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Evaluation of insecticides for curative, preventive, and rotational use on *Scirtothrips dorsalis* South Asia 1 (Thysanoptera: Thripidae)

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Abstract

The chilli thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), is a cryptic species complex of at least 9 distinct species, 2 (South Asia 1 and East Asia 1) of which exist in the USA. To integrate chemical insecticides and mycoinsecticides into the preventive and curative tactics used for *S. dorsalis*, we evaluated 10 older and newer chemical insecticides and 3 mycoinsecticides against *S. dorsalis* South Asia 1, a dominant member of the species complex in the USA. An insecticide was considered effective when it induced greater than 70% mortality of larvae or adults. The older insecticides (acetamiprid, clothianidin, thiamethoxam [foliar application], and imidacloprid [drench application]) were found to be efficacious in reducing *S. dorsalis* populations in both curative and preventive situations (≥7 d after treatment). Among insecticides with newer chemistries, foliar application of spinetoram, cyantraniliprole, tolfenpyrad, and formulations of chlorantraniliprole + thiamethoxam were effective for both preventive and curative control (≥10 d after treatment). Among mycoinsecticides, *Isaria fumosorosea* Wize (Cordycipitaceae) was effective in suppressing thrips curatively (≥10 d after treatment). In the insecticide rotation field trial, effectiveness of a *Chenopodium* (Amaranthaceae) extract and 3 mycoinsecticides alternated with spinetoram was comparable to spinetoram treatment alone. Because *S. dorsalis* South Asia 1 is a serious pest of several economically important crops in many counties of Florida and Texas, and an emerging pest in California, this study is important in providing information to vegetable and ornamental plant growers regarding effective insecticides with different modes of action that can be rotated to suppress *S. dorsalis*, and delay the evolution of insecticide resistance. The results also suggest retention of effective products for an extended period in the marketplace.

Key Words: thrips; mycoinsecticide; biopesticide; chemical control; cryptic species; chilli thrips

Resumen

El thrips del chile, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), es un complejo de especies crípticas de por lo menos 9 especies distintas, 2 de las cuales (Asia del Sur 1 y Asia Oriental 1) existen en los Estados Unidos. Para integrar insecticidas químicos y micoinsecticidas en las tácticas preventivas y curativas utilizadas para *S. dorsalis,* se evaluaron 10 insecticidas químicos conocidos y nuevos y 3 micoinsecticidas contra *S. dorsalis* (Asia del Sur 1), un tipo dominante del complejo de especies en los Estados Unidos. Se consideró un insecticida eficaz cuando indujo una mortalidad superior al 70% de larvas o adultos. Se encontró que los insecticidas conocidos (acetamiprid, clothianidin, thiamethoxam [aplicación foliar] e imidacloprid [aplicación remojada]) fueron eficaces para reducir las poblaciones de *S. dorsalis* en situaciones curativas y preventivas (≥7 dias después del tratamiento). Entre los insecticidas con nuevas sustancias químicas, la aplicación foliar de espinetoram, ciantraniliprole, tolfenpirad y formulaciones de clorantraniliprole + tiametoxam fueron eficaces tanto para el control preventivo como para el control curativo (≥10 días después del tratamiento). Entre los micoinsecticidas, *Isaria fumosorosea* Wize (Cordycipitaceae) fue eficaz en la supresión de trips con curación (≥10 dias después del tratamiento). En la prueba de campo con rotación de insecticidas, la eficacia de un extracto de *Chenopodium* (Amaranthaceae) y 3 mycoinsecticides alternados con espinetoram fue comparable al tratamiento con espinetoram solo. Debido a que *S. dorsalis* (Asia del Sur 1) es una plaga grave de varios cultivos económicamente importantes en muchos condados de Florida y Texas y una plaga emergente en California, este estudio es importante para proveer información a los productores de vegetales y ornamentales sobre insecticidas eficaces con diferentes modos de acción que se pueden rotar para suprimir *S. dorsalis*, y retrasar la evolución de la resistencia a los insecticidas. Los resultados también sugieren la retención de productos eficaces durante un período prolongado en el mercado.

Palabras Clave: thrips; micoinsecticida; biopesticida; control químico; especies crípticas; thrips de chili

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Chilli thrips, *Scirtothrips dorsalis* Hood (Thysanoptera: Thripidae), is a destructive invasive pest of vegetable, ornamental, and fruit crops worldwide (Seal & Kumar 2010; Kumar et al. 2014). Based on the available record in the Global Pest and Disease Database (GPDD 2011), *S. dorsalis* is extremely polyphagous, feeding on more than 200 plant taxa, and is 1 of only 14 species of Thysanoptera known to transmit plant-damaging tospoviruses (Riley et al. 2011). High reproductive potential, multivoltine life history, ability to feed and reproduce on multiple hosts, and adaptation to a wide range of climatic conditions are features that make *S. dorsalis* a major concern for agriculture in many countries. Since this pest invaded the USA in 2005, established populations of *S. dorsalis* have been reported on numerous hosts from 30 counties in Florida and 8 counties in Texas, with detections in Alabama, Louisiana, and Georgia (Seal et al. 2010; Diffie & Srinivasan 2010; Kumar et al. 2011). During the early years of its invasion, climatological modeling to predict distribution in the USA ruled out its establishment in the northern part of the country, as *S. dorsalis* was thought not to overwinter in regions having a temperature below −4 °C for 5 d or more per year (Nietschke et al. 2008). However, recently *S. dorsalis* has been detected on roses (*Rosa* spp.; Rosaceae) in California and was overwintering on hydrangeas (*Hydrangea* spp.; Hydrangeaceae) in New York (Dickey et al. 2015).

Recent work has demonstrated that *S. dorsalis* is a cryptic species complex composed of at least 9 members: South Asia 1 and 2; East Asia 1, 2, 3, and 4; and Australia 1, 2, and 3 (Dickey et al. 2015). In the USA, 2 of these species have been found so far. South Asia 1, which is native to the Indian subcontinent, is known from Florida and Texas. East Asia 1, which is the second member of this complex in the USA, is native to northern Japan, and was initially detected in 2012 in New York (Dickey et al. 2015). Because New York was considered well outside the proposed isothermal line of *S. dorsalis*, detection of this pest in cold regions changes the Cooperative Agricultural Pest Survey (United States Department of Agriculture [USDA] Animal and Plant Health Inspection Services [APHIS]) prediction model and indicates that establishment depends on the origin of the particular cryptic species of *S. dorsalis*. Because thrips differ in many life history traits, misidentification can have serious ecological, biological, management, and epidemiological consequences. Furthermore, concerns exist about a geographical range expansion and potential of this opportunistic pest to cause damage to economically important crops in newly invaded regions. For example, in New York, East Asia 1 has been found on hydrangeas and azaleas (*Rhododendron* spp; Ericaceae) but not on nearby roses, which are considered to be preferred hosts of South Asia 1 in Florida and Texas (Dickey et al. 2015). If any of the *S. dorsalis* species emerges as a major pest of the multiple hosts available in the USA, it would add a huge economic burden on growers by increasing production costs, attenuate our competitiveness in foreign import–export markets, and serve as a trade barrier. In the wake of the economic importance of this pest to the American horticultural industry, of which California and Florida are major contributors, it is essential to take effective steps to safeguard our production units and to minimize economic damage.

Development of a knowledge-based integrated pest management program is essential for the sustainable management of any pest. However, development of an integrated pest management program is a multi-step process, and it often takes time to explore the various parameters affecting a pest's population, such as behavior, life history, and interaction with other arthropods. To avoid the risk of a sudden outbreak of South Asia 1, which is the most widely reported member of the *S. dorsalis* complex in the world (Dickey et al. 2015), and to advise growers about the best management techniques for this pest, we conducted multiple greenhouse and field studies where we evaluated several older and newer insecticides. Previously, we conducted studies of insecticides available for control of *S. dorsalis* in St. Lucia (Seal et al. 2006) and Florida (Seal & Kumar 2010), before it was known to be a thrips complex, and these studies were done in haste for the benefit of growers suddenly affected with this new pest. Both of these studies lacked the evaluation of some new classes of products that could potentially be used in the management of *S. dorsalis*. Although older chemicals are still commercially available, testing of new materials with different modes of action applied alone or in rotation with existing insecticides is useful in avoiding directional selection for resistance in *S. dorsalis* populations. Furthermore, reliance on selective classes of insecticides for this pest by growers can lead to increased pest tolerance to the insecticide (Reddy et al. 1992; Sridhar & Rani 2003; Vanisree et al. 2011), resulting in additional insecticide usage and high economic input to maintain profitability.

In the current study, we focused our efforts on the search of insecticides (chemical and mycoinsecticides) with different modes of action to be used in both preventive and curative approaches, or when used in rotation. Because the different species of the species complex may differ in their characteristics, this study was conducted using only South Asia 1. To extend the implication of this study to regions affected with South Asia 1 in the USA, thrips samples were obtained from growers and extension agents from regions currently reported to have *S. dorsalis* infestations, and were identified with morphological and molecular techniques. The outcome of this study may inhibit the evolution of insecticide resistance and cross-resistance by promoting the rotational use of insecticides with different modes of action.

Materials and Methods

INSECT CULTURE AND HOST PLANTS

The *S. dorsalis* population used in various studies was derived from a colony established in 2005 from an infestation on Knock-Out® rose, *Rosa* hybrid Radrazz in south Florida. The colony was maintained in a greenhouse at the Tropical Research and Education Center, University of Florida, Homestead, Florida (25.50°N, 80.49°W), for several generations on various hosts (i.e., cotton, *Gossypium hirsutum* L. [Malvaceae]; peanut, *Arachis hypogea* L. [Fabaceae]; capsicum pepper, *Capsicum annum* L. [Solanaceae]; and Knock-Out® rose). The pest population was maintained on all hosts during the study by periodically replacing the old plants with young host plants. The host plants for the current studies were grown from seed in seedling trays in Fafard® 2 Mix (Canadian Formula; Sun Gro Horticulture, Agawam, Massachusetts) and placed into a plexiglass screened cage (61 cm length × 91 cm width × 61 cm height) for about 7 wk. Plants in seedling trays were then transplanted into 3.78 L plastic pots. Potted plants were irrigated as needed (about 3 times per wk) and fertilized once each wk with 5 g of nitrogen-phosphorus-potassium (N-P-K): 20-20-20 Multi-Purpose Plus (Diamond R Fertilizer, Fort Pierce, Florida).

THRIPS SPECIES DETERMINATION

The thrips specimens collected from Miami-Dade and Hillsborough counties, Florida; Los Angeles and Orange counties, California; Harris County, Texas; and Barnstable County, Massachusetts, were identified according to morphological characteristics described by Hoddle et al. (2009) using a dissecting microscope at 10× magnification. The detailed information on the thrips samples received is included in Table 1. The identity of thrips specimens was reconfirmed by USDA-APHIS entomologist Thomas Skarlinsky (Thysanoptera specialist in the eastern USA, Miami, Florida). Molecular characterization of thrips samples

Table 1. Details of the thrips specimens collected from different host plants and locations within the USA.

Specimen ID	Host plant	Location (city, county, state)	Collector or sender	Thrips species	GenBank accession (*S. dorsalis*)
CLM 122	*Gossypium hirsutum*	Homestead, Miami-Dade, FL	Catherine Sabines	*Scirtothrips dorsalis*, South Asia 1	KX897168
CLM 125	*Rosa* spp.	La Puenta, Los Angeles, CA	Baldo Villegas	*Scirtothrips dorsalis*, South Asia 1	KX897166
CLM 126	*Rosa* spp.	San Marino, Los Angeles, CA	Baldo Villegas	*Scirtothrips dorsalis*, South Asia 1	KX897167
CLM 127	*Rosa* spp.	San Marino, Los Angeles, CA	Marianne Whitehead	*Frankliniella occidentalis*	—
CLM 128	*Rosa* spp.	Arcadia, Los Angeles, CA	Marianne Whitehead	*Frankliniella occidentalis*	—
CLM 129	*Gossypium hirsutum*	Holtville, Imperial, CA	Eric Natwick	*Leucothrips piercei*	—
CLM 130	*Rosa* spp.	Houston, Harris, TX	Gaye Hammond	*Scirtothrips dorsalis* South Asia 1	KY062166
CLM 131	*Rosa* spp.	San Marino, Los Angeles, CA	Marianne Whitehead	*Frankliniella tritici, F. occidentalis*	—
CLM 132	*Rosa* spp.	San Marino, Los Angeles, CA	Marianne Whitehead	*Frankliniella tritici, F. occidentalis*	—
CLM 133	*Rosa* spp.	Arcadia, Los Angeles, CA	Marianne Whitehead	*Frankliniella tritici*	—
CLM 135	*Rosa* spp.	Orange, CA	Marianne Whitehead	*Scirtothrips dorsalis* South Asia 1, *Frankliniella tritici*	KY062167
CLM 136	*Rosa* spp.	Orange, CA	Marianne Whitehead	*Frankliniella tritici*	—
CLM 137	*Hydrangea* spp.	Sandwich, Barnstable, MA	R. Norton	*Scirtothrips dorsalis*, East Asia 1	KY284604
CLM 138	*Hydrangea* spp.	Sandwich, Barnstable, MA	R. Norton	*Scirtothrips dorsalis* East Asia 1	KY284613
CLM 139	*Hydrangea* spp.	Sandwich, Barnstable, MA	C. L. Fornari	*Scirtothrips dorsalis*	KY284616
CLM 140	*Fragaria × ananassa*	Balm, Hillsborough, FL	Justin Renekama	*Scirtothrips dorsalis* South Asia 1	KY284617

was done following protocols of Dickey et al. (2015) using the hTPG primer set (heat shock protein 83) at the United States Horticulture Research Laboratory, USDA-Agricultural Research Services, Fort Pierce, Florida (27.43°N, 80.40°W). Before sequencing, the amplified products were cleaned using Montage® PCR clean-up filters (Millipore, Billerica, Massachusetts). A quantity of 50 ng of total thrips nuclear DNA was used in BigDye® sequencing reactions. All sequencing was performed bidirectionally with the amplification primers and BigDye® Terminator v.3.1 cycle sequencing kits (Applied Biosystems, Foster City, California). Sequence reactions were analyzed on an Applied Biosystems 3730XL DNA sequence analyzer and were then compared and edited using Sequencher software (Gene Codes, Ann Arbor, Michigan). Species determination was based on direct sequence comparisons using the web-based National Center for Biotechnology Information BLAST sequence comparison application (http://blast.ncbi.nlm.nih.gov/Blast.cgi).

INSECTICIDE EFFICACY

All studies were conducted either in a greenhouse or in a research field at the Tropical Research and Education Center. Insecticide active ingredient, trade name, and formulations, Insecticide Resistance Action Committee classification, manufacturer, application rates, and application methods used in the greenhouse and field trials are listed in Table 2.

Greenhouse Efficacy Trials

Greenhouse trials were conducted to find one or more alternative to standard products used for thrips control. The experimental trials served to evaluate the efficacy of 10 chemical insecticides and 3 mycoinsecticides against *S. dorsalis* on pepper when 1) applied directly to the pest population as a curative management approach, and 2) used to cause residual or persistence impact on the incipient thrips population as a preventive management approach. In trial 1, chemical insecticides were evaluated when applied as foliar application; in trial 2, chemical insecticides were evaluated when applied as drench application; and in trial 3, the foliar-applied mycoinsecticides *Metarhizium anisopliae* (Metschnikoff) Sorokin (Clavicipitaceae), *Isaria fumosorosea* Wize (Cordycipitaceae), and *Beauveria bassiana* (Bals.-Criv.) Vuill. (Cordycipitaceae) were evaluated against *S. dorsalis*. Spinetoram (Radiant®) was used as a chemical standard in trial 3.

Pepper plants at the incipient stage of thrips infestation but with no thrips damage were selected for the preventive studies, whereas plants with established populations of thrips larvae and adults were used for the curative experiments. The treatments in each of the 3 trials (chemical: foliar and drench; mycoinsecticide: foliar) were arranged in a randomized complete block design wherein treated pots were spaced 0.45 m apart. In various trials, depending upon the availability of pepper plants, treatments were replicated 4, 5, or 12 times for each experiment; each replicate consisted of 3 plants. Treatments were applied at the recommended rate using a small hand-held sprayer delivering 65.5 mL/m^2 at 211 kPa for foliar insecticides, whereas in the soil drench each pot received about 100 mL solution of each tested material per 3.78 L pot. The leaf turn method (Tomson et al. 2017) was used for adult and larval population estimates, and no leave was removed from the plant. A population estimate per replicate was made by counting the number of larvae and adult thrips on 5 top leaves selected randomly per plant. Treatment assessments in curative experiments (foliar and drench) were made 3, 5, 7, 10, and 15 d after application of treatments, and in preventive experiments (foliar and drench) assessments were made 3, 7, 10, 15, and 20 d after treatment. Because fungal pathogens take time to germinate and show effect, in trial 3 the treatment assessments were done 5, 10, 15, and 20 d after treatment in both curative and preventive experiments.

Table 2. Commercially formulated insecticides evaluated against *Scirtothrips dorsalis* on Jalapeno pepper in greenhouse and field trials.

Insecticide active ingredient	Trade name	IRAC classification[a]	Manufacturer	Application rate	Application method[b]
Thiamethoxam	Actara®	4A	Syngenta	280.2 g/ha	F
Thiamethoxam + chlorantraniliprole	Voliam Flexi®	4A/28	Syngenta	420.3 g/ha	F
Thiamethoxam + chlorantraniliprole	Durivo®	4A/28	Syngenta	876.0 mL/ha	D
Thiamethoxam	Platinum®	4A	Syngenta	730.0 mL/ha	D
Acetamiprid	Assail® 30SG	4A	United Phosphorous	245.1 g/ha	F, D
Clothianidin	Belay®	4A	Valent	210.1 g/ha	F
Clothianidin	Belay® 50WDG	4A	Valent	420.3 g/ha	D
Chlorantraniliprole	Coragen®	28	Dupont	350.2 g/ha	F, D
Cyantraniliprole	Cyazypyr™	28	Dupont	365.0 mL/ha	F, D
Tolfenpyrad	Hachi-Hachi®	21A	SePro	1,533.0 mL/ha	F, D
Imidacloprid	Provado® 1.6F	4A	Bayer Cropscience	273.5 mL/ha	F
Imidacloprid	Admire® Pro	4A	Bayer Cropscience	292.0 mL/ha	D
Flupyradifurone	Sivanto™ 200SL	4D	Bayer Cropscience	730.0 mL/ha	F, D
Spinetoram	Radiant® SC	5	Dow AgroSciences	584.0 mL/ha	F, D
Extract of *Chenopodium ambrosioides*	Requiem®	N/A	Bayer	4,672.0 mL/ha	F
Isaria fumosorosea	NoFly™	N/A	Natural Industries	1,120.8 g/ha	F
Isaria fumosorosea	PFR-97™ 20%WDG	N/A	Certis USA	1,120.8 g/ha	F
Metarhizium anisopliae	Met 52® EC	N/A	Novozymes	2,117.0 mL/ha	F
Beauveria bassiana strain GHA	BotaniGard® ES	N/A	BioWorks	4,672.0 mL/ha	F

[a]Insecticide Resistance Action Committee (IRAC) classification. N/A, not applicable.
[b]F = foliar, D = drench; Foliar treatments in greenhouse trials were applied as a full coverage foliar spray using a small hand-held sprayer and in field trial CO_2 backpack sprayer 665 L/ha at 211 kPa. Mycoinsecticides were mixed 30 min before application with regular agitation to make sure the solution is thoroughly dissolved. Drenches were applied by pouring 100 mL of the solution evenly over the surface of each pot.

Field Rotational Program

To integrate mycoinsecticide products into management programs for *S. dorsalis*, a field study on Jalapeno pepper was conducted wherein 3 mycoinsecticides were evaluated alone and in rotation with spinetoram, a grower standard for thrips management. In addition to the 3 mycoinsecticides, efficacy of a new botanical insecticide (*Chenopodium ambrosioides* L. extract [Amaranthaceae]) was also assessed in the field. Treatments evaluated in the study were: 1) *Chenopodium* extract (Requiem® 25EC); 2) *M. anisopliae* (Met52®); 3) *I. fumosorosea* (NoFly™); 4) *I. fumosorosea* Apopka Strain 97 (PFR-97™); 5) *B. bassiana* (BotaniGard®); 6) spinetoram (Radiant®); 7) *Chenopodium* extract in rotation with spinetoram; 8) *M. anisopliae* in rotation with spinetoram; 9) *I. fumosorosea* (NoFly™) in rotation with spinetoram; 10) *I. fumosorosea* (PFR-97™) in rotation with spinetoram; 11) *B. bassiana* in rotation with spinetoram; and 12) an untreated control.

The study was conducted on a 0.4 ha research plot at the Tropical Research and Education Center. The soil type was Krome gravelly loam (loamy-skeletal, carbonatic, hypothermic, lithic, udorthents), with a pH of 7.4 to 8.4, was 34 to 76% limestone pebbles (>2 mm diameter), and had a low organic matter content of <2% (Noble et al. 1996; Li 2001). Jalapeno pepper seedlings (about 7 wk old) were planted into 5.0-cm-deep holes on 15-cm-high and 0.91-m-wide beds covered with 1.5-mil-thick black on black polyethylene mulch (Grower's Solution Co., Cookeville, Tennessee). Experimental plots were randomly selected 9.14 m segments of 3 adjacent beds with 1.83 m separation from center to center. The beds were fumigated 2 wk before setting transplants with a mixture containing 67% methyl bromide and 33% chloropicrin at 246 kg/ha. Seedlings were placed 0.45 m apart within rows and drip irrigated with the equivalent of 2.5 cm of precipitation twice daily using 2 parallel drip-tube lines (T-systems, DripWorks Inc., Willits, California). Granular fertilizer (N-P-K: 6-12-12) was applied at 1,345 kg/ha in a 10-cm-wide band on each side of the bed center and incorporated before placement of plastic mulch. Liquid fertilizer (N-P-K: 4-0-8) was applied bi-weekly at 0.56 kg of N/ha/d through the drip system.

Plots were arranged in a randomized complete block design with 4 replications per treatment. A 1.5-m-long untreated planted area separated each replicate. Treatments were applied at weekly intervals for 6 wk using a CO_2 backpack sprayer with 2 nozzles per row delivering 665 L/ha at 211 kPa. Treatments were evaluated by randomly collecting 10 fully expanded young leaves, 1 leaf per plant, from 10 randomly selected plants per replicate bi-weekly, so that the individual or combined effect of both insecticides could be evaluated simultaneously. Leaves from each plot were placed into a labeled re-sealable plastic bag (17 × 22 cm) and transported to the laboratory for further processing. Different life stages of thrips in each sample were separated by washing the leaves with 75% ethanol and pouring the content through a sieve with a 25 µm grating (Seal & Baranowski 1992). The residue in the sieve was washed off with 70% alcohol onto a Petri dish and checked under a dissecting microscope at 12× magnification to record various life stages of thrips in each sample. *Scirtothrips dorsalis* feeding damage on pepper foliage with various treatments was recorded at the end of the study (wk 6) by collecting 10 leaves per plot and rating leaves for damage on a scale from 0 (no damage) to 5 (severely damaged). Furthermore, the treatment effect was also evaluated based on the number of pepper flowers and fruits present in each plot where flower numbers were recorded 2 wk after initiation of flowering, and fruit numbers at the end of the study season.

STATISTICAL ANALYSES

Scirtothrips dorsalis data from the greenhouse trials and insecticides rotation field experiments were analyzed independently using a generalized linear mixed model with the SAS® (SAS Institute 2009) procedure GLIMMIX. The model was used to determine the effect of insecticide treatments, sampling period (time), and their interaction on *S. dorsalis* larval and adult counts, separately (Table 3). Because the response variable was count data with no upper bound, in the model statement distribution was specified as Poisson. The autoregressive correlation structure was applied to account for the correlation in data

Table 3. ANOVA statistics for *Scirtothrips dorsalis* post-treatment populations in the greenhouse and field trials to evaluate various insecticidal treatments applied curatively or preventively on Jalapeno peppers.

					Larvae			Adults		
Trial			N[a]	Effect	df	*F*	*P*	df	*F*	*P*
Greenhouse efficacy trials	(1) Chemical foliar	Curative	4	Treatment	10,165	7.72	<0.001	10,165	6.95	<0.001
				Time	4,165	22.16	<0.001	4,165	12.18	<0.001
				Treatment*time	40,165	1.24	0.180	40,165	0.77	0.830
		Preventive	5	Treatment	10,220	8.10	<0.001	10,220	4.04	<0.001
				Time	4,220	48.24	<0.001	4,220	26.79	<0.001
				Treatment*time	40,220	1.10	0.324	40,220	0.49	0.996
	(2) Chemical drench	Curative	5	Treatment	10,220	13.04	<0.001	10,220	4.35	<0.001
				Time	4,220	33.98	<0.001	4,220	5.66	0.002
				Treatment*time	40,220	0.84	0.736	40,220	0.18	0.100
		Preventive	4	Treatment	10,165	8.20	<0.001	10,165	2.89	0.002
				Time	4,165	25.61	<0.001	4,165	23.68	<0.001
				Treatment*time	40,165	0.56	0.982	40,165	0.40	0.999
	(3) Mycoinsecticides foliar	Curative	12	Treatment	4,220	49.46	<0.001	4,220	18.40	<0.001
				Time	3,220	1.62	0.185	3,220	0.45	0.715
				Treatment*time	12,220	0.20	0.998	12,220	0.36	0.974
		Preventive	12	Treatment	4,220	30.03	<0.001	4,220	19.73	<0.001
				Time	3,220	33.44	<0.001	3,220	1.37	0.253
				Treatment*time	12,220	1.06	0.392	12,220	0.67	0.782
Field efficacy trial	Insecticide rotation		4	Treatment	11,144	6.07	<0.001	11,144	3.39	0.001
				Time	3,144	14.15	<0.001	3,144	22.72	<0.001
				Treatment*time	33,144	1.03	0.429	33,144	0.93	0.579

[a]N = number of replicates in the experiment.

generated by re-sampling the same experimental unit over time. Differences among treatment means were separated using Fisher's LSD test (α = 0.05) in the repeated measures model. One-way ANOVA (PROC GLM) was used to compare *S. dorsalis* feeding damage in different treatment plots and to assess the effect of insecticides on number of pepper flowers and fruits. The Abbott formula (Abbott 1925) and the Henderson–Tilton formula (Henderson & Tilton 1955) were used for estimation of thrips mortality in preventive and curative experiments, respectively.

Results

THRIPS SPECIES DETERMINATION

The thrips samples collected from different locations in Florida, Texas, and California were *S. dorsalis* South Asia 1, whereas specimens collected from Massachusetts were East Asia 1 (Table 1). This is the first report of *S. dorsalis* detected in Massachusetts and the second reported state in the USA (after New York) that has East Asia 1. Sequences obtained from *S. dorsalis* samples collected from different parts of the USA were deposited in GenBank, and their accession numbers are available in Table 1. Apart from *S. dorsalis*, the other thrips species that were detected on roses were *Frankliniella tritici* Fitch and *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae).

THRIPS ABUNDANCE IN GREENHOUSE TRIALS

In the greenhouse efficacy trials with chemical insecticides applied to foliage or as a soil drench, both of the main effects (treatment and time) had significant effects on *S. dorsalis* (larval and adult) densities (Table 3). In the trial with mycoinsecticides, there was a significant effect of treatment on *S. dorsalis* population, but no significant effect of sampling period was detected, except for larval abundance in the preventive experiment. No significant effect of the treatment*time interaction was observed on thrips populations in any of the experiments (Table 3). *Scirtothrips dorsalis* population sizes varied greatly; however, significant reductions in thrips numbers were observed in all treatments as compared with the untreated control. For making recommendations to growers, an insecticide was considered effective when mortality exceeded 70% of the thrips life stages during a sampling period.

Chemical Insecticides (Foliar Application)

A significant reduction in the thrips population as compared with the untreated control was found in all the treatments except chlorantraniliprole (Table 4). Among various insecticides applied curatively, tolfenpyrad, cyantraniliprole, and clothianidin were effective (mortality >70%) in controlling *S. dorsalis* (larval and adult) populations throughout the study period, whereas thiamethoxam, acetamiprid, spinetoram, flupyradifurone, and the formulated combination of thiamethoxam + chlorantraniliprole were effective in suppressing *S. dorsalis* (larval and adult) populations until 10 d after application of treatments. When treatments were applied preventively, spinetoram, clothianidin, and thiamethoxam + chlorantraniliprole were effective against *S. dorsalis* populations until 15 d after treatment (Table 4). Spinetoram was the most effective insecticide for foliar treatment.

Chemical Insecticides (Drench Application)

Among various insecticides tested as drench treatments in the curative strategy, imidacloprid, thiamethoxam, and cyantraniliprole were effective in suppressing larval populations of *S. dorsalis* throughout the study period (Table 5). Imidacloprid was the only insecticide that effectively suppressed adults until 7 d after treatment. In the preventive approach, the 2 effective products for keeping the larval population under control until the end of the study were imidacloprid and thiamethoxam + chlorantraniliprole. Other treatments that provided effective suppression of the larval population for 10 d after treatment or longer were flupyradifurone, thiamethoxam, clothianidin, chlorantraniliprole, and cyantraniliprole (Table 5). Adults remained suppressed for 10 d using imidacloprid and thiamethoxam.

Mycoinsecticides

Curative application of spinetoram (used as the chemical standard in the positive control treatment) consistently suppressed *S. dorsalis* populations (mean larval mortality = 98.5%; adult mortality = 93.5%) and provided >89% reduction on all the sampling dates (Table 6). Among the mycoinsecticides, *I. fumosorosea* and *M. anisopliae* were effective only in suppressing adults of *S. dorsalis* throughout the study period (adult mortality >75%). *Beauveria bassiana* was the least effective of the mycoinseticides, and the efficiency break occurred on the 5th day post treatment for both the curative and preventive approach. Preventive application of spinetoram was the most effective in regulating *S. dorsalis* populations (larvae and adults) for the entire study period, wherein thrips mortality was >81% on all the sampling dates (Table 6). Among the mycoinsecticides, *I. fumosorosea* and *M. anisopliae* effectively suppressed *S. dorsalis* larvae for 10 d.

Field Rotational Program

Overlapping generations of *S. dorsalis* existed on pepper throughout the study, which explained the significant effects of treatment and sampling period. There was no effect of treatment*time interaction on the abundance of either *S. dorsalis* larvae or adults (Table 3). Mycoinsecticides and the *Chenopodium* extract applied alone did not significantly reduce *S. dorsalis* larval abundance on any of the sampling dates when compared with the untreated control (Fig. 1). However, when rotated with spinetoram, mycoinsecticides and the *Chenopodium* extract provided a significant suppression of *S. dorsalis* larvae (compared with the untreated control) on all sampling dates (wk 2: $F_{11,144}$ = 2.79, P = 0.0026; wk 4: $F_{11,144}$ = 1.58, P = 0.0118; wk 6: $F_{11,144}$ = 2.14, P = 0.0207), and the performance of rotational treatments did not differ from spinetoram applied alone (mortality >90%) (Table 7). Similar results for *S. dorsalis* adults were observed where the performance of mycoinsecticides and *Chenopodium* extract each applied alone was not pronounced (Fig. 2), and spinetoram alone or in rotation with mycoinsecticides performed better and provided >85% mortality of thrips adults on all the sampling dates (Table 7). Significant suppression of *S. dorsalis* adults compared with the untreated control was observed in all the spinetoram-treated plots (applied alone or in rotation) in wk 2 ($F_{11,144}$ = 1.95, P = 0.0380) and wk 6 ($F_{11,144}$ = 1.59, P = 0.0169).

All treatments applied alone or in rotation significantly reduced *S. dorsalis* feeding damage on pepper when compared with the untreated control (Table 7). Mean numbers of flowers were significantly higher in all treated plots (except *I. fumosorosea* [NoFly™]) than in the untreated plots (Table 7). Plants treated with the *Chenopodium* extract and mycoinsecticides in rotation with spinetoram showed more flowers per treated plot than plants treated with a mycoinsecticide alone. As was the case with flowers, mean numbers of fruits before harvest (irrespective of size and age) were significantly greater on plants treated with *Chenopodium* extract and each of the mycoinsecticides in rotation with spinetoram than on plants in treatments without spinetoram (Table 7). Plants treated with spinetoram alone had significantly more flowers and fruits than plants in any other treatments.

Table 4. Results of foliar applications of chemical insecticides. Mean numbers of *Scirtothrips dorsalis* larvae and adults on 5 leaves per plant in each replicate.

		Curative application				Preventive application			
		Population mean				Population mean			
Treatment	Thrips life stage	Pre-treatment	Post-treatment	Corrected mean mortality (%)	Efficiency break (d)[a]	Pre-treatment	Post-treatment	Corrected mean mortality (%)	Efficiency break (d)[a]
Thiamethoxam	Larvae	25.50a–d	3.25de	87.0	15	0.0	7.56b	69.6	15
	Adults	4.25	2.20BC	80.0	15	0.0	2.44CD	75.8	20
Acetamiprid	Larvae	11.0b–d	1.80de	82.2	15	0.0	4.24b–d	84.0	20
	Adults	3.50	1.70BC	79.8	*	0.0	3.0BC	61.4	3
Clothianidin	Larvae	84.25a	7.25bc	90.2	*	0.0	2.24cd	91.8	20
	Adults	15.25	1.90BC	94.6	*	0.0	2.52CD	76.2	20
Chlorantraniliprole	Larvae	43.0a–c	13.20ab	66.4	5	0.0	6.20bc	71.4	20
	Adults	6.25	3.10B	80.4	*	0.0	5.36AB	42.6	7
Cyantraniliprole	Larvae	45.75a–c	6.85cd	84.4	*	0.0	3.40b–d	84.2	20
	Adults	8.0	1.25C	93.8	*	0.0	2.60CD	73.0	15
Tolfenpyrad	Larvae	54.0ab	1.55e	97.2	*	0.0	5.36b–d	79.0	20
	Adults	8.75	1.0C	95.8	*	0.0	3.28BC	68.0	15
Imidacloprid	Larvae	5.50d	3.80de	62.4	10	0.0	5.84b–d	79.0	15
	Adults	4.0	1.45C	85.8	15	0.0	4.20BC	43.8	3
Spinetoram	Larvae	23.50a–d	2.05e	90.8	15	0.0	0.16d	99.4	*
	Adults	7.75	1.40C	93.4	*	0.0	0.96D	93.2	20
Flupyradifurone	Larvae	40.0a–c	2.45c–e	93.6	*	0.0	2.80b–d	88.4	20
	Adults	5.75	1.95BC	87.0	15	0.0	3.52BC	56.8	10
Thiamethoxam + Chlorantraniliprole	Larvae	9.0cd	3.15c–e	72.8	15	0.0	4.12b–d	84.6	20
	Adults	3.50	1.95BC	78.6	15	0.0	3.28BC	63.4	20
Untreated control	Larvae	23.75a–d	21.10a	N/A	N/A	0.0	16.24a	N/A	N/A
	Adults	3.50	8.60A	N/A	N/A	0.0	7.32A	N/A	N/A

Mean values followed by different letters in a column are significantly different (Fisher's LSD test, $P < 0.05$). In each column, different lowercase letters (a, b) indicate significant differences among larval means across treatments; different uppercase letters (A, B) indicate significant differences among adult means across treatments. N/A, not applicable.

[a]Efficiency break is the day after application of the treatment at which mortality failed to reach 70% in the respective treatment. * denotes mortality was >70% throughout the study period for a particular treatment.

Table 5. Results of drench applications of chemical insecticides. Mean numbers of *Scirtothrips dorsalis* larvae and adults on 5 leaves per plant in each replicate.

Treatment	Thrips life stage	Curative application				Preventive application			
		Population mean		Corrected mean mortality (%)	Efficiency break (d)[a]	Population mean		Corrected mean mortality (%)	Efficiency break (d)[a]
		Pre-treatment	Post-treatment			Pre-treatment	Post-treatment		
Imidacloprid	Larvae	1.0	1.08e	98.2	*	0.0	1.10d	97.4	*
	Adults	7.0	5.56C	67.2	10	3.0	4.35CD	83.0	15
Acetamiprid	Larvae	1.20	10.84d	86.8	15	0.0	8.0bc	79.0	10
	Adults	6.20	14.08B	15.8	3	1.25	4.50BC	49.0	3
Clothianidin	Larvae	1.20	34.72bc	59.2	7	0.0	11.40bc	74.2	15
	Adults	6.60	22.36AB	5.8	3	1.50	11.85A	35.8	3
Chlotraniliprole	Larvae	1.0	26.52bc	62.6	7	0.0	9.85bc	75.8	15
	Adults	6.40	19.24B	3.8	3	2.25	7.50AB	56.0	7
Cyantraniliprole	Larvae	3.0	20.56cd	90.2	*	0.0	10.20bc	77.4	15
	Adults	5.20	17.56B	2.4	3	2.25	6.40BC	64.0	7
Thiamethoxam + Chlorantraniliprole	Larvae	1.40	17.40cd	82.4	15	0.0	6.45c	84.4	*
	Adults	11.0	14.72B	45.2	5	0.75	2.45C	59.2	3
Tolfenpyrad	Larvae	1.80	46.68b	61.2	7	0.0	13.10bc	62.0	3
	Adults	10.0	25.08AB	16.4	3	2.50	4.45BC	74.6	20
Thiamethoxam	Larvae	1.20	10.16d	88.0	*	0.0	8.90bc	78.6	20
	Adults	10.0	14.96B	39.2	3	3.0	7.30BC	70.4	15
Spinetoram	Larvae	1.40	33.68bc	57.2	7	0.0	17.50b	57.6	10
	Adults	5.20	15.48B	8.0	5	2.0	6.75BC	48.4	3
Flupyradifurone	Larvae	1.20	16.52cd	80.4	15	0.0	5.75c	86.8	20
	Adults	7.40	15.48B	20.4	3	1.75	4.0C	70.8	10
Untreated control	Larvae	1.0	62.32a	N/A	N/A	0.0	34.65a	N/A	N/A
	Adults	13.0	32.0A	N/A	N/A	1.75	11.55A	N/A	N/A

Means values followed by different letters in a column are significantly different (Fisher's LSD test, $P < 0.05$). In each column, different lowercase letters (a, b) indicate significant differences among larval means across treatments; different uppercase letters (A, B) indicate significant differences among adult means across treatments. N/A, not applicable.

[a]Efficiency break is the day after application of the treatment at which mortality failed to reach 70% in the respective treatment. * denotes mortality was >70% throughout the study period for a particular treatment.

Table 6. Results of foliar applications of mycoinsecticides. Mean numbers of *Scirtothrips dorsalis* larvae and adults on 5 leaves per plant in each replicate.

		Curative application				Preventive application			
		Population mean				Population mean			
Treatment	Thrips life stage	Pre-treatment	Post-treatment	Corrected mean mortality (%)	Efficiency break (d)[a]	Pre-treatment	Post-treatment	Corrected mean mortality (%)	Efficiency break (d)[a]
Beauveria bassiana	Larvae	4.08	43.10b	54.7	5	0.0	26.29b	40.5	5
	Adults	9.75A	20.66A	67.7	5	0.0	15.85AB	25.0	5
Metarhizium anisopliae	Larvae	3.50	31.58bc	60.7	5	0.0	14.25c	73.75	15
	Adults	11.83A	16.58AB	78.7	*	0.0	11.77BC	44.5	5
Isaria fumosorosea	Larvae	4.16	26.0c	72.7	15	0.0	11.58c	79.5	15
	Adults	12.66A	13.45B	84.0	*	0.0	9.66C	56.0	5
Spinetoram	Larvae	4.25	1.52d	98.5	*	0.0	0.87d	98.2	*
	Adults	9.0AB	3.85C	93.5	*	0.0	2.64D	87.2	*
Untreated control	Larvae	2.91	69.12a	N/A	N/A	0.0	41.62a	N/A	N/A
	Adults	3.58B	23.81A	N/A	N/A	0.0	21.58A	N/A	N/A

Means values followed by different letters in a column are significantly different (Fisher's LSD test, $P < 0.05$). In each column, different lowercase letters (a, b) indicate significant differences among larval means across treatments; different uppercase letters (A, B) indicate significant differences among adult means across treatments. N/A, not applicable.
[a]Efficiency break is the day after application of the treatment at which mortality failed to reach 70% in the respective treatment. * denotes mortality was >70% throughout the study period for a particular treatment.

Discussion

SCIRTOTHRIPS DORSALIS SPECIES COMPLEX IN THE INFESTED REGIONS

The small size (<1.5 mm), thigmotactic behavior, and adaptability of this thrips to a wide range of climatic conditions help explain its high invasiveness and on exotic pest lists of many countries. Results of our previous study (Dickey et al. 2015) confirmed that *S. dorsalis* South Asia 1 has invaded at least 2 agriculturally important states of the USA, namely Florida and Texas, and the current study confirmed its presence in California. The existence of established populations of South Asia 1 on multiple hosts in *S. dorsalis* infested regions within the USA suggests that this species is more prevalent compared with another member of the *S. dorsalis* species complex, *S. dorsalis* East Asia 1, which has only been reported twice in the past 5 yr on the same host (hydrangea) in 2 neighboring eastern states (New York and Massachusetts). Based on the invasion history of members of this thrips complex around the globe, it appears that South Asia 1 is a thrips with great invasion potential, unlike East Asia 1, which apparently displays a much smaller invasion potential (Dickey et al. 2015). To this date, *S. dorsalis* South Asia 1 occurs in India, Pakistan, Bangladesh, Myanmar, Japan, Vietnam, Thailand, Israel, and the USA. Within a few years of its introduction in Florida, *S. dorsalis* (later characterized to be South Asia 1) was established from the southern to the central region of Florida (Kumar et al. 2013), and Osborne (2008) reported damage on >50 plant taxa that included bedding plants, cut flowers, foliage plants, and perennials (mostly ornamental hosts). In south Florida, South Asia 1 was found on 11 fruit hosts, some of which had never been reported before as reproductive host, suggesting that the host range of this insidious pest is continuing to expand as it invades new regions (Kumar et al. 2012).

INSECTICIDE PERFORMANCE

Synthetic insecticide applications have always been the primary mode of pest management amongst ornamental growers because of the low damage threshold of ornamental plants and zero tolerance for export items. Because *S. dorsalis* is a serious pest of ornamental plants in many counties of Florida and Texas, and an emerging pest in California, determination of materials that can be integrated in the current management practices for this pest is of paramount importance. The current study was initiated when local nurseries in south and central Florida had severe infestations of *S. dorsalis* on multiple ornamental and tropical fruit crops. To reduce impacts on various hosts, we emphasized the evaluation of potentially suitable insecticides with different modes of action that could be used as curative and preventive measures for the suppression of *S. dorsalis* South Asia 1, and some of these materials were assessed for rotational use.

In the greenhouse trials, we evaluated 10 chemical insecticides (14 formulations) representing 5 modes of action as defined by the Insecticide Resistance Action Committee (IRAC), and 3 mycoinsecticides. We found a range of products that were effective in regulating *S. dorsalis* South Asia 1 populations. To make recommendations to growers, insecticides resulting in >70% thrips mortality were considered effective, and their properties are summarized in Table 8. Based on the results, insecticides belonging to IRAC groups 4A: acetamiprid (Assail®), clothianidin (Belay®), and thiamethoxam (Actara®); 4D: flupyradifurone (Sivanto™); 21A: tolfenpyrad (Hachi-Hachi®); 28: cyantraniliprole (Cyazypyr™); and a premix formulation of 4A and 28: thiamethoxam + chlorantraniliprole (Voliam Flexi®) can be recommended to growers for use as foliar sprays in suppressing adult and larval *S. dorsalis* populations for >7 d. Among these insecticides, similar efficacy during drench

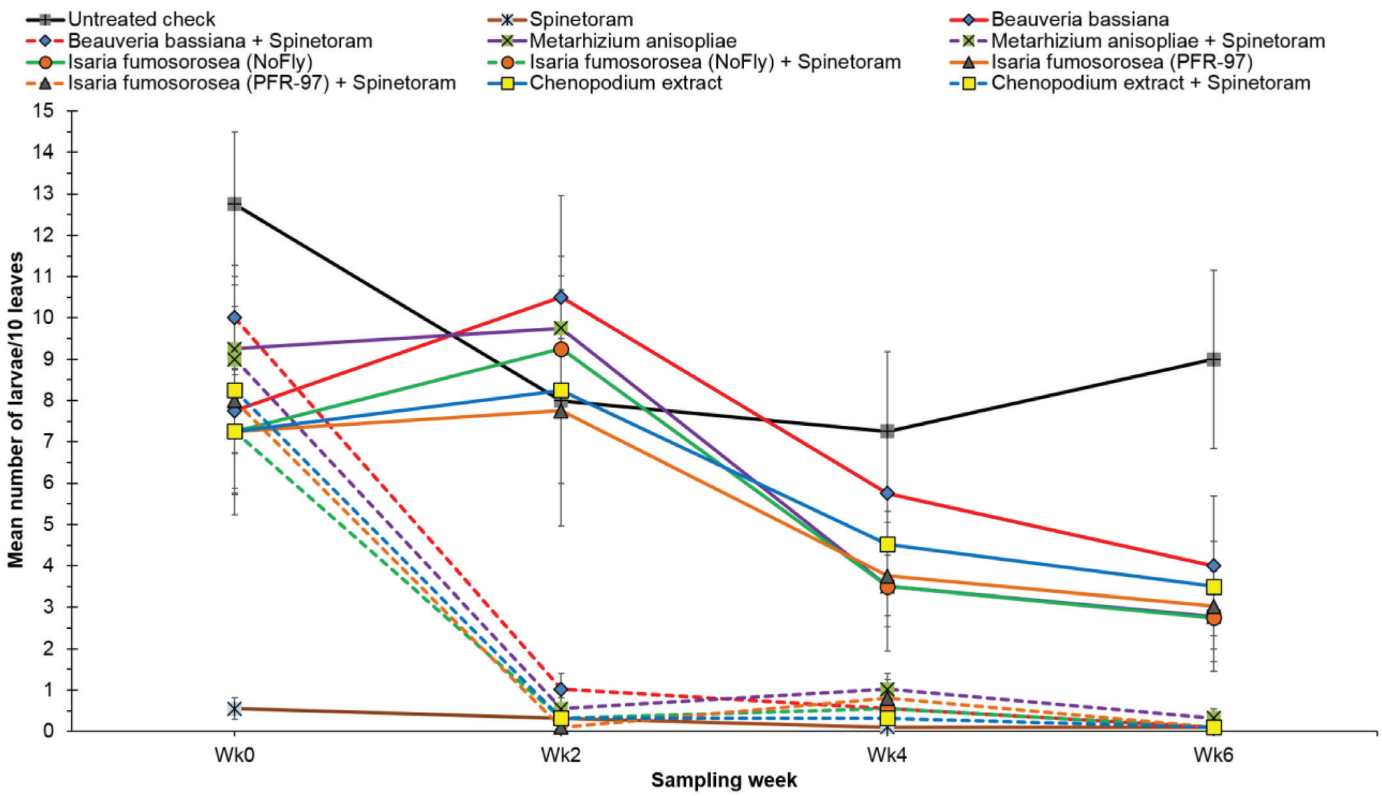

Fig. 1. Mean numbers of *Scirtothrips dorsalis* larvae per 10 leaf samples of Jalapeno pepper treated with different insecticides. Solid lines represent treatments where 1 insecticide was applied alone, and dashed lines show treatments of 2 insecticides applied in rotation. Same color solid and dashed lines represent same insecticide applied alone or in rotation with spinetoram.

application was observed only for imidacloprid (Admire® Pro), whereas other products were effective only in controlling thrips larvae. For the purpose of preventing populations from developing (prophylactic measures), foliar applications of insecticides belonging to IRAC groups 4A: thiamethoxam, clothianidin; 4D: flupyradifurone; 21A: tolfenpyrad; 28: cyantraniliprole; and a premix formulation of 4A and 28: thiamethoxam + chlorantraniliprole, and drench application of flupyradifurone and imidacloprid, can be recommended.

Foliar applications of spinetoram (Radiant®) (IRAC group 5) can be used in both curative and preventive management programs for *S. dorsalis*, because it was effective for more than 10 d and was one of the few insecticides that eliminated the *S. dorsalis* population from treated plants during the study period. Similar results on the efficacy of spinetoram for *S. dorsalis* management were reported by Seal & Kumar (2010), indicating it is still one of the most effective tools growers have for management of *S. dorsalis*.

Thrips mortality due to mycoinsecticides was lower than that caused by the chemical standard (spinetoram), but mycoinsecticides provided suppressive control ranging from 47 to 70%, 55 to 83%, and 68 to 86% when used as a curative measure in 3 treatments involving

Table 7. Mortality of *Scirtothrips dorsalis* larvae and adults on Jalapeno pepper treated with various regimes of insecticides.

	Mean mortality (%)				
Treatment	Larvae	Adults	Damage rating[a]	Mean no. of flowers[b]	Mean no. of fruits[b]
Beauveria bassiana	40.3	5.3	1.87b	16.25de	14.25e
Chenopodium extract	64.3	10.6	1.87b	18.75cd	16.0de
Isaria fumosorosea (NoFly™)	55.6	20.3	2.08b	15.0ef	15.75de
Isaria fumosorosea (PFR-97™)	42.0	20.3	1.87b	17.50d	16.50d
Metarhizium anisopliae	69.6	30.3	1.87b	17.25de	16.0de
Spinetoram	100.0	97.3	0.0c	25.25a	26.0a
Beauveria bassiana + spinetoram	98.3	91.6	1.16b	20.50bc	21.50b
Chenopodium extract + spinetoram	100.0	96.6	1.25b	21.50b	20.25bc
Isaria fumosorosea (NoFly™) + spinetoram	100.0	94.3	1.45b	21.0bc	20.75bc
Isaria fumosorosea (PFR-97™) + spinetoram	93.3	94.6	1.45b	20.50bc	18.75bc
Metarhizium anisopliae + spinetoram	100.0	89.0	1.25b	22.0b	20.25bc
Untreated control	N/A	N/A	3.75a	13.50f	11.0f

Means values followed by different letters in a column are significantly different (Fisher's LSD test, $P < 0.05$). N/A, not applicable.
[a]Values represent mean damage observed on pepper plants on the last sampling day.
[b]Values represent numbers observed on pepper plants on the last sampling day.

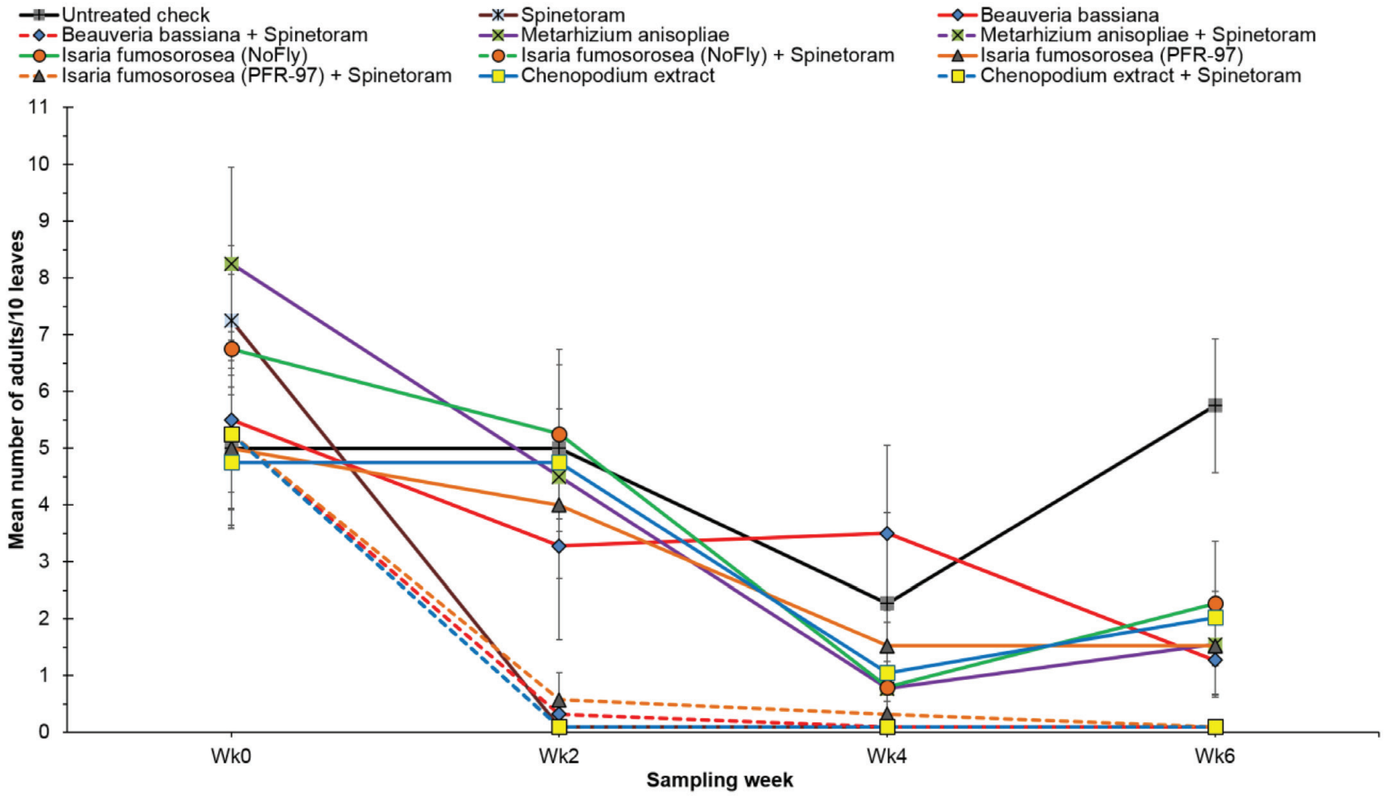

Fig. 2. Mean numbers of *Scirtothrips dorsalis* adults per 10 leaf samples of Jalapeno pepper treated with different insecticides. Solid lines represent treatments where 1 insecticide was applied alone, and dashed lines show treatments of 2 insecticides applied in rotation. Same color solid and dashed lines represent same insecticide applied alone or in rotation with spinetoram.

B. bassiana (mean larval mortality: 54.7%; adult mortality: 67.7%), *M. anisopliae* (larval mortality: 60.7%; adult mortality: 78.7%), or *I. fumosorosea* (larval mortality: 72.7%; adult mortality: 84.0%), respectively. Greater thrips mortalities in curative applications than in preventive applications could be due to the active spores on the upper leaf surface (adaxial side) and their spread (via conidia or blastospores) from affected individuals to the unaffected individuals on both abaxial and adaxial leaf surfaces. However, in preventive applications, the mortality occurs only due to the residual spores present on the leaf surfaces, which can dehydrate or become inviable before the insects occur, resulting in low rates of infection in arriving thrips.

Greater mortality among larvae than adults may be explained by adults being able to escape mycoinsecticide treatments, unlike thrips larvae, which roam around the spore-treated plant surface and have a higher probability of becoming exposed to the spores than adults. Our results indicate that mycoinsecticides are better suited for curative than preventive applications. Among the 3 mycoinsecticides tested, *I. fumosorosea* was the most effective against *S. dorsalis*, suggesting that in the greenhouse and nursery environments, *I. fumosorosea* can be efficiently integrated into management of this pest, and can serve as an important tool for organic growers.

In its native region, *S. dorsalis* populations have been found to be resistant to a range of chemical classes including organochlorine (dichlorodiphenyltrichloroethane, benzene hexachloride, and endosulfan), organophosphate (acephate, dimethoate, phosalone, methyl-o-demeton, and triazophos), and carbamate insecticides (carbaryl) (Reddy et al. 1992; Sridhar & Rani 2003; Vanisree et al. 2011). Thus, it is imperative to evaluate newer classes of insecticides and integrate them in a management program to minimize the risk of the progressive assembly of genes for resistance through selection.

Thiamethoxam is a neonicotinoid precursor that is converted to clothianidin in insects and plants (Nauen et al. 2003). It is a second generation neonicotinoid compound that disrupts the binding of the insect neurotransmitter acetylcholine at its nicotinic acetylcholine receptors present at the post-synaptic cell junctures. Thiamethoxam is a broad-spectrum insecticide known for its activity against many pests, including thrips (Teague et al. 1999; Jacobson & Hara 2003; Aslam et al. 2004; Larral & Ripa 2007; Seal & Kumar 2010; McKenzie et al. 2015). Chlorantraniliprole and cyantraniliprole are novel anthranilic diamide insecticides that selectively bind to the ryanodine receptors in muscle cells, resulting in the uncontrolled release of calcium stores (Lahm et al. 2005). They cause depletion of calcium, feeding cessation, lethargy, muscle paralysis, and ultimately death of target organisms (Cordova et al. 2006; Lahm et al. 2007). Flupyradifurone is the first member of the newly created IRAC subgroup 4D (Nauen et al. 2015), which belongs to the butenolide chemical class. It contains a novel bioactive scaffold isolated from the medicinal plant *Stemona japonica* (Blume) Miq. (Stemonaceae). Tolfenpyrad is a broad-spectrum contact insecticide with a pyrazole carboxamide structure. It acts as a mitochondrial electron transport inhibitor and affects respiration of the target pests resulting in rapid insecticidal responses such as cessation of feeding, cessation of movement, and lack of fecundity. From the current study, it was apparent that the *S. dorsalis* South Asia 1 population was susceptible to several groups of insecticides, among which the older insecticides acetamiprid, clothianidin, and imidacloprid had a long residual impact. So, to keep these chemicals in the marketplace, it is important to use them in rotation programs. The premix insecticide chlorantraniliprole + thiamethoxam showed promising results against larval and adult stages, but such insecticides should be used with care, as the non-judicious use of such premixes can result in the selection of resistance to 2

Table 8. Choices of insecticides for rotational use against *Scirtothrips dorsalis* South Asia 1. An insecticide was considered effective when mortality exceeded 70% for thrips life stages.

			Residual efficacy (d) Curative				Residual efficacy (d) Preventive			
			Foliar		Soil		Foliar		Soil	
Active Ingredient	Trade Name	Mode of action	Adults	Larvae	Adults	Larvae	Adults	Larvae	Adults	Larvae
Acetamiprid	Assail®	Nicotinic acetylcholine receptor disruptor	15	10	0	10	10	15	0	7
Clothianidin	Belay®, Belay® 50WDG	Nicotinic acetylcholine receptor disruptor	15	15	0	5	15	15	0	10
Chlorantraniliprole	Coragen®	Ryanodine receptor modulator	15	3	0	5	3	15	3	10
Cyantraniliprole	Cyazypyr™	Ryanodine receptor modulator	15	15	0	15	10	15	3	10
Flupyradifurone	Sivanto™	Nicotinic acetylcholine receptor competitive modulator	10	15	0	10	7	15	7	15
Imidacloprid	Provado®, Admire® Pro	Nicotinic acetylcholine receptor disruptor	10	7	7	15	0	10	10	20
Spinetoram	Radiant®	Nicotinic acetylcholine receptor allosteric modulator	15	10	5	3	15	20	0	7
Tolfenpyrad	Hachi-Hachi®	Mitochondrial electron transport inhibitors	15	15	0	5	10	15	15	0
Thiamethoxam	Actara®, Platinum®	Nicotinic acetylcholine receptor disruptor	10	10	0	15	15	10	10	15
Thiamethoxam + Chlorantraniliprole	Voliam Flexi®, Durivo®	Multiple modes	10	10	3	10	15	15	0	20
Beauveria bassiana	BotaniGard®	N/A	0	0	—	—	0	0	—	—
Metarhizium anisopliae	Met52®	N/A	20	0	—	—	0	10	—	—
Isaria fumosoroseus	PFR-97™	N/A	20	10	—	—	0	10	—	—

N/A, not applicable.

mode of action classes. In the experiments where foliar-applied (non-systemic) insecticides such as spinetoram and tolfenpyrad were used as drench applications, effective suppression of the thrips population was observed for the next few days. We speculate that such thrips suppression could be due to the movement of thrips to the soil in search of food and in preparation for pupation, leading to direct and indirect contact with the product, causing death.

In the insecticide rotation field trial, we found that the *Chenopodium* extract and the 3 mycoinsecticides when used alone did not provide effective suppression of *S. dorsalis* South Asia 1 populations; consequently, flower and fruit numbers in these plots were sparse, relative to the chemical standard (spinetoram). But when alternated with spinetoram, the effectiveness of these treatments was comparable to the spinetoram treatment. This finding suggests that the use of such effective chemistries can be reduced by half or even more by incorporating mycoinsecticides in the thrips management program, provided weather conditions are conducive to mycoinsecticides spore germination and growth. The use of chemical applications for thrips management can also be reduced by integrating biological control agents such as *Amblyseius swirskii* Athias-Henriot (Mesostigmata: Phytoseiidae) and *Orius insidiosus* (Say) (Hemiptera: Anthocoridae), which have been found effective in regulating several thrips species in both protected and open field conditions in Florida agroecosystems (Arthurs et al. 2009; Srivastava et al. 2014; Kakkar et al. 2016). The older chemistries tested in this study (acetamiprid, imidacloprid) have been reported to have moderate to harmful impact on aforementioned 2 thrips predators (Studebaker & Kring 2003; Cloyd & Bethke 2011; Srivastava et al. 2014; Roubos et al. 2014; Biobest 2017), which further encourages the integration of novel groups with low toxicity to natural enemies in the thrips management program. Further research needs to be conducted to develop the best management program to reduce the application frequency of spinetoram, including its integration with the use of mycoinsecticides.

In conclusion, our limited survey records from the *S. dorsalis* infested regions confirmed that in the USA, South Asia 1 has a wider distribution than East Asia 1. At present, multiple insecticides are available from different chemical classes for regulating their populations. However, to maintain their efficacy for a long period, growers should consider rotating insecticides with different modes of action. We believe that this study can serve as a springboard for implementing management strategies for *S. dorsalis* South Asia 1 and help growers to integrate insecticides in the preventive and curative tactics used for thrips management in the affected regions.

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