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Research

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Delayed spinetoram application is useful in managing *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae) in Florida strawberry

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Scirtothrips dorsalis Hood (Thysanoptera: Thripidae) is an invasive, early-season pest of strawberry in Florida, causing feeding injury to young foliage that results in stunted plant growth and yield loss. Spinetoram, an effective insecticide for thrips pests with up to 3 applications per season permitted in strawberry, is often applied repeatedly during the early-season (Oct–Nov) to manage *S. dorsalis*, leaving few or no applications for flower thrips pests later in the season (Dec–Mar). Therefore, new strategies are needed to manage *S. dorsalis* with less insecticide, with the hypothesis that the first insecticide application can be delayed because young strawberry plants can compensate for minor feeding injury without compromising strawberry yield. Experiments conducted in strawberry field plots in Balm, FL, during 2018 and 2019 showed that delaying a spinetoram application for 14 days after infesting a plant with zero, 5, 10, or 20 *S. dorsalis* adults did not reduce the plant vigor and yield compared to spinetoram application after 4 days. Furthermore, young plants recovered from injury (10–30% bronzing injury on leaf veins and petioles) due to 1 or 2 *S. dorsalis* adults or larvae per trifoliate. A strategy of delaying the first spinetoram application when plants have 4–5 trifoliates should help reduce the number of insecticide applications needed for *S. dorsalis* management and reserve spinetoram applications for later in the season. Lower input costs in Florida strawberry without compromising yields due to thrips damage will improve the economics and sustainability of production systems.

Key words: chilli thrip, insecticide timing, action threshold, control decision, insecticide reduction

Chilli thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), is a foliar pest of more than 200 plant species, including economically important crops such as pepper (*Capsicum* spp. L., Solanaceae) (Seal et al. 2006a, 2006b), rose (*Rosa* spp. L., Rosaceae) (Ring 2012, Mannion et al. 2013), cotton (*Gossypium* spp. L., Malvaceae) (Kumar et al. 2014), citrus (*Citrus* spp., Rosaceae) (Tatara 1995, Hyun et al. 2012), tea (*Camellia sinensis* (L.) Kuntze, Theaceae) (Saha and Mukhopadhyay 2013), strawberry (*Fragaria* × *ananassa* Duchesne, Rosaceae) (Panthi and Renkema 2020, Panthi et al. 2020b), blueberry (*Vaccinium* sp., Ericaceae) (Panthi et al. 2020a, 2021), mango (*Mangifera indica* L., Anacardiaceae) (Aliakbarpour and Rawi 2011), grapes (*Vitis vinifera* L., Vitaceae) (Shibao 1990), and tomato (*Solanum licopersicum* L., Solanaceae) (Venette and Davis 2004, Kumar et al. 2013). Native to the Asia-Pacific region, *S. dorsalis* was first considered established in the United States in 2005 on ornamental plants in Florida (Hodges et al. 2005). By 2008, it invaded Texas (Ludwig 2009), and Kumar et al. (2023) reported that *S. dorsalis* has been found in 13 US states including Alabama, California, Georgia, Louisiana, Massachusetts, Maryland, North Carolina, New Jersey, New York, Pennsylvania, Rhode Island, and Virginia by 2022. Adults and larvae of *S. dorsalis* cause plant injury using piercing-sucking mouthparts to consume cellular contents of leaf tissues. Foliar injury symptoms first appear as bronzing at the base of leaves and on petioles, expanding to leaf midribs, veins, and blades (Panthi and Renkema 2020). Advanced injury appears as darkening and distortion of entire leaves, resulting in necrotic tissue, reduced photosynthetic area, and stunted plants. With a short life cycle (10–14 days) and the relatively long lifespan of adults (20–25 days), *S. dorsalis* has a high reproductive potential and may produce up to 18 generations per year under optimal conditions (Tatara 1995, Nietschke et al. 2008). As *S. dorsalis* expands its range in the United States and is recorded from an increasing number of host plants, it will be important to develop crop-specific strategies to reduce its impact as a pest.

Scirtothrips dorsalis has become a primary pest of Florida strawberry in the past 5 yr and is most problematic on young plants in the weeks after transplants are set in late Sep and early Oct. Hot and humid weather is typical in the fall in the main strawberry growing region of central Florida, favoring rapid population growth of *S. dorsalis* (Kang et al. 2015). Foliar injury on new strawberry growth causes reduced plant vigor and size and feeding injury on the first flushes of green fruit can reduce early marketable yield (Nov–Dec) (Renkema et al. 2020, Panthi et al. 2020b). Florida is the second-leading domestic supplier of fresh strawberries, but there is an increased supply of winter strawberries from other regions (e.g., California, Mexico) motivating the Florida industry to maximize early yields through earlier planting dates and developing new cultivars that are suited to early production (Suh et al. 2017, Whitaker et al. 2023). Therefore, *S. dorsalis* is likely to continue to be a significant pest in Florida strawberry. Thus, management strategies compatible with practices developed for later season control of flower thrips (*Frankliniella* spp., Thripidae) need to be developed to help reduce input costs and retain market competitiveness for Florida producers (Torres Quezada 2017).

Insecticides, primarily spinetoram, acetamiprid, and novaluron, are routinely applied to control *S. dorsalis* in Florida strawberry. It is not uncommon to start applications less than 2 wk after planting and reapply every 1–2 wk, based on sampling for thrips or damage assessments and total number of insecticide applications allowed per season (Whitaker et al. 2023, Renkema et al. 2020). Frequent insecticide use is not a sustainable management approach for *S. dorsalis* because populations may develop resistance to an overused insecticide, as has been documented for organochlorine (DDT, BHC, and endosulfan), organophosphate (acephate, dimethoate, phosalone, methyl-o-demeton, monocrotophos, phoslane, and triazophos), and carbamate (carbaryl) insecticides in India (Reddy et al. 1992, Vanisree et al. 2011), and certain insecticides have negative nontarget impacts on natural enemies or pollinators such as organophosphates, pyrethroids (Morse and Hoddle 2006) and neonicotinoids (Prabhakar et al. 2011). Recently, Kaur et al. (2023) reported an average mortality of ~41% in Florida strawberry field populations of late season *S. dorsalis* compared to ~72% mortality in early-season *S. dorsalis* treated with spinetoram, cyantraniliprole, or acetamiprid. Furthermore, effective thrips insecticides like spinetoram are needed for flower thrips control when strawberry plants are flowering. Also, using multiple applications of spinetoram early in the season against *S. dorsalis* reduces the number of applications available later in the season. While there are new insecticides registered for thrips in strawberry, including cyantraniliprole, flupyradifurone, and sulfoxaflor, that will augment and diversify control programs (Renkema et al. 2020), a sustainable *S. dorsalis* management approach will also include optimizing application timing with the goal of reducing overall insecticide use for thrips without compromising strawberry yield.

In Florida, after strawberry transplants are planted, overhead irrigation is typically applied between 8:00 AM and 7:00 PM following a 15- to 20-min cycle, to reduce desiccation of plants. Overhead irrigation is used for 7–10 days for bareroot transplants. An insecticide is often applied 2–3 days after the termination of overhead irrigation, when *S. dorsalis* injury symptoms are first observed in a strawberry field (Panthi 2020, Panthi and Renkema 2020). However, delaying the first insecticide application could assist with management of *S. dorsalis* as this method has been effective in other insect pest and crop systems (Nault and Shelton 2010, Silvie et al. 2013). An action threshold-based program for onion thrips (*Thrips tabaci* Lindeman) management delayed an initial and subsequent insecticide applications and thus reduced total insecticide application by 34%–46% compared to the standard weekly program, without compromising commercially acceptable onion bulb yields (Fournier et al. 1995, Nault and Huseth 2016). Similarly, to manage tomato fruitworm, *Helicoverpa zea* Boddie (Lepidoptera: Noctuidae), spraying insecticide after ≥1 *H. zea* eggs are present in 10% of tomato plants sampled reduced the number of sprays by more than 50% compared with the existing calendar-based spray program (Kuhar et al. 2006).

Therefore, the goal of this study was to test whether delaying the first insecticide application is effective for managing *S. dorsalis* in Florida strawberry. The objective of this study was to determine whether applying spinetoram at 4 or 14 days after initial *S. dorsalis* infestation affected the growth and yield of strawberry plants. The results of this study will help strawberry growers make decisions about the timing of an initial insecticide application against *S. dorsalis* after planting.

Materials and Methods

Field experiments were conducted at the Gulf Coast Research and Education Center (GCREC), Wimauma, FL (27°45′43″N 82°13′38″W) in 2018 and 2019. Raised, double-pressed, earthen bed rows (1.2 m row spacing) were covered with virtually impermeable film (VIF) (Blockade, Berry Plastics, Evansville, IN), and were fumigated with a soil fungicide/nematicide (Telone C-35, 280 liter/ha, Dow AgroSciences, Indianapolis, IN) at formation on 20 Aug 2018 and 22 Aug 2019. A glyphosate-based herbicide (Round-up, 48.7%, Monsanto Company, St. Louis, MO, USA) was applied to row aisles on 23 Sep 2018 and 25 Sep 2019, before transplanting.

Plugged (with soil) strawberry transplants ("Florida Radiance") from a nursery (G. W. Allen Nursery Ltd., Centreville, Nova Scotia, Canada) were set on 27 Sep 2018, and 30 Sep 2019, in 2 rows per bed (30 cm inter-row spacing). Following transplanting, plants were overhead irrigated during the daytime for 5 days with a 20 min on and 20 min off schedule. Plants were drip fertigated at recommended rates (Whitaker et al. 2023) and received weekly applications of fungicides (primarily Captan 80 WDG, 6.7 kg/ha, Drexel Chemical Company, Memphis, TN, USA) to control botrytis fruit rot (*Botrytis cinerea* Pers.) and powdery mildew (*Podosphaera macularis* Braun & Takamatus). One early-season application of *Bacillus thuringiensis*-based biopesticide (DiPel DF, 1120 g/ha, Valent Biosciences, Libertyville, IL) was made on 24 Oct 2018 and 20 Oct 2019, to control lepidopteran larvae; DiPel (*Bt*) has no activity against thrips.

The experiments were conducted in 8 rows in 2018 and 10 rows in 2019, where the plots were arranged in a randomized complete block design in a checkerboard pattern so that rows adjacent to each plot were unplanted. Each bed row was 38 m long and each plot was 1 m long with 2 plant rows, consisting of 6 plants total, 3 in each row. There was a 2-m unplanted buffer zone at 1 end of the row and 4 m at other end, 2 bed rows constitute 1 replicate or block and there were 4 replicates in 2018 and 5 replicates in 2019. Treatment plots on the same bed row were separated by an unplanted buffer of 5 m. Prior to *S. dorsalis* release, plants were trimmed to the 4–5 youngest trifoliates.

Adult *S. dorsalis* were collected from a colony maintained on 3- to 4-wk-old cotton, *Gossypium hirsutum* L. (Malvaceae), plants in a growth room at GCREC at 26 °C, 50–60% RH, and 14 h photoperiod initiated with *S. dorsalis* collected from Florida strawberry fields in 2016. Prior to these experiments, we have moved *S. dorsalis* from cotton colony plants to strawberries for other experiments without observing any negative effects on host acceptance. *Scirtothrips dorsalis* adults were aspirated into filtered pipette tips (Diamond TipackTM, 100 µl tip: Gilson S.A.S., Villiers-leBel, France) using FisherbrandTM rubber tube (6 mm diameter, Thermo Fisher Scientific, Waltham, MA, USA) from 1 cohort of the colony. Adult *S. dorsalis* were released onto the plants by placing the open ends of pipette tips in the plant crowns and gently tapping the sides of pipette tips to encourage adults to exit. Adult *S. dorsalis* were released onto 1 central plant (the middle plant on the row facing the east) in each plot at 0, 5, 10, or 20 adults per plot on 22 Oct 2018 and 28 Oct 2019.

Plots received an application of the insecticide spinetoram (Radiant SC, 11.7%, Dow AgroSciences at 740 ml/ha) 4 days ("early") (26 Oct 2018 and 1 Nov 2019) or 14 days ("delayed") (5 Nov 2018 and 11 Nov 2019) after *S. dorsalis* infestation or were untreated (control). Applications consisted of 1 over-the-top pass of strawberry plants using a CO_2-pressurized backpack sprayer (R&D Sprayers, Opelousas, LA) with a double-nozzle (30 cm spacing between nozzles) hand-held wand sprayer. The sprayer was calibrated to deliver 465 liter/ha at 2.72391 atm through a flat-fan nozzle (8004VS; Tee Jet Harrisburg, Dillsburg, PA).

All plants in every plot were visually rated for *S. dorsalis* feeding injury 4 days after infestation and every week afterward for 8 wk. A feeding injury rating was assigned to each leaf based on percent injured area (Panthi 2020, Lahiri and Yambisa 2021): 0 was no injury, 1 was <10% injury (bronzing on leaf base and petiole), 2 was 10%–30% injury (bronzing along midrib and veins), 3 was 30%–60% injury (bronzing extending to leaf blade), and 4 was >60% injury (leaf darkening) (Fig. 1). Ripe strawberries were harvested weekly from all plants per plot for 4 wk beginning on 26 Nov 2018 and 2 Dec 2019. Marketable and *S. dorsalis*-injured berries were counted and weighed on a digital scale (Ohaus LS 5000, Ohaus Scale Corporation, Florham Park, NJ). Bronzing, scarring, and cracking on strawberries indicated *S. dorsalis* injury.

A top view of each plot was captured using a digital camera (Cybershot, SONY Inc., Japan) from a height of 1.5 m on 17 Dec 2018, and 24 Dec 2019. The canopy area was measured using open-source imaging software (Fiji, distribution of ImageJ, https://imagej.net/Fiji). A wand tool in the imaging software was used to select the area of interest (canopy of an individual plant) and the selected area was measured after calibrating the scale of measure. At the end of the experiment, plants were cut at the base and weighed on a digital scale (Ohaus LS 5000) on 17 Dec 2018 and 24 Dec 2019.

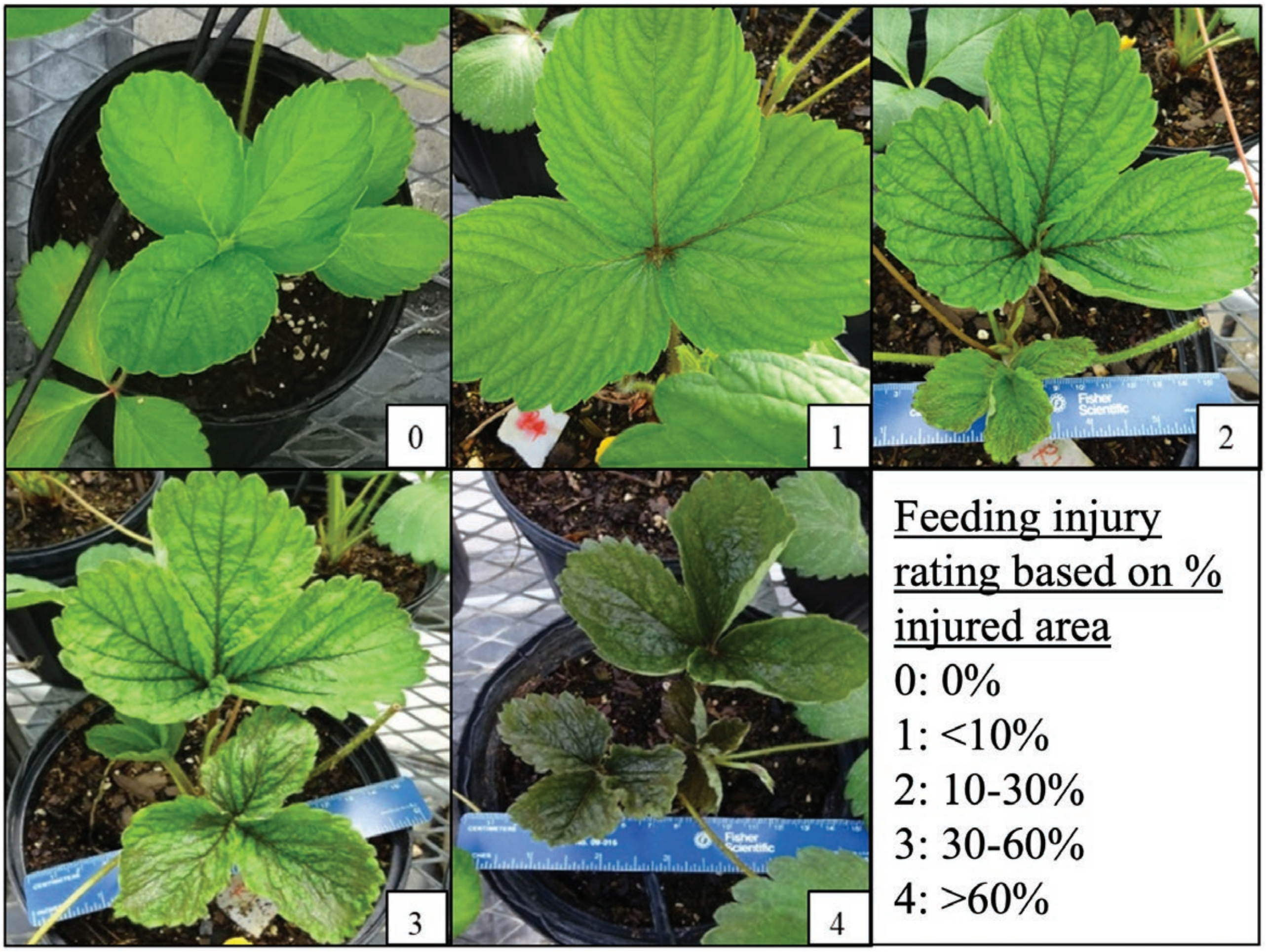

Fig. 1. Progression of *S. dorsalis* feeding injury such as bronzing, curling, darkening, and distortion of leaves and petioles on potted strawberry plants.

Data were analyzed separately for initially infested and uninfested plants in 2018 and 2019. Feeding injury rating were fitted to generalized linear mixed model (PROC GLIMMIX) where insecticide timing, initial *S. dorsalis* density, and week-after-*S. dorsalis* infestation were considered as fixed effects, blocks as random effects, and week-after-*S. dorsalis* infestation within a given plot as repeated measures. Marketable yield, percent fruit injury, plant biomass, and canopy area were also fitted to PROC GLIMMIX with insecticide timing and initial *S. dorsalis* density as fixed effects and blocks as random effect. In all models, residuals were normally distributed and checked by observing diagnostic plots. Mean values were compared with Tukey's HSD test. PROC CORR was used to correlate marketable yield with plant biomass and canopy area by insecticide timing and *S. dorsalis* density. All analyses were done in SAS v. 9.4, (SAS Institute, Cary, NC) at $\alpha = 0.05$.

Results

Feeding Injury Rating

The feeding injury rating on initially infested and uninfested plants was affected by insecticide timing, initial *S. dorsalis* density, weeks-after-*S. dorsalis* infestation, and their interactions in 2018 and 2019 (Table 1). In 2018, no feeding injury was observed in plants with no initial *S. dorsalis* infestation (Figs. 2a and 3a). In 2018, plants with early (4 days) and delayed (14 days) insecticide application attained a maximum feeding injury rating of 1 (<10% feeding injury) and 2 (10%–30%) 1–2 wk after infestation of 5 or 10 and 20 *S. dorsalis* density, respectively (Figs. 2c, e, g and 3c, e, g). The feeding injury rating gradually declined to 0, 5 wk after the insecticide application. In 2019, low levels of injury (<10–30%) occurred on plants not infested with S. *dorsalis* (Figs. 2b and 3b). In 2019, plants with early and delayed insecticide application had a maximum feeding injury rating of 2 (10%–30%) and 3 (30%–60%) after initially infested with 5 or 10 *S. dorsalis* and 20 *S. dorsalis*, respectively (Figs. 2d, f, h and 3d, f, h). The feeding injury rating decreased to 0 by the 7th week (Figs. 2 and 3). In both years, injury levels on uninfested plants did not exceed the feeding injury rating of 1 (<10%) for all initial *S. dorsalis* densities (Fig. 3). In 2019, a small level of injury (rating of <0.5) persisted until the 7th and 8th weeks for all initial *S. dorsalis* densities when spinetoram was applied 4 or 14 days after infestation (Figs. 2 and 3). For both years, the feeding injury on uninfested control plants (no spinetoram applied) plateaued at less than 10%–30% (ratings of 1.0–1.5) (Fig. 3).

Marketable Strawberry Yield and Fruit Injury

In 2018, the marketable strawberry yield was affected by insecticide timing ($F = 16.56$, df = 2, 33, $P < 0.0001$), *S. dorsalis* density ($F = 3.74$, df = 3, 33, $P = 0.0204$), and their interaction ($F = 4.70$, df = 6, 33, $P = 0.0015$). Marketable yields of plants treated either 4 or 14 days after infestation were similar regardless of *S. dorsalis* density (Fig. 4a). Marketable yield was lower on untreated plants initially infested with 10 and 20 *S. dorsalis* compared to plants treated with spinetoram either 4 or 14 days after the infestation. Fruit injury was affected by insecticide timing ($F = 73.65$, df = 2, 33, $P < 0.0001$), *S. dorsalis* density ($F = 9.70$, df = 3, 33, $P < 0.0001$), and their interaction ($F = 9.70$, df = 6, 33, $P < 0.0001$). There were no *S. dorsalis*-injured fruits from treated plants regardless of insecticide timing (Fig. 4b). Untreated plants with initial 5, 10, or 20 *S. dorsalis* had more fruit injury compared to plants without *S. dorsalis* (Fig. 4b).

In 2019, marketable strawberry yield was not affected by insecticide timing ($F = 2.5$, df = 2, 44, $P = 0.0935$), *S. dorsalis* density ($F = 1.27$, df = 3, 44, $P = 0.2975$), or their interaction ($F = 1.1$, df = 6, 44, $P = 0.3804$) (Fig. 4c). Percent fruit injury was also not affected by insecticide timing ($F = 3.99$, df = 2, 44, $P = 0.0511$), *S. dorsalis* density ($F = 1.01$, df = 3, 44, $P = 0.3956$), or their interaction ($F = 0.43$, df = 6, 44, $P = 0.8537$) (Fig. 4d).

Plant Biomass and Canopy Area

In 2018, the canopy area of initially infested plants was affected by insecticide timing, *S. dorsalis* density, and their interaction (Table 2). Untreated plants with 5, 10, or 20 *S. dorsalis* had less canopy area than untreated plants with zero *S. dorsalis* (Fig. 5). There were no differences in canopy area among plants treated with spinetoram after 4 and 14 days across all *S. dorsalis* densities. The canopy area of uninfested plants was affected by insecticide timing and not by *S. dorsalis* density or their interaction (Table 2). Plants treated 4 or 14 days after *S. dorsalis* infestation had more canopy area than untreated plants (Fig. 6c).

In 2019, the canopy area of initially infested plants was affected by insecticide timing, but not by *S. dorsalis* density or their interaction (Table 2). Plants treated 4 or 14 days after *S. dorsalis* infestation had more canopy area than untreated plants (Fig. 6b). The canopy

Table 1. Summary statistics of weekly (22 Oct–17 Dec 2018 and 28 Oct–24 Dec 2019) feeding injury ratings (see Fig. 1 for rating levels) on infested and uninfested-adjacent strawberry plants ("Radiance") in a field plot at GCREC, Balm, Florida, at rates of 0, 5, 10, or 20 *S. dorsalis* adults per plants. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml/ha) either 4 (early) or 14 (delayed) days after *S. dorsalis* infestation or untreated (none) in 2018 and 2019

		Infested plant ($n = 1$)				Uninfested plants ($n = 5$)			
	df	2018		2019		2018		2019	
Effects		*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Insecticide application	2	273.96	<0.0001	38.03	<0.0001	39.42	<0.0001	18.62	<0.0001
Density of *S. dorsalis*	3	75.28	<0.0001	23.16	<0.0001	24.07	<0.0001	5.54	0.0001
Weeks-after-infestation	8	37.75	<0.0001	33.38	<0.0001	16.03	<0.0001	19.50	<0.0001
Insecticide × density	6	34.70	<0.0001	3.38	0.0073	8.12	<0.0001	2.26	0.0378
Weeks × insecticide	16	50.13	<0.0001	45.03	<0.0001	27.64	<0.0001	27.99	<0.0001
Weeks × density	24	5.99	<0.0001	3.95	<0.0001	4.57	<0.0001	2.42	0.0001
Weeks × insecticide × density	48	7.79	<0.0001	3.79	<0.0001	5.34	<0.0001	2.01	<0.0001

Error df: infested plants = 288 (2018), 384 (2019), uninfested plants = 1824 (2018), 2,304 (2019).

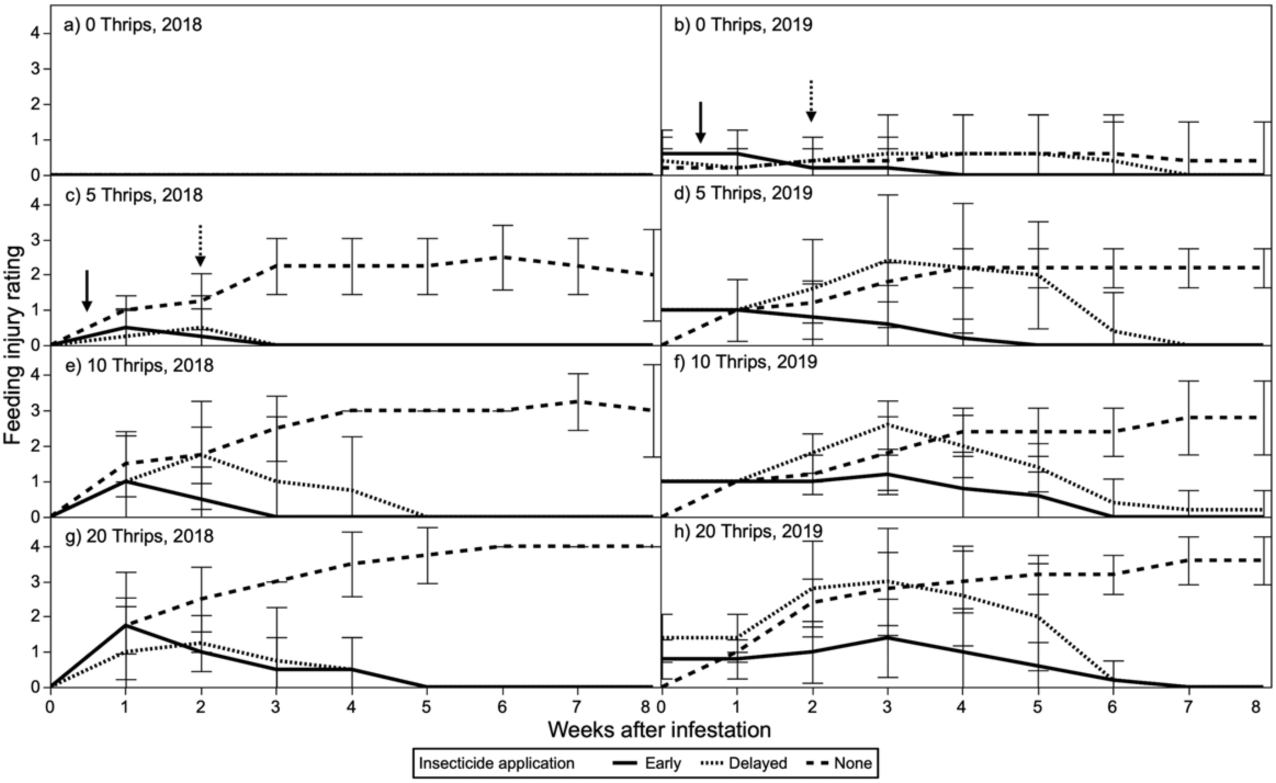

Fig. 2. Weekly (22 Oct–17 Dec 2018 [a, c, e, g] and 28 Oct–24 Dec 2019 [b, d, f, h]) feeding injury ratings (see Fig. 1 for rating levels) (means ± 95% CI) on an infested strawberry plant ("Radiance") in the center of a field plot of 6 plants at GCREC in Balm, FL, at rates of 0, 5, 10, or 20 *S. dorsalis* adults per plants. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml/ha) 4 (early, solid arrows) or 14 (delayed, dotted arrows) days after *S. dorsalis* infestation or untreated (none). In some cases, initially uninfested plants later had thrips.

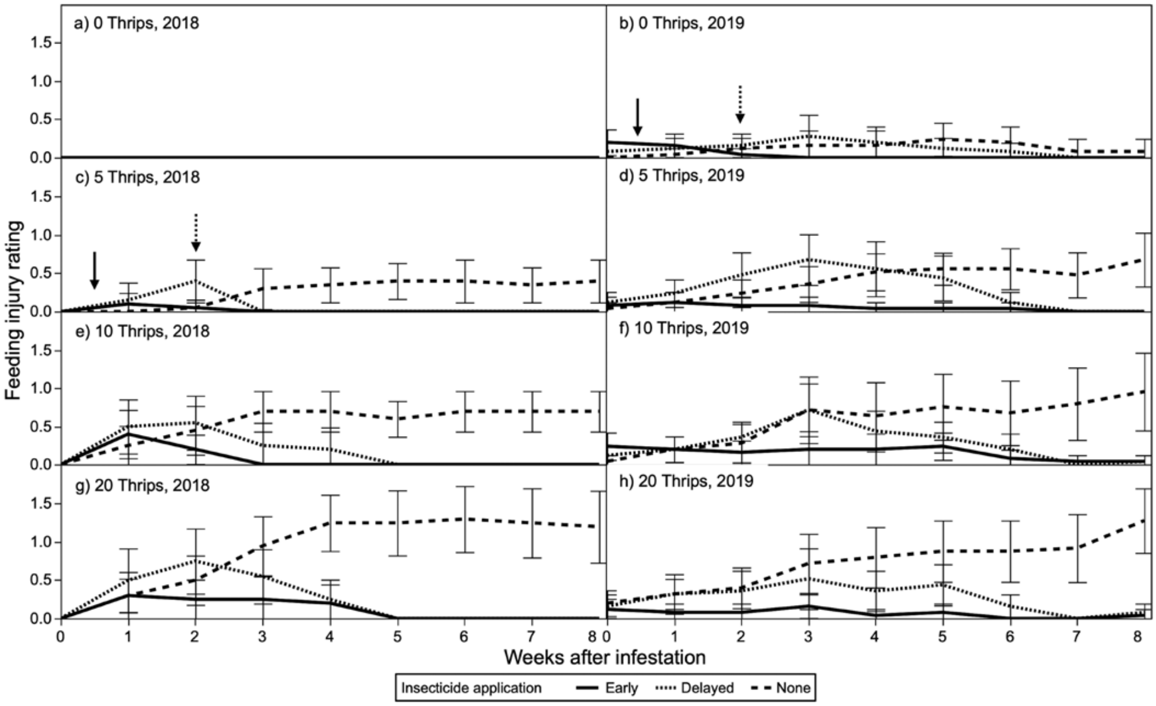

Fig. 3. Weekly (22 Oct–17 Dec 2018 [a, c, e, g] and 28 Oct—24 Dec 2019 [b, d, f, h]) feeding injury ratings (see Fig. 1 for rating levels) (means ± 95% CI) on uninfested-adjacent strawberry plant ("Radiance") in the center of a field plot of 6 plants at GCREC in Balm, FL, at infestation rates of 0, 5, 10, or 20 *S. dorsalis* adults per plants. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml/ha) 4 (early, solid arrows) or 14 (delayed, dotted arrows) days after *S. dorsalis* infestation or untreated (none). In some cases, initially uninfested plants later had thrips.

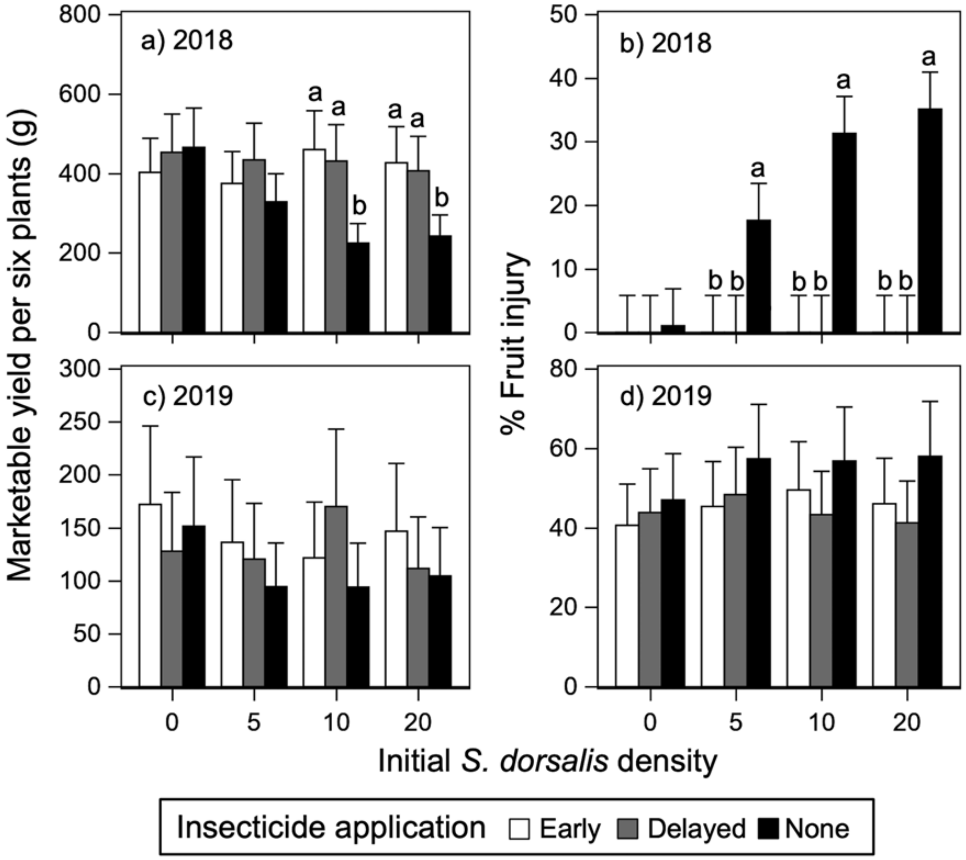

Fig. 4. Marketable yield and % fruit injury (means ± 95% CI) of 6 strawberry plants ("Radiance") in a field plot at GCREC, Balm, FL, at infestation rates of 0, 5, 10, and 20 *S. dorsalis* adults per plant. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml ha^{-1}) 4 (early) or 14 (delayed) days after *S. dorsalis* infestation or untreated (none) in 2018 (a, b) and 2019 (c, d). Bars with different letters are significantly different (Tukey's HSD test, $\alpha = 0.05$).

Table 2. Summary statistics of the canopy area and plant biomass of infested and uninfested-adjacent strawberry plants ("Radiance") in a field plot at GCREC, Balm, FL, at rates of 0, 5, 10, or 20 *S. dorsalis* adults per plants. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml/ha) either 4 (early) or 14 (delayed) days after *S. dorsalis* infestation or untreated (none) in 2018 and 2019

		Canopy area				Plant biomass			
	df	2018		2019		2018		2019	
Effects		*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Initially infested plant									
Insecticide application	2	30.18	<0.001	7.42	0.002	3.14	0.057	1.14	0.330
Density	3	4.29	0.012	1.09	0.363	0.92	0.442	0.25	0.862
Insecticide × density	6	8.02	<0.001	1.55	0.184	0.41	0.867	1.13	0.362
Uninfested plant									
Insecticide application	2	13.14	<0.001	3.38	0.043	1.04	0.364	0.66	0.523
Density	3	0.54	0.655	0.08	0.970	0.90	0.454	0.58	0.632
Insecticide × density	6	0.60	0.731	1.34	0.260	0.56	0.763	2.02	0.083

Error df = 33 in 2018 and 44 in 2019.

area of uninfested plants was not affected by insecticide timing, *S. dorsalis* density, or their interaction (Fig. 6d). Plant biomass of initially infested and uninfested plants was not affected by insecticide timing, *S. dorsalis* density, or their interaction in 2018 and 2019 (Table 2; Fig. 6e, f, g, h). Multivariate analysis showed significant positive correlation between marketable yield and plant biomass when plants were treated early with initial 10 *S. dorsalis* (Pearson's *r* = 0.76), treated delayed with initial 5 (*r* = 0.82), 10 (*r* = 0.73), 20 (*r* = 0.76), and no *S. dorsalis* (*r* = 0.73), and untreated plants with initial 5 (*r* = 0.73), 20 (*r* = 0.90), and no *S. dorsalis* (*r* = 0.71).

Discussion

The results of our study showed that regardless of initial insecticide application timing, *S. dorsalis* was effectively controlled on young strawberry plants during the early growing season in Florida.

Delaying a spinetoram application for 14 days after *S. dorsalis* infestation did not result in an increase in the feeding injury or reduce the plant vigor and yield compared to a spinetoram application 4 days after the infestation. Initial plant injury (before spinetoram was applied) caused by *S. dorsalis* was compensated for by the plants at the end of the 8-wk experiments, as determined by measuring plant biomass and canopy area and the marketable yield and amount of thrips-damaged fruit. We propose a nominal injury level of 10%–30% bronzing on petioles and bases, veins, and midribs of new strawberry leaves before making an initial application of spinetoram in the weeks after planting. However, future research will be needed to determine a dynamic action threshold-based on defining the relationship between numbers of *S. dorsalis* per leaf, plant damage and the efficacy of insecticides. Moreover, these results are based on infestation of strawberry transplants with spinetoram-susceptible *S. dorsalis* colony reared in lab since 2016 and may not be applicable to spinetoram-resistant field populations of *S. dorsalis* (Kaur et al. 2023).

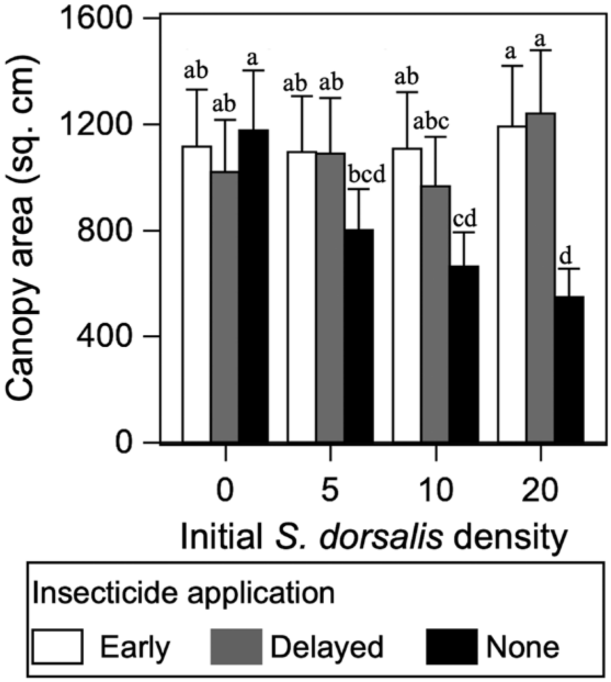

Fig. 5. Canopy area (means ± 95% CI) of an infested strawberry plant ("Radiance") in the center of a field plot of 6 plants at GCREC in Balm, FL, at rates of 0, 5, 10, or 20 *S. dorsalis* adults per plants. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml/ha) 4 (early) or 14 (delayed) days after *S. dorsalis* infestation or untreated (none). Bars with different letters are significantly different (Tukey's HSD test, α = 0.05).

Pest management programs based on action thresholds have been implemented to avoid initial applications of insecticides when low pest pressures do not cause economic damage to crops. However, for effective management, action thresholds should be used in conjunction with the known efficacy of an insecticide. For example, spinetoram was effective against *T. tabaci* in onions when applied at an action threshold of 3 larvae per leaf, which is lower than the threshold used for less effective insecticides like lambda-cyhalothrin or methomyl (Nault and Shelton 2010). In strawberry, spinetoram provided 91%–99% control of *S. dorsalis* originating from a lab colony, but flupyradifurone was less effective at 78% control (Panthi and Renkema 2020). Reduced-risk insecticides such as spinosyns, neonicotinoids, butenolides, benzoylureas, pyrazoles, and diamides have been tested against *S. dorsalis* in strawberry, pepper, and blueberry crops to develop optimal insecticide-rotation programs for *S. dorsalis* (Kumar et al. 2017, Lahiri and Panthi 2020, Panthi and Renkema 2020, Panthi 2020). Further studies should test spinetoram or other effective insecticides (e.g., acetamiprid) at a higher threshold of 2 *S. dorsalis* per trifoliate, and flupyradifurone or other less effective insecticides at a lower threshold of 1 *S. dorsalis* per trifoliate. When applying moderately effective insecticides

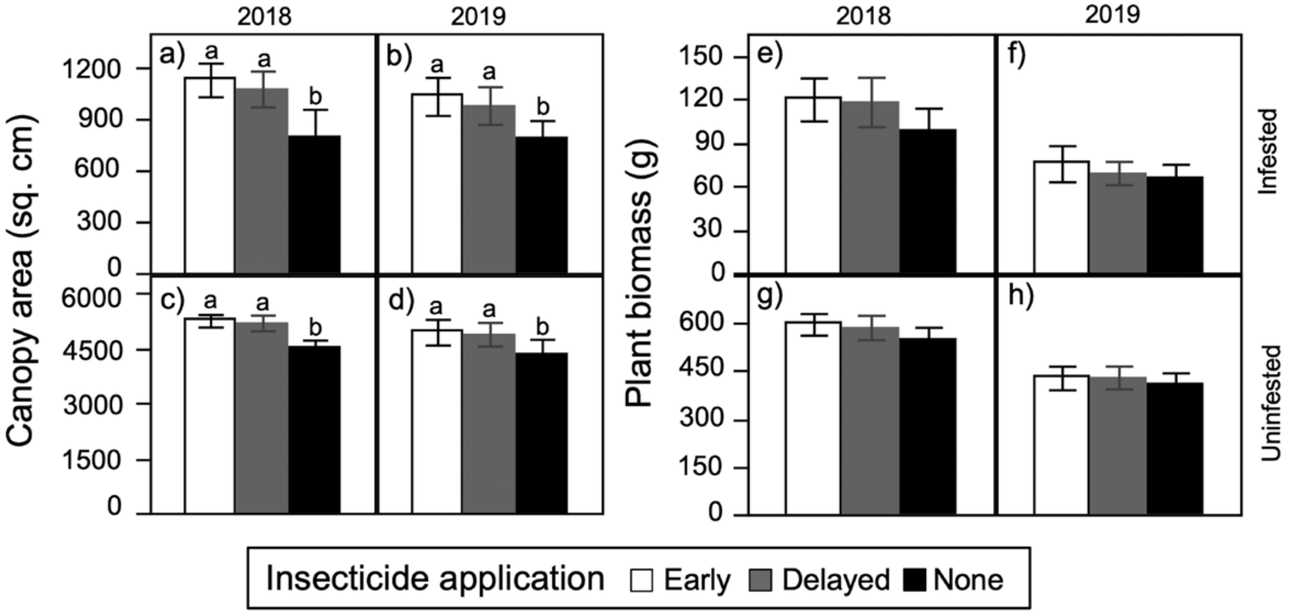

Fig. 6. Canopy area (a, b, c, d) and plant biomass (e, f, g, h) (means ± 95% CI) of infested and uninfested-adjacent strawberry plants ("Radiance") in a field plot at GCREC, Balm, FL, at rates of 0, 5, 10, or 20 *S. dorsalis* adults per plants. Plants were treated with the insecticide spinetoram (Radiant SC, 11.7% at 740 ml/ha) 4 (early) or 14 (delayed) days after *S. dorsalis* infestation or untreated (none) in 2018 and 2019. Bars with different letters are significantly different (Tukey's HSD test, α = 0.05).

such as flupyradifurone, either the action threshold should be less than that for spinetoram or such insecticides should not be used for longer intervals of 14 days as for spinetoram.

Previous greenhouse and field studies showed that *S. dorsalis* moved slowly among strawberry plants and feeding injury remained on initially infested plants without spreading to adjacent plants for at least 2 wk (Panthi et al. 2020b). Similarly, in this study, the central plant per plot that was singled out and artificially infested with *S. dorsalis* showed >60% injury after 8 wk compared to the other 5 plants in the same plots showing only 10%–30% plant injury. In addition, there was a little *S. dorsalis* feeding injury in plots with no artificial infestation, meaning that during the 2 yr of this study, natural populations were low at the study site. Since it appears that *S. dorsalis* has low potential to spread within fields in short periods, field blocks that have plants exceeding nominal injury levels or with *S. dorsalis* densities above thresholds may be targeted for insecticide applications rather than treating entire fields if there are areas without injury or *S. dorsalis*. Management of pests in smaller areas reduces the amount of pesticides, water, fuel, and labor compared to whole-field application (Weisz et al. 1996, Park et al. 2007). In addition, or as an alternative to insecticides, predatory mites such as *Amblyseius swirskii* Athias-Henriot and *Neoseiulus cucumeris* Oudemans (Arachnida: Phytoseiidae), effective against *S. dorsalis* adults and larvae in other crops (Arthurs et al. 2009), may be more feasibly introduced in a field block-specific rather than whole-field application for management of *S. dorsalis* in strawberries.

In the current study, there were differences in total fruit injury between 2018 and 2019. In 2019, there was plant injury throughout the experiment including in control plots where no thrips were added compared to 2018 where control plots had no injury after 8 wk. However, the amount of injury in plots treated with spinetoram was similar between years. In fact, Lahiri and Yambisa (2021) reported that *S. dorsalis* adult and larval populations remained significantly suppressed even 21 day-after-treatment with spinetoram in a greenhouse potted strawberry plant study. Higher injury levels in 2019 might have resulted from higher immigration rate of thrips from surrounding vegetation coupled with warmer temperatures in 2019 than in 2018 (NOAA 2019). Therefore, spinetoram application also reduced immigrating *S. dorsalis* in 2019.

There are multiple positive implications of making an initial insecticide application for *S. dorsalis* in Florida strawberry 10 days later than recommended without compromising early-season yield. First, delaying the initial application should result in fewer total applications of insecticides for *S. dorsalis*, thereby reducing labor and input costs for pest management and resulting in higher profit margins for growers. Second, fewer insecticide applications for *S. dorsalis* means that at least 1 application, particularly of spinetoram but also other effective insecticides, can be reserved for flower thrips if needed. Flower thrips are a perennial pest in Florida strawberry, but populations can vary year-to-year without predictability (Northfield et al. 2008, Frantz and Mellinger 2009, Kakkar et al. 2012). Third, knowing that *S. dorsalis* can be managed effectively with delayed and thus fewer overall insecticide applications may also increase the likelihood of successful integration of biological control with chemical control, as has been tested in other crops (Arthurs et al. 2009, Doğramaci et al. 2011). Overall, our results herein support that management decisions for *S. dorsalis* in Florida strawberry continue to be based on scouting for plant injury, but that a delayed application of spinetoram, even when *S. dorsalis* numbers are relatively high at 20 per plant, does not compromise early-season yield. Delaying an early-season application of spinetoram may sound risky to growers, but if the *S. dorsalis* rate-of-increase during a 10-day delay is known, the precise risk factor can be calculated and used to make an accurate control decision. Further research is also needed on the timing of subsequent insecticide applications, particularly for the period when strawberry plants begin to flower and attract flower thrips, as our 2019 data suggest.

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