Biological Control 92 (2016) 85–91

Contents lists available at ScienceDirect

Biological Control

journal homepage: www.elsevier.com/locate/ybcon

Predation by *Neoseiulus cucumeris* and *Amblyseius swirskii* on *Thrips palmi* and *Frankliniella schultzei* on cucumber ☆

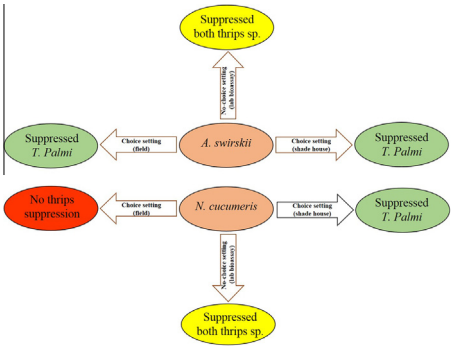
Garima Kakkar [a], Vivek Kumar [b,*], Dakshina R. Seal [c], Oscar E. Liburd [d], Philip A. Stansly [e]

[a] Fort Lauderdale Research and Education Center, University of Florida/IFAS, 3205 College Avenue, Davie, FL 33314, United States
[b] Mid-Florida Research and Education Center, University of Florida/IFAS, 2725 S. Binion Road, Apopka, FL 32703, United States
[c] Tropical Research and Education Center, University of Florida/IFAS, 18905 SW 280 Street, Homestead, FL 33031, United States
[d] Entomology and Nematology, University of Florida/IFAS, Steinmetz Hall Natural Area Dr., Gainesville, FL 32611, United States
[e] Southwest Florida Research and Education Center, University of Florida/IFAS, 2685 State Road 29 North, Immokalee, FL 34142, United States

HIGHLIGHTS

- Predator potential of two phytoseiid mites was evaluated.
- In lab bioassay, both the mites were effective in suppressing two thrips species.
- None of the mite species controlled *F. schultzei* in shade house and field trial.
- Unlike shade house, *A. cucumeris* failed to suppress *T. palmi* in field conditions.
- *A. swirskii* was consistent in suppressing *T. palmi* in all the studies.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 January 2015
Revised 30 September 2015
Accepted 6 October 2015
Available online 24 October 2015

Keywords:
Biological control
Phytoseiidae
Thrips
Predators
Melon thrips
Common blossom thrips

ABSTRACT

Thrips palmi Karny and *Frankliniella schultzei* Trybom (Thysanoptera: Thripidae) are serious pests of various crops of economic importance across the globe. Two species of phytoseiid mites were evaluated as potential predators of *T. palmi* and *F. schultzei* in the laboratory, a shade house and a commercial cucumber production field. In a no-choice lab bioassay, both *Amblyseius swirskii* (Athias-Henriot) and *Neoseiulus cucumeris* Oudemans (Mesostigmata: Phytoseiidae) preyed in equal measure on larvae of *T. palmi* and *F. schultzei* placed on leaf disks. In the shade house, mites were only recovered from leaf samples and not in flowers. Consequently, they were only effective in controlling *T. palmi* on leaves. Two rates of mites (20 and 40 mites/plant) were tested in the field. Neither species nor rate suppressed *F. schultzei* in blooms. In contrast, both rates of *A. swirskii* suppressed *T. palmi* on leaves, although the high rate acted more rapidly and therefore had a greater overall effect over the course of the 22-day study. These results suggest that *A. swirskii* can serve as an effective alternative to conventional insecticide-based management of *T. palmi* in commercial open field cucumber production in Florida.

1. Introduction

The melon thrips, *Thrips palmi* Karny (Thysanoptera: Thripidae) is a polyphagous pest of vegetable crops in various parts of the world (CABI, 1998) including Hawaii, Puerto Rico and southern parts of Florida (Capinera, 2000). Following detection in Florida

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* Corresponding author.
E-mail address: vivekiari@ufl.edu (V. Kumar).

http://dx.doi.org/10.1016/j.biocontrol.2015.10.004
1049-9644/

(Mead, 1991), *T. palmi* was reported as a serious pest of various greenhouse and field crops including, eggplant (*Solanum melongena* L.), pepper (*Capsicum annum* L.), potatoes (*Solanum tuberosum* L.), beans (*Phaseolus vulgaris* L.), and cucumber (*Cucumis sativus* L.) (Seal and Baranowski, 1992).

Adults and larvae of *T. palmi* feed preferably on foliage causing bronzing and premature abscission. Heavy infestations may result in scarred and/or deformed fruit with no marketable value (Seal et al., 2013). Besides the feeding and oviposition damage, *T. palmi* is known vector of several plant-damaging tospoviruses (Honda et al., 1989; Reitz et al., 2011). In Homestead, Florida, it has caused economic damage to all vegetable crops except tomato, emerging in recent years as a key pest of field cucumbers and posing serious threat to cucumber growers in the region (Seal per. obs.).

Appearance in Florida of a new invasive thrips species, *Frankliniella schultzei* (Trybom) (Thysanoptera: Thripidae) on various vegetable crops has further aggravated thrips problems encountered by vegetable growers in this region. Previously reported from flowers of ornamental plants in southern and central Florida (Funderburk et al., 2007), *F. schultzei* has now established on vegetable crops in southeastern region of the state (Kakkar et al., 2012a; Seal et al., 2014). Also known as a key pest of tomato in South America, *F. schultzei* has been recently associated with the economically important Tomato Chlorotic Spot Virus (TCSV) on tomato in Florida (Londoño et al., 2012). *F. schultzei* is an anthophilous pest and inhabits flowers of its host crop which can lead to improper setting of fruits or production of deformed fruit (Kakkar et al., 2012a). *F. schultzei* has been found to be most abundant in south on cucumber followed by tomato (Kakkar et al., 2012b). Together with *T. palmi*, *F. schultzei* poses a serious economic threat to cucumber and other vegetable crops in the region.

Insecticides are a primary mode of controlling thrips infesting various field crops (Bao et al., 2014; Morse and Hoddle, 2006; Seal and Kumar, 2010). However, the use of insecticides may not be the best solution to thrips problem owing to its high costs, rapid selection for resistance by rapidly reproducing thrips and adverse effects on natural enemies and environment (Herron et al., 2007; Jensen, 2000). Nevertheless, insecticides have been widely used for control of *T. palmi* in the region and the recent reports suggest reduced susceptibility to a wide range of chemical insecticides (Seal et al., 2013). There is very little known about the effectiveness of control tactics other than insecticide use for managing *F. schultzei* in cucumber in Florida. However, biological control of thrips in peppers and potential compatibility with insecticides has been well documented (Srivastava et al., 2014).

In the last two decades, predatory mites belonging to the family Phytoseiidae have received much attention as biological control agents of various vegetable pests including whiteflies, broad mites, thrips, etc. *Neoseiulus cucumeris* (Oudemans) (Mesostigmata: Phytoseiidae), a phytoseiid mite has been reported as an effective predator of several thrips species under greenhouse conditions, including onion thrips (Gillespie, 1989; Van Houten and Van Stratum, 1993) flower thrips (Jacobson, 1997; Jacobson et al., 2001; Van de Veire and Degheele, 1995) and chilli thrips (Arthurs et al., 2009). In recent years, another predatory mite species within this genus, *Amblyseius swirskii* (Athias-Henriot), has been reported in Florida as an effective predator of chilli thrips (Dogramaci et al., 2011) and *Frankliniella occidentalis* (Pergande) (Xiao et al., 2012). Considering the success of phytoseiid mites in regulating various thrips species (Brodsgaard and Stengaard Hansen, 1992; Messelink et al., 2005, 2006), we evaluated the role of *N. cucumeris* and *A. swirskii* as potential predators of *F. schultzei* and *T. palmi* inhabiting different microhabitats of the same crop. The specific objectives of this study were to (a) assess the potential of *N. cucumeris* and *A. swirskii* to control *F. schultzei* and *T. palmi* in laboratory, shade house and field, (b) compare two rates of mite application for control of thrips complex in the field, (c) investigate the persistence of predacious mites on leaves and flowers of cucumber in the field.

2. Materials and methods

2.1. Arthropods

For laboratory and shade house studies, *T. palmi* and *F. schultzei* were obtained from a commercial cucumber field infested with the two thrips species at Homestead, Florida. *A. swirskii* and *N. cucumeris* were obtained from Koppert Biological Systems Inc. (Romulus, MI). Upon arrival, mites were stored at the most for 24 h in a growth chamber maintained at 11 ± 2 °C, RH 60 ± 5%, and 14:10 h L:D until the day of release. For mite release in the field experiment, volume of bran that contained desired number of mites (20 mites/plant or 40 mites/plant) was quantified. The quantified volume was standardized by repeatedly (10 times) drawing bran from the product received from the company and counting predatory mites under a stereoscopic microscope. Individual estimates were made for *N. cucumeris* and *A. swirskii*.

2.2. Laboratory bioassay

A no-choice leaf disc bioassay was conducted following protocol of Arthurs et al. (2009) to investigate potential of two phytoseiid mites to act as predators of the two thrips species. The experimental arena consisted of a 9 cm diameter Petri dish lined on the bottom with a thin layer of moist cotton wool. A 2 cm diameter cucumber leaf disc was placed in the center of the Petri dish onto which a single female mite individual and 15 s instar larvae of one or the other of the thrips species were released. Dishes covered with thrips-proof screen (No-Thrips Insect Screens, BioQuip Products, USA) lid were placed at 25 ± 2 °C, L16: D8, and 65–70% R.H for 24 h, after which treatments were evaluated by recording the number of dead larvae. There were 6 replicates per treatment and the bioassays were repeated 5 times.

2.3. Shade house study

The study was conducted in spring 2010 to assess the biocontrol potential of two predatory mites in an open shade house that was pest free at the beginning of the study (20 ± 3.5 °C, and 75–82% R. H). Cucumber plants (*var.* 'Vlaspek') were grown from seeds in 3.8 l plastic pots. Plants were irrigated twice a day and fertilized weekly with 20-20-20 (N:P:K). Once flowering began, pots were moved adjacent to an experimental cucumber field to become infested with a naturally occurring thrips population. After 10 days, pots were brought back to the shade house and predatory mites were released on the thrips-infested plants. Treatments were *N. cucumeris* (20 adults/plant), *A. swirskii* (20 adults/plant based on preliminary data) and control (no mites). Each treatment had five replicates with each replicate comprised of five plants. Plants were assessed at the interval of five days by sampling five leaves and five flowers (one/plant) for a period of 20 days. Leaves and flowers were collected and placed by replicates in separate Ziploc bags (17 × 22 cm). Bags were transported to the Vegetable IPM laboratory, TREC, Homestead where flower samples were placed in a one-quart plastic cup with 75% ethanol for 30 min to dislodge various life stages of thrips. Thrips were extracted from the alcohol by sieving through a 25 μm grating, USA Standard Testing Sieve (W. S. Tyler, Inc.) as per Seal and Baranowski (1992). The residue in the sieve was washed off with 75% alcohol into a Petri dish and checked under a dissecting microscope at 12× to record number of thrips larvae, mites (nymphs and adults) and their eggs.

Thrips larvae, mites (nymphs and adults) and mite eggs present on leaf samples were directly counted under stereo microscope at 12× magnification. Because *T. palmi* is found mainly on leaves of cucumber plants and *F. schultzei* in flowers (Kakkar et al., 2012a) and identification of numerous larvae was impractical, thrips larvae from flowers were assumed to be *F. schultzei* and thrips from leaves *T. palmi*.

2.4. Field study

The field experiment was conducted in summer 2010 (27 ± 1.5 °C, and 78–85% R.H), at the Tropical Research and Education Center (TREC-University of Florida), Homestead, FL. Cucumber seeds (*var.* 'Vlaspek') were seeded directly into flat ground of Krome gravelly loam soil, consisting of about 33% soil and 67% limestone pebbles (>2 mm) on April 22, 2010. Seeds were spaced 15 cm within the row and 91.5 cm between rows. Fertilizer (8-16-16 N-P-K) was applied at planting, at 908 kg/ha in furrow; and halosulfuron methyl at 55 ml/ha (Sandea®, Gowan Company LLC., Yuma Arizona) was used as a pre-emergence herbicide to control weeds. Pyraclostrobin + boscalid at 0.8 l/ha (Pristine, BASF Ag Products, Research Triangle Park, NC) and chlorothalonil at 1.75 l/ha (Bravo®, Syngenta Crop Protection, Inc., Greensboro, NC) were used in rotation at two-week intervals to prevent fungal diseases. Crops were irrigated twice a week using overhead sprinklers delivering 3 cm of water. Additional fertilizer (4-0-8 N-P-K) was added once a week as an in-furrow band from the third week onward. *Bacillus thuringiensis* based insecticides, Dipel DF® (*var.* kurstaki) at 1.1 kg/ha and XenTari DF® (*var.* aizawai) at 1.2 l/ha (Valent Biosciences Corporation, Libertyville, IL) were used in rotation to control melon worms (*Diaphania hyalinata* L.) and pickle worms (*Diaphania nitidalis* Stoll).

Phytoseiid mites were evaluated as a curative (post-infestation) practice using a randomized complete plot design with 4 replications and 5 treatments: (1) *N. cucumeris* (20 mites/plant), (2) *N. cucumeris* (40 mites/plant), (3) *A. swirskii* (20 mites/plant), (4) *A. swirskii* (40 mites/plant), and (5) control (no mites). Each replicate (=block) consisted of five equal sized plots, which represented a treatment. A 4.5 m wide buffer zone was maintained between two adjacent blocks. Each plot in a block measuring 28 m^2 was also separated by a buffer zone. The buffer zones were planted to sunhemp, *Crotalaria juncea* L. to restrict movement and mixing of predatory mites among plots. *In-situ* counts were conducted during the first week of flowering on both leaves and flowers to check the abundance of thrips larvae. On detection of larvae on leaves and in flowers, a single release of *A. swirskii* and *N. cucumeris* was made by the end of first week of flowering (May 27, 2010). Mites were released from Ziplock bags filled with a standardized volume of bran + mites estimated to contain the desired number of mites per plot. Bottles were gently shaken before withdrawing bran to ensure uniform distribution of mites in the bran. Bags were perforated on the bottom and held upright above the plant canopy, 15 cm above the plants while walking at uniform speed to release a uniform number of mites. Sampling was initiated on the sixth day after mite release (June 2, 2010) and repeated at four-day intervals for the duration the study. One flower and one leaf were randomly selected from 5 plants per plot and placed by plot in Ziplock bags. Bags were transported to the Vegetable IPM laboratory, TREC, Homestead where samples were processed following the method described above.

2.5. Statistical analysis

For lab bioassay, mean number of dead larvae from the three treatments was compared using one way analysis of variance (ANOVA) (PROC GLM, SAS Institute Inc., 2003). Data was analyzed independently for the two thrips species. For the shade house and field trial, data was analyzed independently for flower and leaf samples. The mean number of thrips larvae, mites (nymphs and adults) and mite eggs was compared from all the treatments for each sample day using one way ANOVA (PROC GLM, SAS Institute Inc., 2003). Data for all the studies were transformed, if necessary, either using square root or $\log_{10}(x+1)$ to homogenize variance before analysis. Differences among treatment means for sampling dates were separated using the Tukey's honestly significant difference (HSD) mean separation test ($\alpha = 0.05$).

For the field study, density of arthropods on leaves was also expressed as accumulated mite × days and *T. palmi* × days per leaf for the five treatments and compared using ANOVA. Accumulated thrips and mite days on flowers was not estimated due to low number/absence of mites on flowers in this study. Mite days and *T. palmi* days were calculated by averaging the count of mites and *T. palmi* over successive pairs of sampling days per leaf multiplied by four (number of intervening day between two samplings) and accumulated over the entire study period:

$$\left[\left(\frac{x_n + x_{n+4}}{2}\right) \times t\right]$$

where x_n = number of mites or *T. palmi* at *n*th sampling and t is number of intervening days between two successive samplings. All the analysis for this study was done on Statistical Analysis System (SAS Institute Inc., 2003).

3. Results

3.1. Laboratory bioassay

The two phytoseiid mite species consumed larvae of *F. schultzei* and *T. palmi* on leaf disks in equal numbers. Thrips mortality was significantly greater on leaf disks receiving either of the two predatory mites (*A. swirskii* and *N. cucumeris*) compared to control, with no significant differences between either mite species or thrips species (Fig. 1).

3.2. Shade house study

3.2.1. Population abundance of N. cucumeris and A. swirskii

Mite eggs and motile stages were found only on leaf samples obtained from treated plants, while none were recovered from flower samples. Mite eggs were first observed on *A. swirskii* treated plants at 5 DAR and later on plants receiving *N. cucumeris* at 10 DAR. Observation of eggs at all subsequent sample dates indicated that mites of both the species reproduced throughout the study

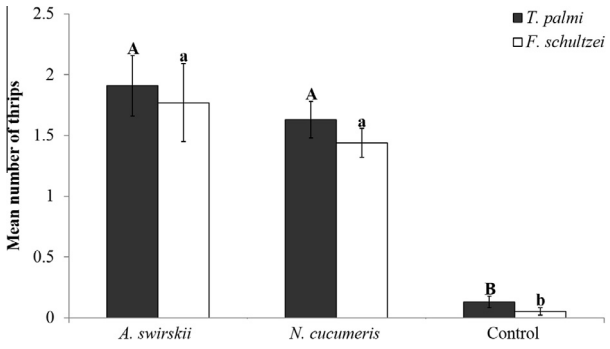

Fig. 1. Daily consumption of *F. schultzei* and *T. palmi* larvae by two phytoseiid mites in leaf disc bioassays. Control represents natural mortality. Uppercase letters show significant differences ($P > 0.05$, Tukey's HSD test) between mite treatments for *Thrips palmi*; lowercase letters show significant differences ($P > 0.05$, Tukey's HSD test) between mite treatments for *F. schultzei*.

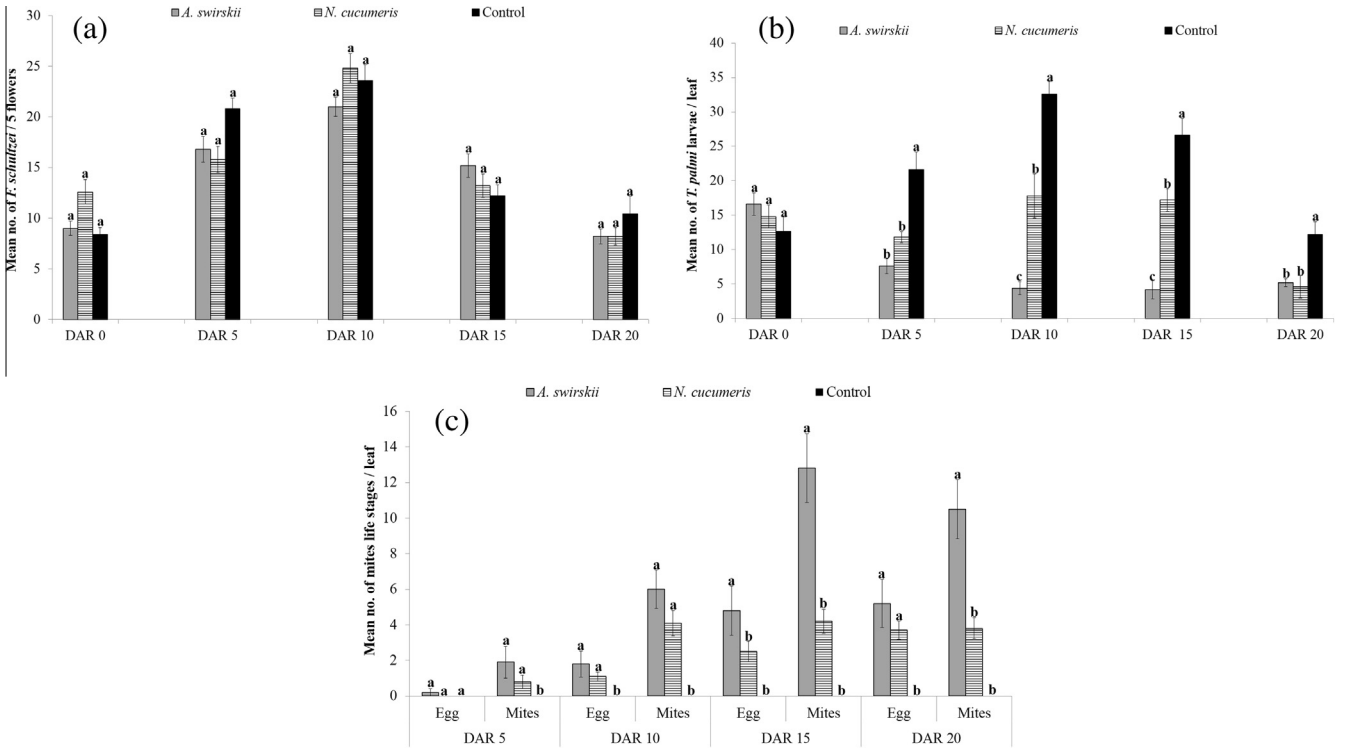

Fig. 2. (a) Number of *F. schultzei* larvae (mean ± SEM) per 5 flowers sampled on four sampling dates after the release of *N. swirskii* and *N. cucumeris*. Mites were released on day 0. On each day of sampling, treatments with no letters are not significantly different ($P > 0.05$, Tukey's HSD test). (b) Number of *T. palmi* larvae (mean ± SEM) per cucumber leaf sampled on four sampling dates after the release of *N. swirskii* and *N. cucumeris*. Mites were released on day 0. On each day of sampling, treatments with no letters are not significantly different ($P > 0.05$, Tukey's HSD test). (c) Number of mites (mean ± SEM) per cucumber leaf sampled on four sampling days from three treatment plots: (1) *N. cucumeris* (20 mites/plant), (2) *A. swirskii* (20 mites/plant), and (3) Control. Means for each sampling with the same letter are not significantly different ($\alpha = 0.05$) by Tukey's HSD test.

(Fig. 2a). However, more mites were found on plants receiving *A. swirskii* than *N. cucumeris*, with significant differences observed during the last two samplings (DAR 15 and DAR 20).

3.2.2. Effect of mites on thrips populations

Host plants were found infested with *T. palmi* and *F. schultzei* soon after being placed next to infested cucumber field. Both the thrips species were found on cucumber plants throughout the study (Fig. 2b and c). Numbers of *F. schultzei* in flowers increased through 10 days after mite release (DAR), then declined through 20 DAR with no significant effect from either mite species (Fig. 2b). In contrast, both the mites suppressed *T. palmi* larvae at all sample dates (Fig. 2c). *A. swirskii* was more effective in suppressing the *T. palmi* population compared with *N. cucumeris* with fewer than 8 larvae/leaf compared with 17/leaf, respectively.

3.3. Field study

3.3.1. Abundance of mites in cucumber flowers

Few mites were recovered from flower samples of plants receiving either *A. swirskii* or *N. cucumeris* (Table 1). Most *N. cucumeris* mites on flowers were captured at 6 and 10 DAR from plots treated with the high and low rate of mites, respectively (Table 1). Mites were not recovered from control plants which were not significantly different from treated plots during the study.

3.3.2. Abundance of mites on cucumber leaves

Numbers of *N. cucumeris* on cucumber leaves fluctuated throughout the study with most observed at 6 DAR although not significantly different than the control (Table 2). The egg count on plants receiving *N. cucumeris* at the high rate was also greatest at 6 DAR (Table 3). The number of eggs on leaf samples in plots receiving low and high rate of *N. cucumeris* was not different for the entire study period. Accumulated mite days per leaf was low and not significantly different from the control (Table 4). Numbers of *A. swirskii* on leaves was high on the 10 DAR, especially in response to the high release rate of *A. swirskii* (Table 2). Mite numbers subsequently decreased with the high rate but continued to increase with the low rate such that more mites were found with the low rate at 14 and 22 DAR. Egg densities followed similar trends (Table 3). These effects were seen in the number of mite × days which were greatest for the high rate of *A. swirskii*, followed by the low rate and then either rate of *N. cucumeris* which were not different from the control (Table 4).

3.3.3. Effect of mites on thrips populations

Neither of the two treatment rates of *N. cucumeris* (20 and 40 mites/plant) or *A. swirskii* (20 and 40 mites/plant) was effective in reducing the *F. schultzei* population inhabiting flowers of cucumber plants (Fig. 3). Mean numbers of *F. schultzei* in various treatment plots did not differ from control plants except on the 14 DAR. More *F. schultzei* were found on plants receiving *N. cucumeris* than control plants at 14 DAR (Fig. 3).

In contrast, the high rate of *A. swirskii* (40 mites/plant) significantly reduced the *T. palmi* population from 6 DAR onward (Fig. 4). The low rate of *A. swirskii* was also effective at 14 DAR and 18 DAR. Significantly fewer thrips were seen with the high compared to low release rate of *A. swirskii* on 6 and 10 DAR but not at 14, 18 and 22 DAR. However, both rates of *N. cucumeris* showed significant reduction of *T. palmi* only at 18 DAR (Fig. 4). *T. palmi* × days over the study period were greatest for the control receiving no mite releases, followed by either rate of *N. cucumeris* and the low rate of *A. swirskii*, which were not significantly different, and least for the high rate of *A. swirskii* (Table 4).

Table 1
Number of mites (mean ± SEM) per 10 flowers sampled on five sampling days from five treatment plots: (1) Low rate of *N. cucumeris* (20 mites/plant), (2) High rate of *N. cucumeris* (40 mites/plant), (3) Low rate of *A. swirskii* (20 mites/plant), (4) High rate of *A. swirskii* (40 mites/plant) and (5) Control.

		Mean numbers of mites recovered				
Treatments		6 DAR	10 DAR	14 DAR	18 DAR	22 DAR
A. cucumeris	Low rate (20 mites/plant)	0.16 ± 0.10a	0.33 ± 0.30a	0a	0a	0.16 ± 0.10a
	High rate (40 mites/plant)	0.50 ± 0.30a	0.16 ± 0.10a	0a	0a	0a
A. swirskii	Low rate (20 mites/plant)	0.50 ± 0.20a	0.33 ± 0.30a	0a	2.33 ± 1.5a	0.50 ± 0.34a
	High rate (40 mites/plant)	0.16 ± 0.10a	0.16 ± 0.10a	1.00 ± 0.68a	2.00 ± 1.3a	0.33 ± 0.33a
Control		0a	0a	0a	0a	0a

Means in columns followed by the same letter are not significantly different (6th DAR: $F = 1.12$; df = 4, 15; $P = 0.36$; 10th DAR: $F = 0.35$; df = 4, 15; $P = 0.84$; 14th DAR: $F = 1.63$; df = 4, 15; $P = 0.19$; 18th DAR: $F = 1.90$; df = 4, 15; $P = 0.14$; 22nd DAR: $F = 1.63$; df = 4, 15; $P = 0.19$).

Table 2
Number of mites (mean ± SEM) per leaf sampled on five sampling days from treatment plots: (1) Low rate of *N. cucumeris* (20 mites/plant), (2) High rate of *N. cucumeris* (40 mites/plant), (3) Low rate of *A. swirskii* (20 mites/plant), (4) High rate of *A. swirskii* (40 mites/plant) and (5) Control.

		Mean number of mites recovered				
Treatments		6 DAR	10 DAR	14 DAR	18 DAR	22 DAR
A. cucumeris	Low rate (20 mites/plant)	0.53 ± 0.19a	0c	0.06 ± 0.06c	0.20 ± 0.1b	0b
	High rate (40 mites/plant)	0.93 ± 0.18a	0.20 ± 0.10c	0.46 ± 0.10c	0.60 ± 0.3b	0b
A. swirskii	Low rate (20 mites/plant)	2.80 ± 0.25a	12.53 ± 2.0b	26.46 ± 2.5a	24.60 ± 7.5a	16.00 ± 2.1a
	High rate (40 mites/plant)	1.93 ± 0.50a	67.40 ± 4.74a	9.13 ± 1.6b	11.93 ± 2.8a	4.80 ± 0.5b
Control		0a	0c	0c	0b	0b

Means in columns followed by the same letter are not significantly different (6th DAR: $F = 1.61$; df = 4, 95; $P < 0.37$; 10th DAR: $F = 81.68$; df = 4, 95; $P < 0.0001$; 14th DAR: $F = 26.82$; df = 4, 95; $P < 0.0001$; 18th DAR: $F = 11.16$; df = 4, 95 $P < 0.0001$; 22nd DAR: $F = 3.23$; df = 4, 95; $P < 0.0001$).

Table 3
Number of mite eggs (mean ± SEM) per leaf sampled on five sampling days from treatment plots: (1) Low rate of *N. cucumeris* (20 mites/plant), (2) High rate of *N. cucumeris* (40 mites/plant), (3) Low rate of *A. swirskii* (20 mites/plant), (4) High rate of *A. swirskii* (40 mites/plant) and (5) Control.

		Mean number of mite eggs				
Treatments		6 DAR	10 DAR	14 DAR	18 DAR	22 DAR
A. cucumeris	Low rate (20 mites/plant)	0.13 ± 0.09a	0.20 ± 0.10b	0.11 ± 0.08b	0b	0b
	High rate (40 mites/plant)	0.80 ± 0.30a	0.20 ± 0.10b	0b	0b	0.40 ± 0.13b
A. swirskii	Low rate (20 mites/plant)	0.60 ± 0.0a	5.40 ± 1.20a	10.00 ± 2.40a	6.00 ± 2.00a	15.00 ± 2.55a
	High rate (40 mites/plant)	1.20 ± 0.71a	16.93 ± 1.56a	5.40 ± 1.00ab	5.80 ± 2.02a	2.80 ± 0.68b
Control		0a	0b	0b	0b	0b

Means in columns followed by the same letter are not significantly different (6th DAR: $F = 1.03$; df = 4, 95; $P = 0.41$; 10th DAR: $F = 60.76$; df = 4, 95; $P < 0.0001$; 14th DAR: $F = 9.98$; df = 4, 95; $P < 0.0001$; 18th DAR: $F = 7.24$; df = 4, 95; $P < 0.0001$; 22nd DAR: $F = 8.23$; df = 4, 95; $P < 0.0001$).

Table 4
Number of cumulative *Thrips palmi* × days (mean ± SEM) and mite × days (mean ± SEM) per leaf on five sampling days from the following treatment plots: (1) Low rate of *N. cucumeris* (20 mites/plant), (2) High rate of *N. cucumeris* (40 mites/plant), (3) Low rate of *A. swirskii* (20 mites/plant), (4) High rate of *A. swirskii* (40 mites/plant) and (5) Control.

Treatment	*Thrips palmi* × days (No./leaf)	Mite × days (No./leaf)
A. cucumeris (low rate)	947.73 ± 53.8b	1.93 ± 0.2c
A. cucumeris (high rate)	1108.47 ± 56.78b	4.63 ± 0.6c
A. swirskii (low rate)	800.07 ± 48.9b	160.53 ± 16.5b
A. swirskii (high rate)	266 ± 8.8c	282.90 ± 14.0a
Control	1303.63 ± 64.57a	0c

Means in columns followed by the same letter are not significantly different when compared by Tukey's ($\alpha = 0.05$). *Thrips palmi* × days: $F = 54.76$; df = 4, 295; $P < 0.0001$; Mite × days: $F = 173.76$; df = 4, 295; $P < 0.0001$).

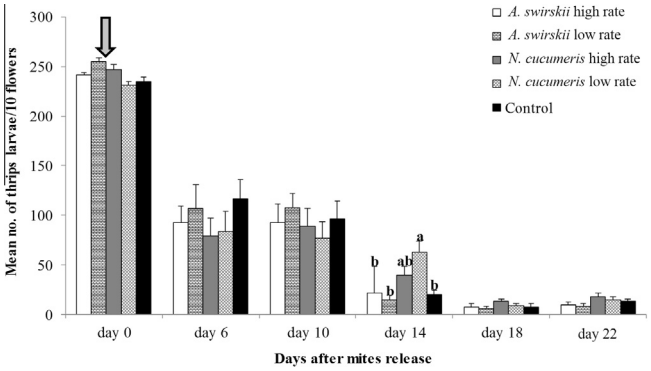

Fig. 3. Number of *F. schultzei* larvae (mean ± SEM) per 10 flowers sampled on five sampling dates after the release of *A. swirskii* (high rate and low rate) and *N. cucumeris* (high rate and low rate). Mites were released on day 0 indicated by an arrow. On each day of sampling, treatments with no letters are not significantly different ($P > 0.05$, Tukey's HSD test).

4. Discussion

Lab study demonstrated the predatory potential of *N. cucumeris* and *A. swirskii* on *T. palmi* and *F. schultzei* larvae when tested on leaves under no-choice conditions. The two phytoseiid mites were effective in shade house and field trial against *T. palmi* on cucumber leaves, but failed to control *F. schultzei* in flowers. These results are in agreement with Arevalo et al. (2009) who found that phytoseiid mites were not effective in regulating flower thrips

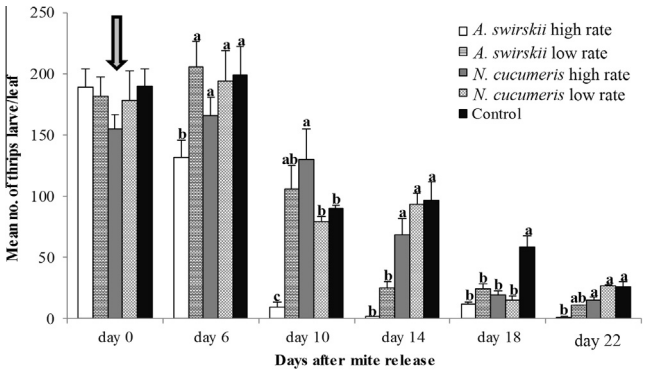

Fig. 4. Number of *T. palmi* larvae (mean ± SEM) per cucumber leaf sampled on five sampling dates after the release of *A. swirskii* (high and low rate) and *N. cucumeris* (high and low rate). Mites were released on day 0 indicated by an arrow. On each day of sampling, treatments with same letter are not significantly different ($P > 0.05$, Tukey's HSD test).

inhabiting blueberry and pepper flowers, respectively. In the present study, few mites were recovered from flowers of thrips-infested plants receiving *N. cucumeris* or *A. swirskii*, which can explain their apparent inability to control *F. schultzei*. Low mite density in flowers could be due to behavioral preference for *T. palmi* vs. *F. schultzei* or the microhabitat (leaves vs. flowers), as leaves may have provided an open arena for mite-thrips encounter, better refuge and breeding area in comparison to flowers for the two mite species.

A biological control study by Chow et al. (2008) suggested that *Orius insidiosus* (Say) often switched between available preys on a particular crop. They reported that this generalist predator prefers feeding on easily available prey whether foraging on flowers or foliage. Similarly, we speculate that the presence of an abundant *T. palmi* population on cucumber leaves might have been an important factor resulting in low persistence of mites on flowers leading to failure of *F. schultzei* control in the shade house. Had there been no food available on leaves, the mite would likely have moved to flowers since both species are known to feed on pollen (Swirskii et al., 1967; Kumar et al., 2014; Ranabhat et al., 2014; Avery et al., 2014). For this reason, we released the double dose of mites (40 mites/plant) in the field study with expectation that *T. palmi* population will be suppressed to a level which will compel mites to forage in flowers. However, high numbers of thrips larvae were present on leaves throughout the study except for the last sample date in the high *A. swirskii* release treatment (Fig. 4). We speculate that higher *T. palmi* density in the field compared with the shade house provided sufficient food for mites which were therefore not compelled to forage in flowers, although our observation do not allow us to assure this.

Numbers of *T. palmi* within plots treated with two rates of *A. swirskii* were found to be significantly lower than in control plots. The high rate of *A. swirskii* performed better than the low rate by providing significant suppression of *T. palmi* within a week of application. Populations of *A. swirskii* in low rate treated plots took longer to build up to sufficient numbers but were effective against *T. palmi* at 14 DAR. Here we speculate that the early application of the lower dose of *A. swirskii* before arrival of thrips or threshold number of thrips is reached could have provided adequate suppression at lower cost. Early application of *A. swirskii* supplemented with pollen or other food resource might allow mites to adapt, reproduce and establish successfully in the host crop in order to suppress an upcoming thrips populations (Kumar et al., 2015). Thus, the application of a low rate of *A. swirskii* into a 2-week old crop with low thrips infestation could perform better in regulating thrips population than the application in a highly infested 4 week old crop as in our study.

N. cucumeris was effective in regulating *T. palmi* in the lab bioassay and shade house study, but exhibited little ability to control *T. palmi* in the field trial. Populations of *N. cucumeris* were also low during most of the cropping season compared to *A. swirskii* (Tables 2 and 3). Significant thrips suppression by *N. cucumeris* in the field trial was only observed at 18 DAR by which time thrips numbers had decreased greatly in the control. Such delayed response by *N. cucumeris* towards prey could be due to their slow rate of adaptability to the environment. Competition with *A. swirskii* cannot explain these results because the sunhemp barriers were apparently effective in limiting movement of mites among plots as indicated by their absence in controls. Thus, sampled mites were assumed to be the same as the released species during the study. Results from our study agree with Arthurs et al. (2009) who reported that *A. swirskii* performed better than *N. cucumeris* in regulating another thrips pest species under landscape conditions. Similarly, Stansly and Castillo (2010) observed poor persistence and control of broad mites and whiteflies with *N. cucumeris* compared to *A. swirskii* in on open field pepper and eggplant in south Florida. These results suggest that *A. swirskii*, which is of Mediterranean origin with an optimum temperature for survival and growth of 20–32 °C (Lee and Gillespie, 2011) may be better adapted to temperatures in Florida than *N. cucumeris*.

Our results demonstrate that *A. swirskii* can provide effective control of *T. palmi* that may rival the effectiveness of chemical control strategies generally used for management of this pest. Application of chemical insecticides on a calendar basis is expensive, and could inflict long-term ecological and environmental damage. Furthermore, *T. palmi* has been known to exhibit reduced susceptibility towards various groups of insecticides including spinosad (Seal et al., 2013; Bao et al., 2014), further favoring biological control of this pest. The use of generalist predatory mites may not only reduce the cost of chemicals and labor, but would also target multiple pests (thrips, whiteflies, broad mites) of vegetable productions (Nomikou et al., 2002; Messelink et al., 2008; Arthurs et al., 2009; Stansly and Castillo, 2010; Dogramaci et al., 2011; Calvo et al., 2011; Xiao et al., 2012), thereby increasing the reliability of biological control strategies and reducing overall insecticide use.

5. Conclusion

Few studies have evaluated mites as predator of thrips species in uncontrolled field conditions (Arevalo et al., 2009; Fraulo and Liburd, 2007). We observed significant potential for control of *T. palmi* by *A. swirskii* in both shade house and field condition. In contrast, *N. cucumeris* was not found to be effective in shade house and neither mite species controlled *F. schultzei* in blooms. Future studies are necessary to evaluate the predation potential of phytoseiid mites on *F. schultzei* in the absence of *T. palmi*. It will be interesting to see if the higher rates of phytoseiid mites can control the two co-existing thrips species on cucumber, and the possible role of plant structure in differential predation behavior of phytoseiid mites.

Acknowledgments

We thank vegetable IPM laboratory (TREC-UF) members for technical support and field preparations. Funding for this study was provided through grants by Florida Agricultural Experiment Station and the University of Florida's Center for Tropical

Agriculture. We are grateful to Ms. Catherine Sabine for technical support and suggestions in manuscript preparation. Mention of a proprietary product does not constitute endorsement by the University of Florida.

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