diamides to Ryr causes the calcium channel to remain open, resulting in an uncontrolled release of calcium stores, eventually leading to feeding cessation and death (Cordova et al. 2006). Currently, tetraniliprole is not registered for use in ornamental nurseries against any arthropod pests in the USA, although it is registered against white grubs, (such as immatures of *Phyllophaga* spp., *P. japonica* (Coleoptera: Scarabaeidae); billbugs. *Sphenophorus* spp. (Coleoptera: Curculionidae), annual bluegrass weevil, *Listronotus maculicollis* Dietz (Coleoptera: Curculionidae) and fall armyworm, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) in turfgrass. Cyclaniliprole is registered for use against many arthropod pests on ornamentals in nurseries. Sulfoxaflor + spinetoram (XXpire) is a combination of sulfoximines and spinosyns, respectively. Sulfoximines are competitive modulators affecting the nicotinic acetylcholine receptor (nAChR) in the nervous system of insects. Spinosyns consist of site I nicotinic acetylcholine receptor (nAChR) allosteric modulators and Glutamate-gated chloride channel (GluCl) allosteric modulators, which affect the nervous and muscle system of insects (IRAC 2022). Similarly, sulfoxaflor + spinetoram is registered for control of leaf-feeding beetles and other economically important insect pests, such as Silverleaf whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), thrips, *Thysanoptera* spp. (Thysanoptera: Thripidae), in ornamental nurseries.

Although they effectively reduced adult *S. frontalis* densities and feeding damage foliage in other studies, cyantraniliprole, azadirachtin, imidacloprid, and bifenthrin did not show any efficacy against *S. frontalis* adults in the current study. Foliar application of cyantraniliprole (diamide) reduced adult *S. frontalis* feeding damage on forsythia (*F. intermedia* Zabel) foliage (Kunkel 2016) and sweetspire *I. virginica* var 'Little Henry' (Kunkel 2021). *S. frontalis* adult mortality was notable on cyantraniliprole-treated filter paper (Herrick and Cloyd 2020). Foliar applied bifenthrin significantly reduced adult feeding on Joe Pye weed, *Eutrochium purpureum*

(L.), for up to 14 d (Kunkel 2016). Similarly, foliar-applied imidacloprid effectively reduced adult *S. frontalis* damage in nursery setting (Lauderdale 2021c). Azadirachtin and imidacloprid drench application reduced *S. frontalis* larval densities in container plants (Lauderdale 2021a, c).

The progression of feeding damage on treated foliage indicates how quickly the insecticide would effectively suppress adult feeding. Foliage treated with tetraniliprole developed negligible damage over time with fresh and 7 d old residues. Overall severity of damage was lower for cyclaniliprole, sulfoxaflor + spinetoram, and cyantraniliprole treatment, and they developed at a slower pace than the rest of the treatments when exposed to the fresh residue. When exposed to 7 d old residues, only cyclaniliprole delayed the development of damage as the severity of feeding was lower than other treatments. For the remaining insecticides, the feeding damage steadily developed when exposure period increased up to 7 d. This suggests that tetraniliprole, cyclaniliprole, and sulfoxaflor + spinetoram are quick acting on fresh residues and tetraniliprole and cyclaniliprole are effective even after residues were aged for a week.

In summary, this study evaluated the residual activity of 13 insecticides against *S. frontalis* adults in the laboratory. The results show that three insecticides were most effective against *S. frontalis* adults. These three insecticides warrant further studies in the field. Future studies should also be conducted using tetraniliprole, cyclaniliprole, and sulfoxaflor + spinetoram to determine the best application sequence and timing relative to market windows in spring and fall. In the current study, all the insecticides were tested as foliar sprays and other delivery options, such as top dressing, drenching, soil incorporation, etc., should be studied. These results will help develop an IPM program to manage *S. frontalis* adults in nurseries.

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Table 4. 1. The brand name, class, IRAC, manufacturer, and application rate used in various experiments.

Insecticide (a.i.)	Brand name	Class	IRAC group	Manufacturer	Rate (per ha)
Azadirachtin (4.5%)	Azatin® O	Azadirachtin	-	OHP Inc., Mainland, PA	1169.2 mL
Bifenthrin (7.9%)	Talstar® P	Pyrethroids	3A	FMC Corporation, Philadelphia, PA	789.2 mL
Chlorantraniliprole (18.4%)	Acelepryn®	Diamides	28	Syngenta Crop Protection LLC., Greensboro, NC	1169.2 mL
Cyantraniliprole (18.66%)	Mainspring® GNL	Diamides	28	Syngenta Crop Protection LLC., Greensboro, NC	876.9 mL
Cyclaniliprole (4.55%)	Sarisa™	Diamides	28	OHP Inc., Mainland, PA	1973.1 mL
Tetraniliprole (4.07%)	Tetrino™	Diamides	28	Bayer Environmental Science, Research Triangle Park, NC	946. 5 mL
Flonicamid (50%)	Aria®	Flonicamid	29	FMC Global Specialty Solutions, Philadelphia, PA	301.2 g
Flupyradifurone (17.09%)	Altus™	Butenolides	4D	Bayer Environmental Science, Research Triangle Park, NC	1023.1 mL
Imidacloprid (21.4%)	Marathon® II	Neonicotinoids	4A	OHP, Inc, Bluffton, SC	124.2 mL
Indoxacarb (30%)	Provaunt®	Oxadiazines	22A	Syngenta Crop Protection LLC., Greensboro, NC	525.4 g
Pyrifluquinazon (20%)	Rycar®	Pyridine azomethine derivatives	9B	SePro Corporation, Carmel, IN	467.7 mL
Spirotetramat (22.4%)	Kontos®	Tetronic and tetramic acid derivatives	23	Bayer Environmental Science, Research Triangle Park, NC	248.5 mL
Sulfoxaflor (20%) + Spinetoram (20%)	XXpire®	Sulfoximines + Spinosyns	4C + 5	Corteva AgriScience, Indianapolis, IN	245.2 g

Table 4. 2. Analysis of variance (ANOVA) for insecticide and exposure time on adults of *Systena frontalis* by age of the insecticide residue in the laboratory conditions.

Age of residue (day)	Parameter	Insecticide			Exposure time			Insecticide × Exposure time		
		F	df	*P*	*F*	df	*P*	*F*	df	*P*
0										
	Adult mortality	43.3	13, 389	< 0.001	82.6	2, 389	< 0.001	2.9	26, 389	< 0.001
	Incidence of damage	40.4	13, 388	< 0.001	107.8	2, 388	< 0.001	1.7	26, 388	0.021
	Severity of damage	32.1	13, 389	< 0.001	94.6	2, 389	< 0.001	3.2	26, 389	< 0.001
7										
	Adult mortality	41.1	13,392	< 0.001	30.3	2, 392	< 0.001	1.2	26, 392	0.193
	Incidence of damage	29.4	13,392	< 0.001	119.8	2, 392	< 0.001	1.7	26, 392	0.016
	Severity of damage	33.3	13,392	< 0.001	169.9	2, 392	< 0.001	2.7	26, 392	< 0.001

Table 4. 3. ANOVA of exposure time on adults of *Systena frontalis* by age of the insecticide residue in the laboratory conditions.

Age of residue (day)	Days after exposure (day)	Adult mortality			Incidence of damage			Severity of damage		
0		*F*	df	*P*	*F*	df	*P*	*F*	df	*P*
	1	12.9	13, 117	< 0.001	10.9	13, 116	< 0.001	6.70	13, 117	< 0.001
	3	17.5	13, 117	< 0.001	21.3	13, 117	< 0.001	15.2	13, 117	< 0.001
	7	13.8	13, 117	< 0.001	12.7	13, 117	< 0.001	12.2	13, 117	< 0.001
7	1	21.6	13, 116	< 0.001	13.1	13, 116	< 0.001	12.2	13, 116	< 0.001
	3	13.0	13, 115	< 0.001	8.3	13, 115	< 0.001	10.9	13, 115	< 0.001
	7	10.9	13,113	< 0.001	10.2	13,113	< 0.001	12.7	13, 113	< 0.001

Table 4. 4. ANOVA of insecticides by age of the insecticide residue in the laboratory conditions.

Age of residue (day)	Insecticide (a. i.)	Adult mortality			Incidence of damage			Severity of damage		
		F	df	*P*	*F*	df	*P*	*F*	df	*P*
0										
	Azadirachtin	2.6	2, 18	0.105	11.7	2, 18	< 0.001	47.5	2, 18	< 0.001
	Bifenthrin	6.3	2, 18	0.009	20.4	2, 18	< 0.001	17.1	2, 18	< 0.001
	Chlorantraniliprole	3.7	2, 18	0.044	13.1	2, 18	< 0.001	15.0	2, 18	< 0.001
	Cyantraniliprole	7.1	2, 18	0.005	12.2	2, 18	< 0.001	15.0	2, 18	< 0.001
	Cyclaniliprole	73.1	2, 18	< 0.001	5.5	2, 18	0.014	6.7	2, 18	0.007
	Tetraniliprole	21.3	2, 18	< 0.001	0.7	2, 18	0.496	1.0	2, 18	0.380
	Flupyradifurone	12.4	2,18	< 0.001	7.7	2, 18	0.004	5.3	2, 18	0.016
	Imidacloprid	7.9	2, 18	< 0.001	11.8	2, 17	< 0.001	0.3	2, 18	0.759
	Indoxacarb	17.8	2, 18	< 0.001	14.7	2, 18	< 0.001	25.6	2, 18	< 0.001
	Pyrifluquinazon	11.7	2, 18	< 0.001	16.8	2, 18	< 0.001	15.6	2, 18	< 0.001
	Spirotetramat	2.1	2, 18	0.154	33.3	2, 18	< 0.001	48.1	2, 18	< 0.001
	Sulfoxaflor + Spinetoram	36.7	2, 18	< 0.001	7.4	2, 18	0.005	4.6	2, 18	0.024
	Flonicamid	1.5	2,18	0.256	10.7	2, 18	0.001	9.9	2, 18	0.001
	Nontreated	0.9	2, 38	0.403	42.2	2, 38	< 0.001	95.8	2, 38	< 0.001
7										
	Azadirachtin	2.1	2, 18	0.155	19.1	2, 18	< 0.001	51.6	2, 18	< 0.001
	Bifenthrin	1.6	2, 18	0.232	48.6	2, 18	< 0.001	33.7	2, 18	< 0.001
	Chlorantraniliprole	1.0	2, 18	0.387	12.7	2, 18	< 0.001	13.6	2, 18	< 0.001
	Cyantraniliprole	7.5	2, 18	0.004	33.6	2, 18	< 0.001	30.8	2, 18	< 0.001
	Cyclaniliprole	3.6	2, 18	0.049	19.9	2, 18	< 0.001	20.3	2, 18	< 0.001
	Tetraniliprole	35.7	2, 18	< 0.001	1.4	2, 18	0.270	1.4	2, 18	0.276
	Flupyradifurone	27.7	2, 18	< 0.001	32.9	2, 18	< 0.001	25.2	2, 18	< 0.001
	Imidacloprid	3.3	2, 15	0.066	11.4	2, 15	0.001	43.8	2, 15	< 0.001
	Indoxacarb	7.6	2, 18	0.004	36.7	2, 18	< 0.001	22.9	2, 18	< 0.001
	Pyrifluquinazon	2.8	2, 16	0.091	32.0	2, 16	< 0.001	21.7	2, 16	< 0.001
	Spirotetramat	9.9	2, 18	0.001	13.5	2, 18	< 0.001	49.1	2, 18	< 0.001
	Sulfoxaflor + Spinetoram	8.6	2, 18	0.002	9.9	2, 18	0.001	17.2	2, 18	< 0.001

Flonicamid	4.3	2, 18	0.029	8.0	2, 18	0.003	27.0	2, 18	< 0.001
Nontreated	1.0	2, 47	0.368	62.1	2, 47	< 0.001	70.3	2, 47	< 0.001

Fig. 4. 1. The setup of experimental assay in the laboratory, where clear film cylinder was covered the terminal shoot inserted into 20 mL polypropylene cup and mounted with mesh screen.

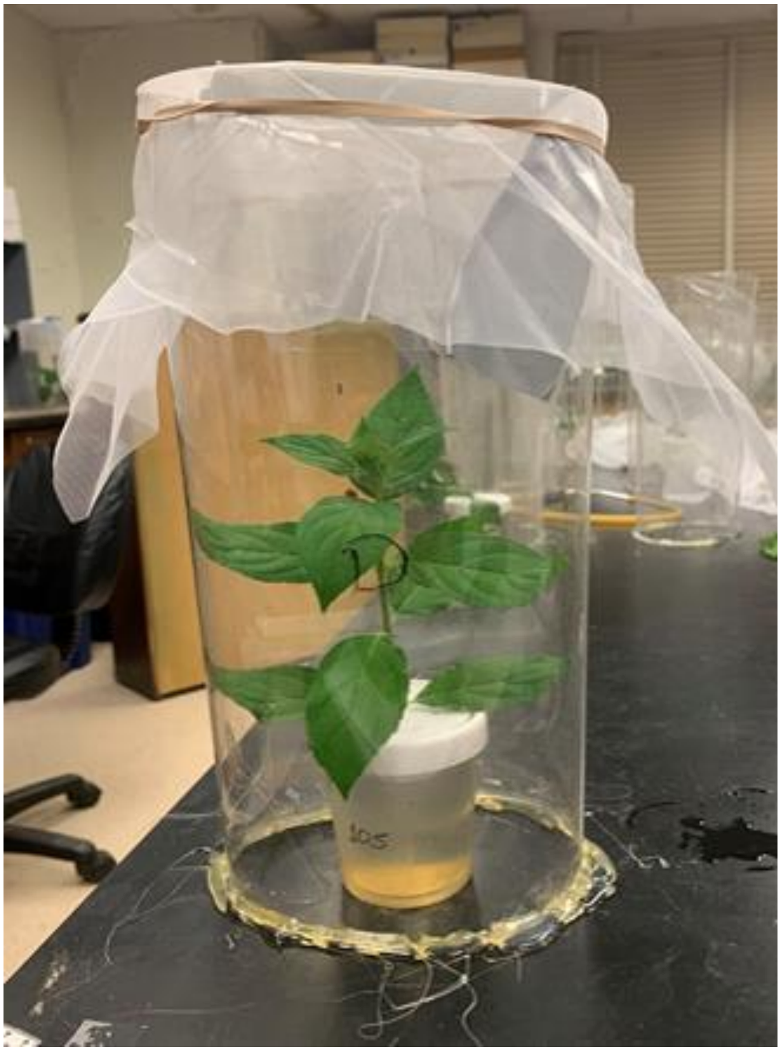
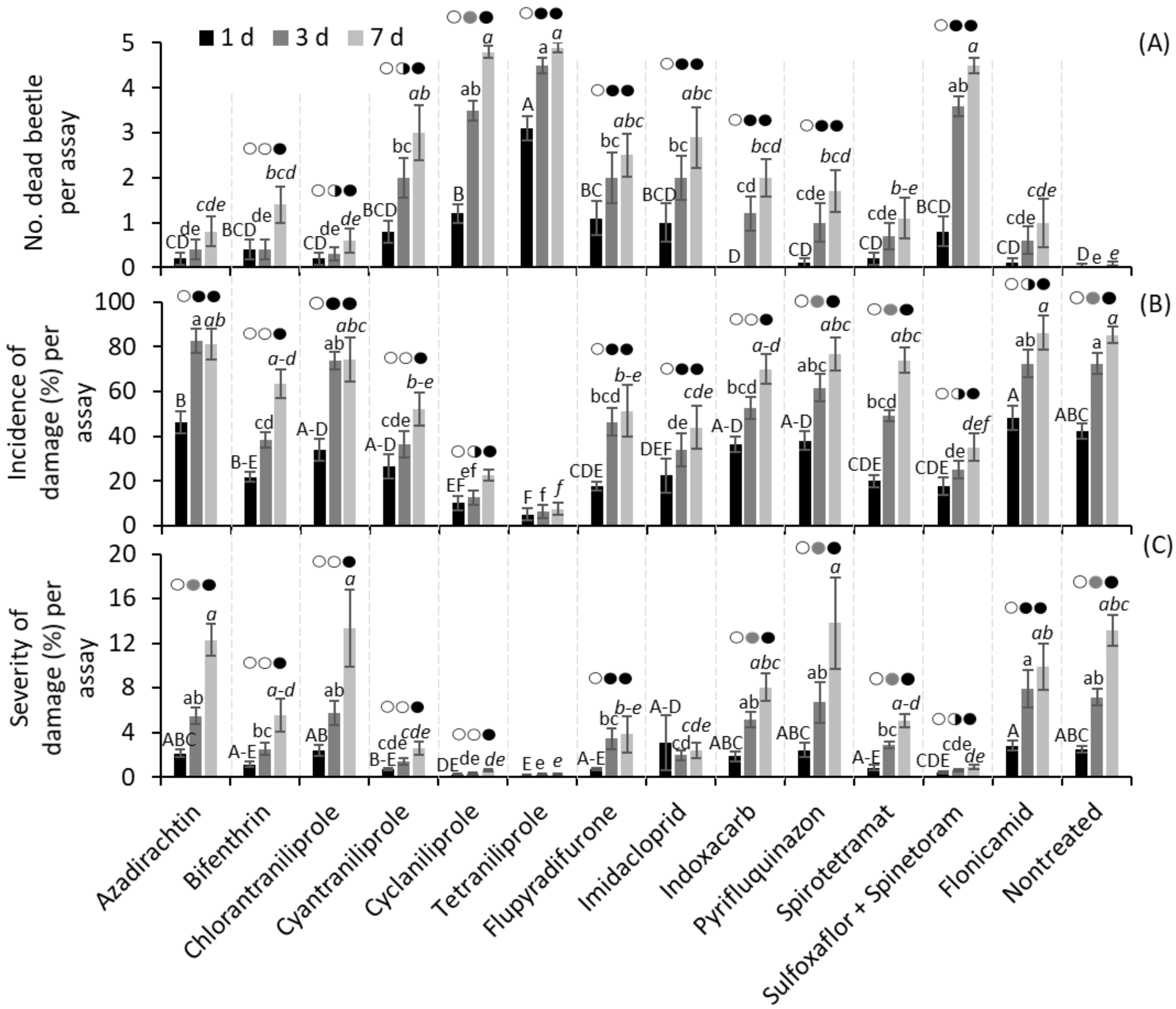
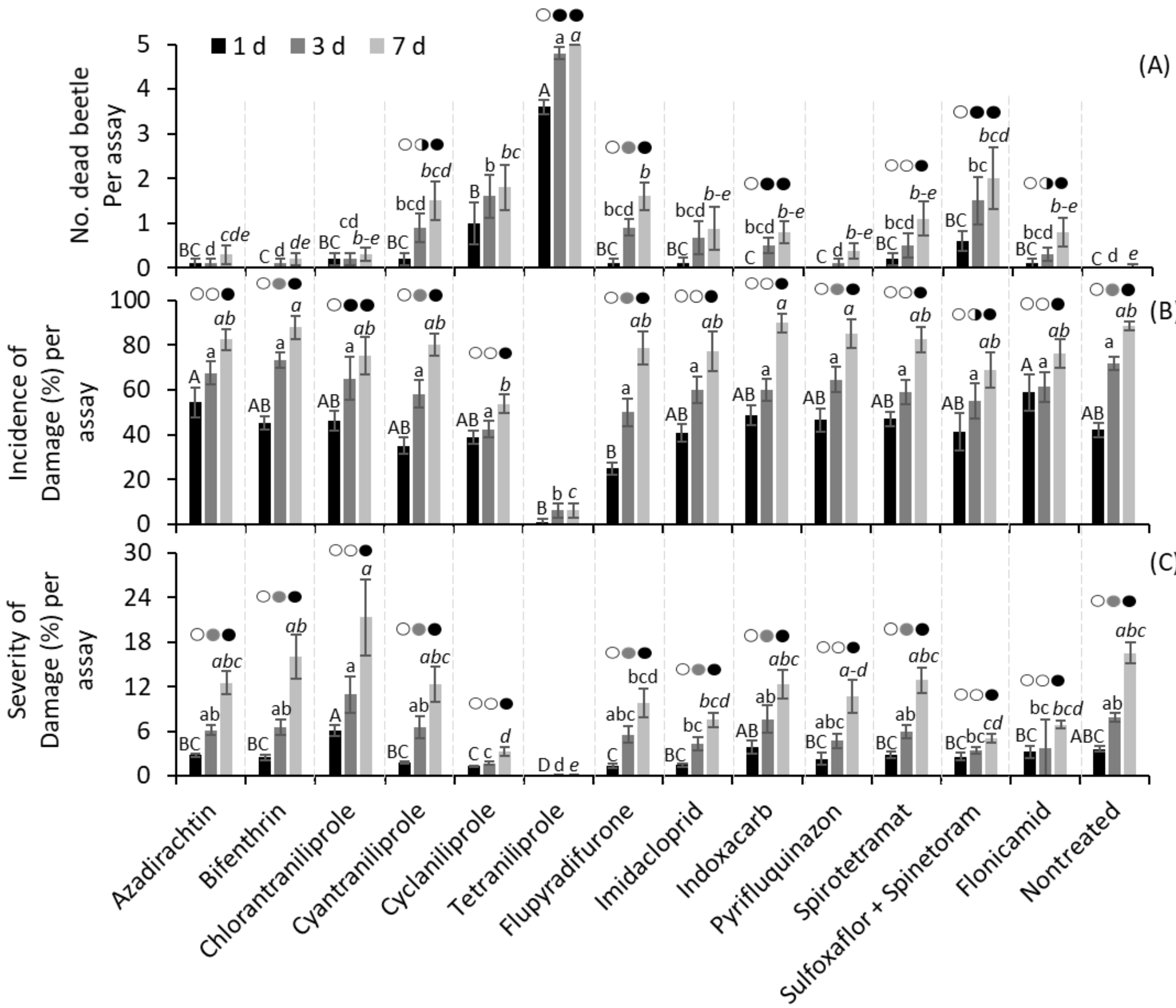


Fig. 4. 2. Mean (±SE) *S. frontalis* (A) adult mortality, (B) incidence (%), and (C) severity of damage (%) per assay for 0 d old insecticidal residue. Bars with the same letter types (upper case, italics, and regular case) were compared among treatments, and the same letters among treatments are not significantly different (Tukey's HSD Test, α = 0.05). Similarly, three circles with each treatment compare exposure time (1, 3, and 7 d). Same-colored (either ○ or ● or ●) are not significantly different (Tukey's HSD Test, α = 0.05), whereas, two-colored circle (◑) is not significantly different with ○ or ● (Tukey's HSD Test, α = 0.05).



1 d
3 d
7 d
(A)
(B)
(C)
No. dead beetle per assay
Incidence of damage (%) per assay
Severity of damage (%) per assay
Azadirachtin
Bifenthrin
Chlorantraniliprole
Cyantraniliprole
Cyclaniliprole
Tetraniliprole
Flupyradifurone
Imidacloprid
Indoxacarb
Pyrifluquinazon
Spirotetramat
Sulfoxaflor + Spinetoram
Flonicamid
Nontreated

Fig. 4. 3. Mean (±SE) *S. frontalis* (A) adult mortality, (B) incidence (%), and (C) severity of damage (%) per assay for 7 d old insecticidal residue. Bars with the same letter types (upper case, italics, and regular case) were compared among treatments, and the same letters among treatments are not significantly different (Tukey's HSD Test, $\alpha = 0.05$). Similarly, three circles with each treatment compare exposure time (1, 3, and 7 d). Same-colored (either ○ or ● or ●) are not significantly different (Tukey's HSD Test, $\alpha = 0.05$), whereas, two-colored circle (◑) is not significantly different with ○ or ● (Tukey's HSD Test, $\alpha = 0.05$).


1 d
3 d
7 d
(A)
No. dead beetle Per assay
(B)
Incidence of Damage (%) per assay
(C)
Severity of Damage (%) per assay
Azadirachtin
Bifenthrin
Chlorantraniliprole
Cyantraniliprole
Cyclaniliprole
Tetraniliprole
Flupyradifurone
Imidacloprid
Indoxacarb
Pyrifluquinazon
Spirotetramat
Sulfoxaflor + Spinetoram
Flonicamid
Nontreated

CHAPTER 5

CONCLUSION

Adult of *Systena frontalis* (Fabricius) (Coleoptera: Chrysomelidae) is a serious foliage-feeding pest of many ornamental plants in container plants throughout the central and eastern United States. Limited studies have been conducted on *S. frontalis*. *S. frontalis* adults cause plant damage by feeding on the leaf surfaces, resulting in numerous shot holes. Container plants with noticeable foliar damage have reduced aesthetic value and are not marketable. In addition to a loss of aesthetic value and sales, *S. frontalis* cause further economic losses by increasing labor and additional management costs, such as pesticides, fertilizer, irrigation, and equipment in nurseries, as affected plants remain in the nursery for an extended period of time until the next market window. The major goal of our studies was to develop sustainable management options for *S. frontalis*. Moreover, our study also focused to understand the biology and phenology of the pest. Integrated pest management options for *S. frontalis* were investigated for container ornamental nursery plants in the field and laboratory in 2021 and 2022.

The first objective was to determine if potting media of plant containers could serve as a potential overwintering site for *S. frontalis* immature in nurseries. In 2021 and 2022, experiments were conducted on panicle hydrangea in Georgia, North Carolina, and Virginia nurseries. The treatments were: 1) canopy caged, 2) whole plant caged, and 3) hydrangea plants not caged. The adult densities and damage caused by feeding were recorded. Overall, significantly more adult *S. frontalis* were found on the foliage in the fully caged and noncaged treatments than in the caged canopy treatment. Significantly greater incidence and severity of *S. frontalis* feeding damage were observed in the fully caged and noncaged treatments compared to the caged canopy treatment. This suggests that a large number of *S. frontalis* adults emerged consistently from the potting media of the plant containers after winter in the nurseries. Because plant containers can harbor large numbers of *S. frontalis* larvae during the winter, control measures that target overwintering *S. frontalis* larvae populations in potting media may reduce adult damage in the spring.

The effects of barrier fences with overhangs on *S. frontalis* adult densities and their feeding damage on panicle hydrangea in the ornamental nursery in 2021 and 2022 were investigated to mitigate the influx of incoming adults into ornamental container plants. The treatments were: 1) deltamethrin-impregnated netting enclosed barrier, 2) nontreated netting enclosed barrier, and 3) no barrier. Four plant containers were placed inside a 150 cm tall exclusion fence with an overhang. Regardless of deltamethrin impregnation, both barrier treatments reduced the incidence and severity of damage caused by adult feeding on panicle hydrangea. The findings suggest that an exclusion or inclusion overhang barrier fence can protect plants from adult *S. frontalis* attacks.

In 2021 and 2022, the residual activity of 13 common and potential insecticides was evaluated against adult *S. frontalis* after exposing them to fresh and 7 d field-aged residues in the laboratory. Fresh residues of tetraniliprole, cyclanilirole, and sulfoxaflor + spinetoram were the most effective against *S. frontalis* adults. In contrast, only tetraniliprole and cyclaniliprole showed evidence of efficacy after a week-old residue of insecticide.