Environmental Entomology, 50(1), 2021, 12–18
doi: 10.1093/ee/nvaa149
Advance Access Publication Date: 4 December 2020
Research

OXFORD

Behavioral Ecology

The Short-Range Movement of *Scirtothrips dorsalis* (Thysanoptera: Thripidae) and Rate of Spread of Feeding Injury Among Strawberry Plants

Babu R. Panthi,[1,2,4] Justin M. Renkema,[1,3] Sriyanka Lahiri,[1] and Oscar E. Liburd[4]

[1]Gulf Coast Research and Education Center, University of Florida, Wimauma, FL-33598, [2]Current address: Crop and Soil Science Department, Oregon State University, Corvallis, OR-97330, [3]Current address: London Research and Development Centre – Vineland Campus, Agriculture and Agri-Food Canada, Vineland, Ontario-L0R 2E0, Canada, [4]Department of Entomology and Nematology, University of Florida, Bldg. 970 Natural Area Drive, Gainesville, FL-32611, and [4]Corresponding author, e-mail: panthib@oregonstate.edu

Subject Editor: William Morrison

Received 16 June 2020; Editorial decision 22 October 2020

Abstract

Scirtothrips dorsalis Hood infest strawberry (*Fragaria x ananassa* Duchesne, Rosaceae) fields from nearby crop fields and surrounding vegetation and cause injury to plants by feeding on young leaf tissues. Greenhouse and field studies were conducted to determine the short-range movement of *S. dorsalis* to assess the risk of an early *S. dorsalis* population to spread to adjacent plants. In a greenhouse, 25 potted strawberry plants were arranged in two concentric rows around a central plant, where plants in inner rows were 20 cm, and those in the outer rows were 40 cm from the central plant. In the field, 20 strawberry plants were arranged in two beds (90 cm apart), ten in each bed, and five plants in each row, with plants 30 cm apart. White sticky cards were placed at 60–120 cm from the central plant. Fifty *S. dorsalis* adults were released on a centrally located plant, and the numbers of *S. dorsalis* adults and larvae and feeding injury were recorded for 9–17 d on adjacent plants and sticky cards. Results showed that significantly more *S. dorsalis* adults and larvae remained on the initially infested plant compared to adjacent plants, although few adults were found up to 120 cm on sticky cards. The rate of spread of feeding injury was low with slight bronzing injury (<10% injury) on adjacent plants by 14–17 d. Since most *S. dorsalis* remained on initially infested plants for at least 2 wk, it is feasible to delay management actions and 'rescue' plants around a plant with minor injury symptoms.

Key words: invasive species, berry crop insect, ecology and behavior, insect–plant interaction, insecticide reduction

Thrips (Thysanoptera) are often successful invaders in new geographical regions due in part to their small size and thigmotactic behavior. They are known to disperse long distances on atmospheric air currents, frontal winds, agricultural products, or personal luggage (Lewis 1964, 1991; Ananthakrishnan et al. 1982; Morse and Hoddle 2006). As expected, the global rate of invasion of thrips has increased with the increased international movement of agricultural products and the frequency of air travel (Mound and Marullo 1996, Kumar et al. 2013). In the United States, an invasive pest *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), commonly known as chilli thrips was first intercepted in the port of Miami in 1991 and later recorded in ornamental retail stores in southern Florida in 2005 (Coolidge 2005). Since then it has become widespread in Florida (Diffie et al. 2008), emerging as a significant pest of pepper (*Capsicum* spp., Solanaceae) and rose (*Rosa* X 'Radrazz', Rosaceae) in southern Florida (Seal and Kumar 2010, Aristizábal et al. 2016), strawberry (*Fragaria* × *ananassa* Duchesne, Rosaceae) and blueberry (*Vaccinium corymbosum* L. X *V. darrowi*, Ericaceae) in central Florida (Lahiri and Panthi 2020, Panthi et al. 2020), and as a minor pest of landscape and nursery plants throughout the state (Mannion et al. 2014, Dale and Borden 2018). *Scirtothrips dorsalis* is one of 14 thrips species capable of transmitting tospoviruses (Riley et al. 2011). However, there are no reports of virus transmission by *S. dorsalis* on crops grown in the United States.

Adults (1–2 mm with dark-fringed wings) and larvae of *S. dorsalis* cause significant injury to young leaves by feeding on green leaf tissues using their piercing-sucking mouthparts (Harrewijn et al. 1996, Childers 1997, Kumar et al. 2011). In strawberry, the initial feeding injury symptom of *S. dorsalis* is bronzing along leaf veins and petioles, with injury expanding to cause darkened, curled, and hardened leaves (Panthi and Renkema 2020). *Scirtothrips dorsalis* adults are relatively weak fliers but likely infest Florida strawberry fields from nearby crop fields and other surrounding vegetation. At the same time, a few *S. dorsalis* may be inadvertently moved within fields through plant materials, farm equipment, or farm workers (Arévalo and

© The Author(s) 2020. Published by Oxford University Press on behalf of Entomological Society of America. All rights reserved.
For permissions, please e-mail: journals.permissions@oup.com.

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024

Liburd 2007). Once *S. dorsalis* land on a plant, spread to adjacent plants depends on the short-range movement of *S. dorsalis* among plants. The aggregated distribution of *S. dorsalis* in strawberry (Panthi 2020), pepper (Seal et al. 2006), rose (Aristizábal et al. 2016), and mango (Aliakbarpour and Salmah 2011) crops suggest the limited movement of *S. dorsalis* within fields and relatively slow expansion of *S. dorsalis* populations. However, the field movement of *S. dorsalis* is currently unknown in strawberry. Knowledge of a pest's ability to spread within a field will help forecast effects on crops and will be useful in developing new management strategies (Loxdale et al. 1993, Masui 2007, Pedigo and Rice 2014).

The short-range movement of insects or rate of spread of feeding injury can be quantified by assessing insect counts and feeding injury on plants as a function of distance from insect release point over time (Itô and Miyashita 1965; Freeman 1977; Taylor 1978; Taylor et al. 1979; Cronin et al. 2000, 2001; Roslin 2000). In the field, the flight activity of an insect is influenced by the innate flight ability of the pest (Sane 2016), oviposition and feeding site preferences (Chu et al. 1995), inter-plant distances (Ims 1995, Cronin 2003), and meteorological conditions (Harding 1961). When factors such as inter-plant distances and meteorological conditions are kept constant in closed greenhouse settings, the pest's innate flight behavior affected through oviposition and feeding-site preference can be tested on a group of plants (Rhainds and Shipp 2004). The goal of this study was to assess the risk of the initial *S. dorsalis* population to spread from initially infested to adjacent plants in strawberry fields. The objectives of this study were to determine the short-range movement of *S. dorsalis* and the rate of spread of feeding injury among strawberry plants.

Materials and Methods

Greenhouse Study

Two experiments were conducted in a greenhouse at the Gulf Coast Research and Education Center (GCREC), Balm, FL (27°45′43″N; 82°13′38″W) in April and May 2017. Bare-root strawberry transplants of 'Florida Radiance' (G. W. Allen Nursery Ltd., Centreville, Nova Scotia Province, Canada) were planted on 17 March 2017, in black plastic pots (3.8 liters) filled with Fafard 4 Potting Mix (Sun Gro Horticulture, Agawam, MA), and 25 g of granular fertilizer (Osmocote Smart-Release 25, The Scotts Company, Marysville, OH) per pot was applied. Liquid fertilizer was applied twice a week (Miracle-Gro Lawn Products, Inc., Marysville, OH), 200 ml per pot, after mixing 15 g of fertilizer in 3.8-liter water. Plants were watered twice a day for 5 min using drip irrigation with a water flow of 32 ml per minute. No pesticides were applied to the plants. In the greenhouse, the average temperature (±SE) was 21.6 ± 0.2°C and 24.5 ± 0.1°C, and average relative humidity (±SE) was 67.7 ± 0.8% and 78.0 ± 0.3% for experiments 1 and 2, respectively, recorded using temperature and relative humidity sensors and data loggers (HOBO U23 Pro v2, Onset Computer Corporation, Bourne, MA).

Twenty-five potted strawberry plants were arranged in a five by five configurations in two concentric rectangles around a central plant, where plants in the inner rectangle were at a distance of 20 cm, and plants in the outer rectangle were at a distance of 40 cm from the central plant (Fig. 1). Plants were categorized to fall either at 'center' (n = 1), 'inner' (n = 8), or 'outer' (n = 16) rows based on their locations from the central plant (thrips release point). White sticky cards (7.5 × 7.5 cm) were placed vertically using metal wires at 60 and 120 cm in all cardinal directions at the same height as the strawberry plants to record if any adults were dispersing out of the experimental plots. There were four replicates of each group of 25 plants, and replicates were 7 m apart. At the beginning of each experiment, plants were trimmed so that they had three young trifoliates or nine leaflets each (one strawberry trifoliate = three leaflets). Adult *S. dorsalis* used in the study were collected from a thrips colony maintained on 3–4-wk-old cotton, *Gossypium hirsutum* L. (Malvaceae) plants in a growth room set at 26°C, 50–60% RH and 14:10 h of L:D photoperiod initiated with *S. dorsalis* collected from strawberry fields in 2016. The greenhouse was kept empty for 10 d between experiments and heated to about 40°C before the start of each experiment to kill any insects. Thrips were monitored before the start of the experiments by placing yellow sticky cards (7.5 × 5.0 cm) throughout the greenhouse at a distance of 2–3 m between cards; no thrips were found on sticky cards.

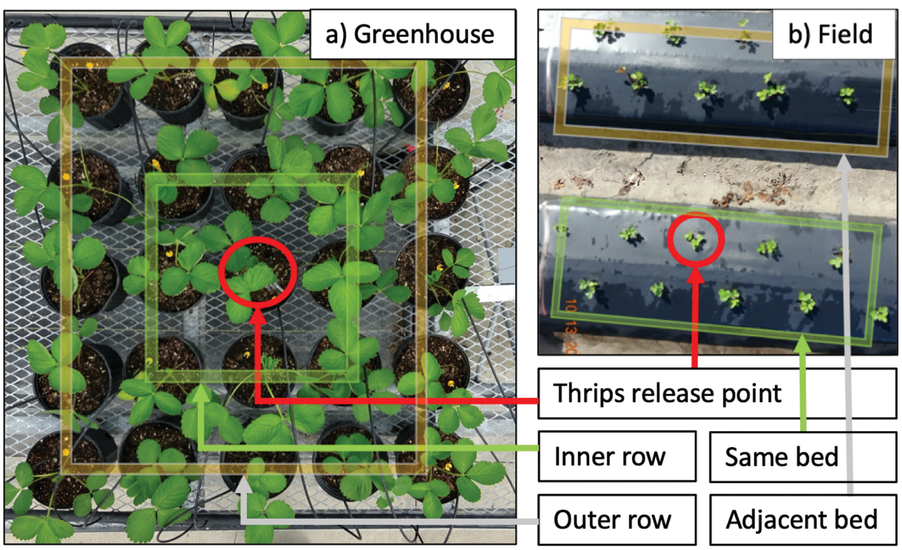

Fig. 1. Arrangement of strawberry plants where 50 adult *S. dorsalis* were released on to a central plant (circle) in the (a) greenhouse and (b) field research plots at the Gulf Coast Research and Education Center, Balm FL. In the greenhouse, plants were 20 cm apart and arranged in inner and outer rows, and in the field, plants in the same raised bed were 30 cm apart and adjacent raised beds were 90 cm apart.

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024

Experiment 1

Fifty *S. dorsalis* adults were released onto the central strawberry plant of each 25-plant arrangement on 3 April 2017. *Scirtothrips dorsalis* adults were aspirated into filtered pipette tips (Diamond Tipack, 100 µl tip: Gilson S.A.S., Villiers-leBel, France) using Fisherbrand rubber tube (6 mm diam., Thermo Fisher Scientific, Waltham, MA) from the same cohort colony and released onto the plants by placing the open ends of pipette tips close to the plants and gently tapping the sides of pipette tips to encourage *S. dorsalis* to exit onto the strawberry plant. Two days after *S. dorsalis* release, individual leaflets were destructively sampled from 24 surrounding plants for seven consecutive days. Leaf samples were placed in sealable plastic bags (Ziploc, S.C. Johnson and Son, Inc., Racine, WI), and thrips were immobilized by filling the bag with CO_2. Numbers of adult and larval *S. dorsalis* were counted using a stereomicroscope at 25× magnification (LEICA LED3000 SLI, Leica Microsystems Inc, Wetzlar, Germany). All the leaves from the central plant and the remaining leaves from surrounding plants were collected at the end of the experiment and washed with 70% ethanol to dislodge thrips from leaf samples, the contents of the solution were then filtered, and *S. dorsalis* in the filtered content were counted. Sticky cards were replaced every day after the day of release, and *S. dorsalis* adults were counted using a stereomicroscope at 25× magnification.

Experiment 2

Fifty *S. dorsalis* adults were released onto the central plant of a 25-plant arrangement on 18 April 2017, through pipette tips as previously described. After 6 d, all the leaves were visually rated daily for *S. dorsalis*-feeding injury for eight consecutive days, and the number of thrips-injured leaves was also counted. The following rating scales were used for visual rating; zero: no injury, one: <10% injury (bronzing on leaf base and petiole), two: 10–30% injury (bronzing along midrib and vein), three: 30–60% injury (bronzing extending to leaf blade), and four: > 60% injury (darkening of the leaf). At the end of the study, 14 d-after-thrips-release on 2 May 2017, all the leaves were collected and placed in sealed plastic bags as described previously for each plant. The sticky cards were placed at the beginning and collected at the end of the experiment. Leaf samples were washed with 70% ethanol as described previously, and the number of *S. dorsalis* on leaf samples and sticky cards were counted using a stereomicroscope at 25× magnification.

Field study (experiment 3)

A field experiment was conducted at GCREC, Wimauma, FL. Strawberry plug transplants 'Florida Radiance' (G. W. Allen Nursery Ltd., Centreville, Nova Scotia Province, Canada) were established on 27 September 2017 (30 cm in-row spacing) in two rows in raised, double-pressed beds (1.2 m spacing) covered with black virtually impermeable film (Blockade, Berry Plastics, Evansville, IN) that were fumigated with a soil fungicide/nematicide (Telone C-35, 280 l ha^{-}1, Dow AgroSciences, Indianapolis, IN) at bed formation on 20 August 2017. A glyphosate-based herbicide (Round-up, 48.7%, Monsanto Company, St. Louis, MO) was applied to row aisles before transplanting. Plants were overhead irrigated for 5 d during daytime hours following transplanting and drip fertigated at recommended rates (Whitaker et al. 2017). Plants received weekly applications of fungicides (primarily Captan 80 WDG, 6.7 kg ha^{-1}, Drexel Chemical Company, Memphis, TN) to control powdery mildew (*Phaerotheca macularis* (Wallr.) U. Braun & S. Takam). One early-season application of *Bacillus thuringiensis*-based biopesticide (DiPel DF, 1120 g ha^{-1}, Valent Biosciences, Libertyville, IL) was made to control lepidopteran larvae; DiPel has no known activity against thrips (Kakkar et al. 2012).

Twenty strawberry plants (= one plot) were arranged in two beds (90 cm apart), ten in each bed, and five plants in each row, with plants 30 cm apart (Fig. 1b). Plants were categorized as thrips release point (n = 1), same bed (n = 9), or adjacent bed (n = 10) based on their location within the plot. Six replicated plots (15 m apart) received *S. dorsalis*, and one plot was treated as control receiving no *S. dorsalis*. The control plot was used as a check to determine if there was a movement of *S. dorsalis* from other sources in the plots during the experiment but was not included in the analysis. Just before the beginning of the experiment, plants were cleaned by removing dead and old leaves, keeping three to four young leaves per plant. Any insects were vacuumed from plants with a D-Vac (Rincon Insectaries, Ventura, CA) attached to a reverse leaf blower motor (BG 86-Z Blower, STIHL INC). Fifty *S. dorsalis* adults were released onto the central plant of one inner row bed out of two-row beds per plot on 16 October 2017, through filtered pipette tips, a similar procedure as in the greenhouse experiments. Four white sticky cards (7.5 × 7.5 cm) were placed around each plot at plant height in each cardinal direction at 1 m from the plot edge. Sticky cards were collected and replaced on 3 d: October 19, 24, and 2 November 2017. Each plant was given a feeding injury rating (zero to four scale) on October 17, 18, 19, 24, 25, 26, 31, November 1 and 2, 2017. On 2 November 2017, all leaves from plants were collected 17 d-after-thrips-release and placed in sealable plastic bags (Ziploc, S.C. Johnson and Son, Inc., Racine, WI). Leaf samples were washed with 70% ethanol as described previously, and the number of *S. dorsalis* in leaf samples and on the sticky cards were counted under a stereomicroscope. Air temperature, relative humidity, and wind speed in the field were obtained from the FAWN weather station of Balm, FL (FAWN 2017). Temperature and relative humidity (±SE) in the field during experiment 3 were 21.03 ± 1.29°C and 77.44 ± 2.27 RH%. Wind gusts were high during daytime reaching up to 50 kph in some days and low during nighttime 0–4 kph; average wind speed per day ranged from 5 to 16 kph.

Statistical Analysis

Generalized linear mixed models (PROC GLIMMIX: SAS 9.4 version, SAS Institute Inc., 2018, Cary, NC) were used to test the effect of distance on the number of *S. dorsalis* adults and larvae, feeding injury rating, and injured/total leaves. Data from sticky cards placed at 60 (n = 16) and 120 cm (n = 16) in experiment 1 and 2, and 90 cm (n = 24) in a field study in all four cardinal directions were analyzed separately in factorial model with direction, distance, and direction × distance as fixed effects. For all the models, replications were considered random effects, and the sampling date was a repeated measure with an autoregressive error structure. Count data (adults and larvae) were fit to a Poisson distribution and categorical data (% injury and injury rating) were fit to a normal distribution. Scatter plots were used to check residuals for normality. Means were compared with Tukey's HSD test ($P < 0.05$). Linear regression was used to model the relationship of *S. dorsalis* adult, feeding injury rating, and proportion of damaged leaves as a function of days-after-thrips release grouped by distance.

Results

Greenhouse Study (experiment 1)

In 9 d, a total (± SE) of 34.27 ± 7.14 *S. dorsalis* were recovered from strawberry plants and sticky cards, out of which, 15.52 ± 3.98 adults

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024

and larvae were on plants and 18.75 ± 3.16 adults on sticky cards. On plants, there were 13.5 ± 3.18 adults and 2.25 ± 1.29 larvae. A significantly high number of *S. dorsalis* adults remained on the central plant (91%) compared to the plants inner (7%) and outer (2%) rows (F = 10.4; df = 2, 6; P = 0.011; Table 1). The number of *S. dorsalis* larvae did not differ between plants at center, inner and outer rows (F = 0.68; df = 2, 6; P = 0.543; Table 1). There was no significant effect of direction, distance, and direction × distance on adult occurrences on sticky cards (direction: F = 0.74; df = 3, 24; P = 0.539, distance: F = 0.62; df = 1, 24; P = 0.44, direction × distance: F = 0.45; df = 3, 24; P = 0.719; Table 1). Movement of *S. dorsalis* adults occurred throughout the experiment, but there was no trend (P > 0.05) in the rate of dispersal among adjacent strawberry plants for 9 d (Fig. 2).

Greenhouse Study (experiment 2)

In 14 d, a total (± SE) of 127.4 ± 16.52 *S. dorsalis* were recovered from strawberry plants and sticky cards, out of which 121.9 ± 14.86 adults and larvae were on plants and 5.5 ± 1.66 adults were on sticky cards. On plants, there were 6.75 ± 2.12 adults and 114.9 ± 15.15 larvae. The number of *S. dorsalis* adults did not differ significantly between plants (F = 1.05; df = 2, 6; P = 0.405; Table 2). The number of larvae was significantly high on initially infested plants (93%) compared to plants at 20 (6%) and 40 cm (1%) away (F = 60.66, df = 2, 6; P < 0.001; Table 2). There was no significant effect of direction, distance, and direction × distance on adult occurrences on sticky cards (direction: F = 1.92; df = 3, 21; P = 0.09, distance: F = 0.0; df = 1, 21; P = 1, direction × distance: F = 1.66; df = 3, 21; P = 0.21; Table 2). By 14 d, significantly high number of leaves were injured on initially infested plant (92%) compared to plants at inner (30%) and outer (11%) rows (F = 27.52; df = 2, 94; P < 0.001; Table 2). By 14 d, the initially infested plant had a significantly higher amount of injury (30–60% injury) compared to the plants at inner and outer rows (< 10% injury) (F = 75.33; df = 2, 94; P < 0.001; Table 2). The percent leaf injury at inner and outer rows reached 29% and 16% by 14 d, respectively (Fig. 3a and Table 4). Whereas, the rate of increase of injury on plants at inner and outer rows was 0.01–0.04 units on the injury rating scale per day with injury reaching up to less than 10% by 14 d (Fig. 3b and Table 4).

Table 1. Mean numbers (± SEM) of *S. dorsalis* adults and larvae recovered on central, inner, and outer row potted strawberry plants or on sticky cards 9 d after 50 *S. dorsalis* adults were released on to the central plants in a greenhouse (experiment 1)

Recovery location		*n*	*S. dorsalis* recovered	
			Adults	Larvae
Plants	Center (release point)	1	6.75 ± 1.33b	0.75 ± 0.43
	Inner row	8	4.00 ± 1.01c	0.50 ± 0.35
	Outer row	16	2.75 ± 0.84c	1.00 ± 0.50
Sticky cards	60 cm from release point	4	8.50 ± 1.50ab	
	120 cm from release point	4	10.25 ± 1.66a	

Columns with different letters are significantly different (Tukey's HSD test, P < 0.05).

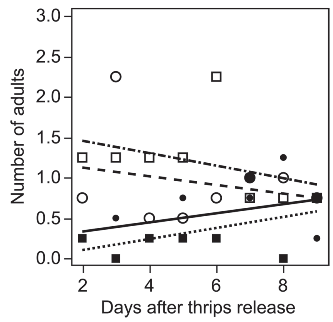

Fig. 2. Numbers of *S. dorsalis* adults per leaflet from strawberry plants located at the inner (solid line and filled circle) and outer (dotted line and filled square) rows or on sticky cards at 60 cm (dashed line and circle) and 120 cm (dot-dashed line and square), 9 d after 50 *S. dorsalis* adults were placed on central plants in potted greenhouse strawberries.

Field Study (experiment 3)

After 17 d, a total (± SE) of 8.5 ± 3.4 *S. dorsalis* were recovered from strawberry plants, of which, 2.5 ± 0.9 were adults, and 6.0 ± 2.5 were larvae. The number of adults and larvae was significantly higher on the initially infested plant (thrips release point) then on the plants at 30–120 cm (same and adjacent beds) (adults: F = 3.02; df = 4, 20; P = 0.044; larvae: F = 3.43; df = 4, 20; P = 0.027; Table 3). The amount of injury was significantly higher on initially infested plants (30–60% injury) compared to all other plants in the plot (<10% injury) (F = 20.84; df = 4, 110; P < 0.001; Table 3). The rate of increase of injury on plants at 30–120 cm (same and adjacent beds) was 0.003–0.02 units on the injury rating scale per day with the injury not exceeding 10% by 17 d (Fig. 4 and Table 4). There were no thrips found in the control plot and no *S. dorsalis*-feeding injury symptoms. In experiments 2 and 3, numbers of recovered *S. dorsalis* were significantly and positively correlated with feeding injury ratings (Pearson correlation coefficient: r_p = 0.79 (experiment 2), r_p = 0.63 (experiment 3); P < 0.0001).

Discussion

This study showed that *S. dorsalis* moved slowly among strawberry plants for 2 wk after the initial infestation of a central plant. As a result, there was a slow spread of injury symptoms, with plants adjacent to the central plant having less than 10% bronzing injury of strawberry trifoliates at 2 wk after infestation. Limited movement of *S. dorsalis* may be due to the adults' preference to stay on initially infested plants, as food sources and oviposition sites were likely not limited. Although many *S. dorsalis* adults remained on initially infested plants, a few *S. dorsalis* adults were found at least up to 120 cm on sticky cards. In groups of potted cotton, peanut, and pepper plants in the greenhouse, the most *S. dorsalis* were also found on initially infested plants by 6 wk, although a few adults were also up to 12 m from the initial site of infestation (Kumar et al. 2014).

Low recovery of *S. dorsalis* adults was likely due to wind gusts in the field that did not allow them to settle on the plants and to females that moved to plants further away after ovipositing on initially infested plants. High numbers of larvae found on initially infested plants compared to adjacent plants across greenhouse and field studies also showed female adults oviposited more on the initially infested plant than on adjacent plants. Furthermore, severe feeding injury on initially infested plants than on adjacent plants showed high numbers of adults and larvae remained on initially infested and moved slowly between plants.

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024

Table 2. Mean numbers (± SEM) of *S. dorsalis* adults, larvae, injury ratings, and percent injured leaves on central, inner, and outer row potted strawberry plants or on sticky cards 14 d after 50 *S. dorsalis* adults were released on to the central plants in the greenhouse (experiment 2)

Recovery location		*n*	*S. dorsalis* recovered		Feeding injury	
			Adults	Larvae	Injury ratings	% injured leaves
Plants	Center (release point)	1	1.00 ± 0.50	71.01 ± 8.65a	3.50 ± 0.94a	0.95 ± 0.05a
	Inner row	8	4.50 ± 1.06	35.26 ± 4.78b	0.69 ± 0.41b	0.35 ± 0.11b
	Outer row	16	1.25 ± 0.56	8.63 ± 1.72c	0.25 ± 0.25b	0.12 ± 0.08b
Sticky cards	60 cm from release point	4	2.75 ± 0.83			
	120 cm from release point	4	2.75 ± 0.83			

Columns with different letters are significantly different (Tukey's HSD test, $P < 0.05$).

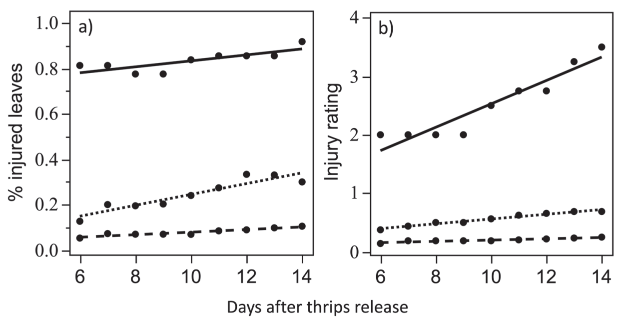

Fig. 3. Mean (a) percent injured leaves and (b) injury ratings on strawberry plants located at the center (solid line), inner (dotted line), and outer (dashed line) rows, 14 d after 50 *S. dorsalis* adults were placed on central plants in potted greenhouse strawberries.

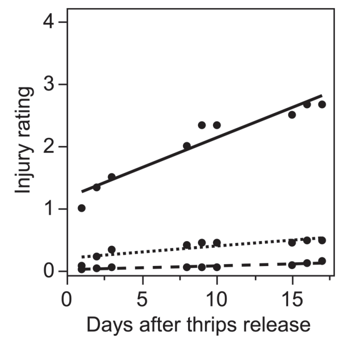

Fig. 4. Injury ratings for strawberry plants onto which 50 adult *S. dorsalis* were released (solid line), plants in the same raised beds as the release plant (dotted line), and plants in adjacent raised beds (dashed line) 17 d after release in research plots at the Gulf Coast Research and Education Center, Balm FL.

Table 3. Mean numbers (± SEM) of *S. dorsalis* adults, larvae, and injury ratings on strawberry plants at thrips release point, same row bed, and adjacent row bed 17 d after 50 *S. dorsalis* adults were released on to the central plants in the field (experiment 3)

Recovery location	*n*	*S. dorsalis* recovered		Feeding injury ratings
		Adults	Larvae	
Release point	1	0.64 ± 0.35	3.16 ± 1.38a	2.67 ± 0.67a
Same bed	9	0.40 ± 0.27	0.44 ± 0.29b	0.48 ± 0.28b
Adjacent bed	10	0.95 ± 0.44	0.51 ± 0.32b	0.15 ± 0.16b

Columns with different letters are significantly different (Tukey's HSD test, $P < 0.05$).

The movement of insects from central release points to adjacent plants can be quantified using several marking and tracking techniques (Lavandero et al. 2004). Fluorescent powder and rabbit immunoglobulin G have been used to mark thrips in mark-recapture experiments (Rhainds and Shipp 2004, Jasrotia and Ben-Yakir 2006). However, marking thrips with fluorescent powder can modify adult flight behavior restricting movement from the release point (Henderson and Southwood 2016), leading to low recovery on adjacent plants. Immunological marking is expensive, and markers on thrips were retained for only 6 d in the field (Jasrotia and Ben-Yakir 2006), not long enough to accurately track movement for up to 17 d as in this experiment. Since we did not use marking techniques, we isolated replicates (7 m in the greenhouse and 15 m in the field) to minimize *S. dorsalis* movement among them, conducted two greenhouse experiments, and inferred *S. dorsalis* movement by measuring feeding injury on strawberry trifoliates over time. Our results indicated consistent movement patterns of *S. dorsalis* in the greenhouse and field, but future experiments with appropriate thrips-marking techniques may provide a more complete description of *S. dorsalis* movement in strawberry.

In this study, the movement of *S. dorsalis* was tested on small, young strawberry plants for 14–17 d to determine the risk of the spread of initial *S. dorsalis* populations on new strawberry growth. Field surveys during the early strawberry season in Florida resulted in a maximum of 55 *S. dorsalis* on 10 trifoliates from 10 strawberry plants (Panthi 2020), and were used to select an initial density of 50 *S. dorsalis* per plant with five trifoliates. Since insect movement rates vary with host plant size, age, and phenology and insect density (Kindvall 1999, Rhainds et al. 2005), our results cannot be extrapolated to larger plants later in the season that may have higher *S. dorsalis* densities. Also, initial densities of less than 50 *S. dorsalis* per plant may result in different movement patterns than those reported in these experiments.

Scirtothrips dorsalis has an aggregated distribution in strawberry fields, with highly infested plants next to uninfested healthy plants (Panthi 2020). During the early season, *S. dorsalis* appear to colonize a relatively small number of young plants in a field, and since adults move slowly among plants, populations become highly aggregated. Some thrips species aggregate due to aggregation pheromones produced by males that attract males and females (Kirk 2017). The aggregation pheromones of *Frankliniella occidentalis* Pergande and *Thrips palmi* Karny (Thysanoptera: Thripidae) have been identified and tested for their use in pest management (Kirk 2017), but an aggregation pheromone for *S. dorsalis* has not been identified. An

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024

Table 4. Regression models relating the numbers of *S. dorsalis* adults, injury ratings, and percent injured leaves to days after *S. dorsalis* adults were released on to the central plants for locations (20–120 cm) from release point in greenhouse and field experiments

Experiment (duration)	Response variable	Location	Model[a]	R^2
1) Greenhouse (9 d)	Adult[b]	Inner row	y = 0.22 + 0.06 x*	0.14
		Outer row	y = −0.03 + 0.07 x*	0.23
		60 cm†	y = 1.23 – 0.05 x*	0.05
		120 cm†	y = 1.61 – 0.08 x*	0.15
2) Greenhouse (14 d)	Injury rating	Center[c]	y = 0.76 + 0.17 x***	0.91
		Inner row	y = 0.15 + 0.04 x***	0.97
		Outer row	y = 0.09 + 0.01 x***	0.88
	% injured leaves	Center	y = 0.70 + 0.01 x**	0.64
		Inner row	y = 0.01 + 0.02 x***	0.87
		Outer row	y = 0.02 + 0.01 x***	0.88
3) Field (17 d)	Injury rating	Thrips release point	y = 1.17 + 0.10 x***	0.92
		Same bed	y = 0.19 + 0.02 x***	0.37
		Adjacent bed	y = 0.01 + 0.01 x***	0.19

[a]Where y = response variable and x = days-after-thrips-release.
[b]Cumulative number.
[c]Thrips release point.
Asterisks indicate *P*-values of slope; *> 0.05, **< 0.05, ***< 0.0001. †sticky cards at 60 and 120 cm from thrips release point.

S. dorsalis-aggregation pheromone may help explain its movement patterns and aggregated distribution and also be useful for improving monitoring and management through a mass trapping strategy, as with other pestiferous thrips (Kirk 2017).

Since *S. dorsalis* remained primarily on the initially infested plants for up to 2 wk, it has low potential to spread widely and quickly in strawberry fields. Field surveys have shown *S. dorsalis* 'hotspots' in strawberry fields (Panthi 2020). Field areas with high *S. dorsalis* densities can be identified after systematic sampling, and it may be feasible to apply insecticides only to areas exceeding a threshold. From a practical perspective, areas to which insecticides are needed would have to be large enough to accommodate tractor-mounted sprayers. Site-specific management of pests in smaller areas reduces the amount of pesticides, water, fuel, and labor compared to whole field applications (Weisz et al. 1996, Park et al. 2007). As an alternative to insecticides, predatory mites such as *Amblyseius swirskii* Athias-Henriot and *Neoseiulus cucumeris* Oudemans (Arachnida: Phytoseiidae), which are effective against *S. dorsalis* adults and larvae (Arthurs et al. 2009), maybe more feasibly incorporated using a site-specific rather than field-wide management strategy for *S. dorsalis* in strawberries.

As injury on strawberry plants adjacent to an infested plant was less than 10% after 2 wk it may be feasible and advantageous to delay management actions and 'rescue' plants around a plant with minor injury symptoms. When an application of the insecticide spinetoram was delayed for 14 d, there was no reduction in yield or plant vigor on young strawberry plants with 10–30% injury caused by initial densities of 5, 10, and 20 *S. dorsalis* per plant compared to an application 4 d after *S. dorsalis* were placed on plants (Panthi 2020). Delaying an insecticide application is a successful strategy for managing *Thrips tabaci* Lindeman (Thripidae), as onion crops compensated for minor injury when insecticides were applied when the action threshold for *T. tabaci* was reached (Nault and Shelton 2010). Since feeding injury is positively correlated with *S. dorsalis* density, scouting for 10–30% injury to leaves could be a useful tool in addition to or instead of *S. dorsalis* counts. Scouting for injury symptoms helps mitigate the difficulty in identifying multiple species of small insects and removes an obstacle in adopting integrated pest management practices (Rodriguez-Saona et al. 2014). Delaying an insecticide application for *S. dorsalis* in strawberry should lead to fewer overall applications, preserving natural enemies and potentially reducing the risk of insecticide resistance. Fewer insecticide applications will reduce input costs for Florida strawberry producers, resulting in increased competitiveness with imported and domestic strawberries from other regions. Future experiments are needed to test which insecticides are most effective and for how long they can be delayed without compromising plant vigor and yield on initially infested and adjacent plants.

Acknowledgments

We are grateful to Marc Santos for technical assistance, Vance Whitaker for providing strawberry transplants, and Jose Moreno for managing field plots. This research was funded by a Florida Specialty Crop Block Grant Program, grant number 024135 and in part by the Florida Strawberry Research and Education Foundation grant.

References Cited

Aliakbarpour, H., and M. R. C. Salmah. 2011. Seasonal abundance and spatial distribution of larval and adult thrips (Thysanoptera) on weed host plants in mango orchards in Penang, Malaysia. Appl. Entomol. Zool. 46: 185–194.

Ananthakrishnan, T. N., A. M. Daniel, and N. S. Kumar. 1982. Spatial and seasonal distribution patterns of some phytophagous thrips (Thysanoptera: Insecta) infesting *Ricinus communis* Linn. (Euphorbiaceae) and *Achyranthes aspera* Linn. (Amaranthaceae), pp. 183–189. *In* Proceedings of the Indian National Science Academy. https://insa.nic.in/UI/Archivesection.aspx?JYrs=MTk4Mg==&&JID=MA==

Arévalo, H. A., and O. E. Liburd. 2007. Horizontal and vertical distribution of flower thrips in southern highbush and rabbiteye blueberry plantings, with notes on a new sampling method for thrips inside blueberry flowers. J. Econ. Entomol. 100: 1622–1632.

Aristizábal, L. F., G. M. Mascarin, R. H. Cherry, B. Chaves-Cordoba, and S. P. Arthurs. 2016. A rapid sampling plan for *Scirtothrips dorsalis* (Thysanoptera: Thripidae) on container shrub rose (*Rosa* 'Radrazz'). J. Eco. Entomol. 109: 2543–2550.

Arthurs, S., C. L. McKenzie, J. Chen, M. Dogramaci, M. Brennan, K. Houben, and L. Osborne. 2009. Evaluation of *Neoseiulus cucumeris* and *Amblyseius swirskii* (Acari: Phytoseiidae) as biological control agents of chilli thrips, *Scirtothrips dorsalis* (Thysanoptera: Thripidae) on pepper. Biol. Control. 49: 91–96.

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024

Childers, C. C. 1997. Feeding and oviposition injuries to plants, pp. 505–537. *In* T. Lewis (ed.), Thrips as crop pests, CAB International, New York.

Chu, C.-C., T. J. Henneberry, and A. C. Cohen. 1995. *Bemesia argentifolii* (Homoptera: Aleyrodidae): host preference and factors affecting oviposition and feeding site preference. Environ. Entomol. 24: 354–360.

Coolidge, G. 2005. 'New thrips' cause significant damage to rose foliage and blooms. Wind Chimes Newsletter. Central Florida Rose Society 19: 4–6.

Cronin, J. T. 2003. Movement and spatial population structure of a Prairie Planthopper. Ecology 84: 1179–1188.

Cronin, J. T., J. D. Reeve, R. Wilkens, and P. Turchin. 2000. The pattern and range of movement of a checkered beetle predator relative to its bark beetle prey. Oikos 90: 127–138.

Cronin, J. T., K. Hyland, and W. G. Abrahamson. 2001. The pattern, rate, and range of within-patch movement of a stem-galling fly. Ecol. Entomol. 26: 16–24.

Dale, A. G., and M. A. Borden. 2018. Evaluation of reduced-risk insecticides to control chilli thrips (Thysanoptera: Thripidae) and conserve natural enemies on ornamental plants. Fla. Entomol. 101: 237–243.

Diffie, S., G. B. Edwards, and L. A. Mound. 2008. Thysanoptera of southeastern USA: a checklist for Florida and Georgia. Zootaxa 1787: 45–62.

Freeman, G. H. 1977. A Model relating numbers of dispersing insects to distance and time. J. Appl. Ecol. 14: 477–487.

Harding, J. A. 1961. Effect of migration, temperature, and precipitation on thrips infestations in South Texas. J. Econ. Entomol. 54: 77–79.

Harrewijn, P., W. F. Tjallingii, and C. Mollema. 1996. Electrical recording of plant penetration by western flower thrips. Entomol Exp. Appl. 79: 345–353.

Henderson, P. A., and T. R. E. Southwood. 2016. Ecological methods. John Wiley & Sons, New Jersey.

Ims, R. A. 1995. Movement patterns related to spatial structures, pp. 85–109. *In* Hansson, L., Fahrig, L., Merriam, G. (eds.), Mosaic landscapes and ecological processes. Springer, Netherlands, Dordrecht.

Itô, Y., and K. Miyashita. 1965. Studies on the dispersal of leaf- and planthoppers. III. An examination of the distance–dispersal rate curves. Jap. J. Ecol. 15: 85–89.

Jasrotia, P., and D. Ben-Yakir. 2006. An immuno-marking technique for thrips. Entomol. Exp. Appl. 120: 155–160.

Kakkar, G., D. R. Seal, and V. Kumar. 2012. Assessing abundance and distribution of an invasive thrips *Frankliniella schultzei* (Thysanoptera: Thripidae) in south Florida. Bull. Entomol. Res. 102: 249–259.

Kindvall, O. 1999. Dispersal in a metapopulation of the bush cricket, *Metrioptera bicolor* (Orthoptera: Tettigoniidae). J. Anim. Ecol. 68: 172–185.

Kirk, W. D. J. 2017. The aggregation pheromones of thrips (Thysanoptera) and their potential for pest management. Int. J. Trop. Insect Sci. 37: 41.

Kumar, V., D. R. Seal, D. J. Schuster, C. Mckenzie, L. S. Osborne, J. Maruniak, and S. Zhang. 2011. S*cirtothrips dorsalis* (Thysanoptera: Thripidae): scanning electron micrographs of key taxonomic traits and a preliminary morphometric analysis of the general morphology of populations of different continents. Fla. Entomol. 94: 941–955.

Kumar, V., G. Kakkar, C. L. Mckenzie, D. R. Seal, and L. S. Osborne. 2013. An overview of chilli thrips, *Scirtothrips dorsalis* (Thysanoptera: Thripidae) biology, distribution and management. *In* S. Soloneski and M. Larramendy (eds.), Weed and pest control: conventional and new challenges. Intechopen, London.

Kumar, V., G. Kakkar, D. R. Seal, C. L. Mckenzie, J. Colee, and L. S. Osborne. 2014. Temporal and spatial distribution of an invasive thrips species *Scirtothrips dorsalis* (Thysanoptera: Thripidae). Crop Prot. 55: 80–90.

Lahiri, S., and B. Panthi. 2020. Insecticide Efficacy for Chilli Thrips Management in Strawberry, 2019. Arthropod Manag. Tests. 45: 1–2.

Lavandero, B., S. Wratten, J. Hagler, and M. Jervis. 2004. The need for effective marking and tracking techniques for monitoring the movements of insect predators and parasitoids. Intl. J. Pest Manag. 50: 147–151.

Lewis, T. 1964. The weather and mass flights of Thysanoptera. Ann. Appl. Biol. 53: 165–170.

Lewis, T. 1991. Feeding, flight and dispersal in thrips, pp. 63–70. *In* Towards understanding Thysanoptera: proceedings, international conference on thrips, Burlington, Vermont USA. Plenum, New York.

Loxdale, H. D., J. Hardie, S. Halbert, R. Foottit, N. A. C. Kidd, and C. I. Carter. 1993. The relative importance of short- and long-range movement of flying aphids. Biol. Rev. 68: 291–311.

Mannion, C. M., A. I. Derksen, D. R. Seal, L. S. Osborne, and C. G. Martin. 2014. Population dynamics of *Scirtothrips dorsalis* (Thysanoptera: Thripidae) and other thrips species on two ornamental host plant species in Southern Florida. Environ. Entomol. 43: 849–858.

Masui, S. 2007. Synchronism of immigration of adult yellow tea thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae) to citrus orchards with reference to their occurrence on surrounding host plants. Appl. Entomol. Zool. 42: 517–523.

Morse, J. G., and M. S. Hoddle. 2006. Invasion biology of thrips. Annu. Rev. Entomol. 51: 67–89.

Mound, L. A., and R. Marullo. 1996. The thrips of Central and South America: an introduction. Memoirs on entomology, International, vol. 6, Gainesville, FL. 487 pp.

Nault, B. A., and A. M. Shelton. 2010. Impact of insecticide efficacy on developing action thresholds for pest management: a case study of onion thrips (Thysanoptera: Thripidae) on onion. J. Econ. Entomol. 103: 1315–1326.

Panthi, B. 2020. Ecology, behavior, and management of *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae) in Florida strawberry and blueberry. PhD Dissertation. University of Florida.

Panthi, B., and J. Renkema. 2020. Managing *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae) in Florida strawberry with flupyradifurone. Intl. J. Fruit Sci. 0: 1–11.

Panthi, B., O. Liburd, S. Lahiri, and E. Rhodes. 2020. Efficacy test of various insecticides to control *Scirtothrips dorsalis* in southern highbush blueberries. Arthropod Manag. Tests. 45: 1–3.

Park, Y.-L., R. K. Krell, and M. Carroll. 2007. Theory, technology, and practice of site-specific insect pest management. J. Asia Pac. Entomol. 10: 89–101.

Pedigo, L. P., and M. E. Rice. 2014. Entomology and pest management. Sixth edition. Waveland Press Inc., Illinois.

Rhainds, M., and L. Shipp. 2004. Dispersal of adult western flower thrips (Thysanoptera: Thripidae) in greenhouse crops. Can. Entomol. 136: 241–254.

Rhainds, M., L. Shipp, L. Woodrow, and D. Anderson. 2005. Density, dispersal, and feeding impact of western flower thrips (Thysanoptera: Thripidae) on flowering chrysanthemum at different spatial scales. Ecol. Entomol. 30: 96–104.

Riley, D. G., S. V. Joseph, R. Srinivasan, and S. Diffie. 2011. Thrips vectors of tospoviruses. J. Integr. Pest Manag. 2: I1–I10.

Rodriguez-Saona, C. R., D. Polk, and L. L. Stelinski. 2014. Integrating Research and Extension for Successful Integrated Pest Management, pp. 355–392. *In* D. Pimentel and R. Peshin (eds.), Integrated pest management: pesticide problems, Vol.3. Springer Netherlands, Dordrecht.

Roslin, T. 2000. Dung beetle movements at two spatial scales. Oikos. 91: 323–335.

Sane, S. P. 2016. Neurobiology and biomechanics of flight in miniature insects. Curr. Opin. Neurobiol. 41: 158–166.

Seal, D. R., and V. Kumar. 2010. Biological response of chilli thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), to various regimes of chemical and biorational insecticides. Crop Prot. 29: 1241–1247.

Seal, D. R., M. A. Ciomperlik, M. L. Richards, and W. Klassen. 2006. Distribution of chilli thrips, *Scirtothrips dorsalis* (Thysanoptera: Thripidae), in pepper fields and pepper plants on St. Vincent. Fla. Entomol. 89: 311–320.

Southwood, T. R. E., and P. A. Henderson. 2016. Ecological methods, 4th ed. John Wiley & Sons.

Taylor, R. A. J. 1978. The relationship between density and distance of dispersing insects. Ecol. Entomol. 3: 63–70.

Taylor, L. R., I. P. Woiwod, and R. A. J. Taylor. 1979. The migratory ambit of the hop aphid and its significance in aphid population dynamics. J. Anim. Ecol. 48: 955–972.

Weisz, R., S. Fleischer, and Z. Smilowitz. 1996. Site-specific integrated pest management for high-value crops: Impact on potato pest management. J. Econ. Entomol. 89: 501–509.

Whitaker, V. M., N. S. Boyd, N. A. Peres, J. Desaeger, J. W. Noling, and J. Renkema. 2017. Chapter 16. Strawberry Production. EDIS. University of Florida. Gainesville, FL.

Downloaded from https://academic.oup.com/ee/article/50/1/12/6020067 by University of Florida user on 09 February 2024