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This contribution is dedicated
to the memory of Prof. Dan Gerling,
a scientist, a colleague and a friend

Management of insect and mite pests with predaceous mites in open-field vegetable crops

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ABSTRACT

Mites of the family Phytoseiidae (Acari) have been widely used to control vegetable pests in greenhouses, but less is known of their effectiveness in open field crops. Sweet potato whitefly *Bemisia tabaci* (Gennadius), broad mite *Polyphagotarsonemus latus* (Banks), spider mites *Tetranychus evansi* (Baker & Pritchard) and *T. urticae* (Koch), and melon thrips *Thrips palmi* (Karny) are serious pests that cause economic damage to many vegetables crops. Predatory mites *Amblyseius swirskii* Athias-Henriot and *Neoseiulus californicus* McGregor (Phytoseiidae) are used routinely to control these pests in greenhouse specialty crops and have shown potential in trials with open field eggplant and pepper in Florida. Here we report results from field experiments aimed at four specific objectives: (1) assess effectiveness on different host plants, (2) assess release time and the value of providing supplemental food for predaceous mites in the field, (3) compare results with mixtures of two predaceous mite species compared to rotations or single species releases, and (4) compare control obtained with predaceous mites to that of standard pesticides. All experiments were conducted on eggplant (*Solanum melongena* L.) with some also including zucchini squash (*Cucurbita pepo* L.), cantaloupe (*Cucumis melo* L.) or pepper (*Capsicum annuum* L.).

Notable reductions of target pests were observed with most treatments receiving releases of predacious mites soon after transplanting. Predacious mites persisted longer and control was more notable on eggplant, probably due to higher pest populations than on other crops tested. Although no effect on pest control was seen from pollen of *Typha latifolia* L. and dried fruit mite (*Carpoglyphus lactis* (L.)) applied as supplementary food just after planting, evidence for competitive interactions among mite species suggests its potential importance. Such competition was observed when both mites were released in a mixture although spider mite control appeared to improve when the two predators were released in succession. In contrast, broad mite and whitefly were best controlled by releases of *A. swirskii* alone. In general, biological control was more effective than chemical control for broad mites, comparable for spider mites but less effective for whiteflies. These results confirm earlier studies attesting to the effectiveness of these mites to control several key pests of fruiting vegetable crops while also indicating that more work is needed on the practical aspects of this strategy for open field crops.

KEYWORDS: Agricultural pests, biocontrol, *Bemisia*, *Polyphagotarsonemus*, *Tetranychus*, *Thrips*, Phytoseiidae.

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RESUMEN

Los ácaros de la familia Phytoseiidae (Acari) son ampliamente utilizados para controlar plagas vegetales en invernaderos, pero su efectividad es menos conocida en cultivos de campo abierto. Mosca blanca de la batata *Bemisia tabaci* (Gennadius), ácaro blanco *Polyphagotarsonemus latus* (Banks), arañuelas *Tetranychus evansi* (Baker & Pritchard) y *T. urticae* (Koch), y trips del melón *Thrips palmi* (Karny) son plagas graves que causan daño económico a muchos cultivos de hortalizas. Los ácaros depredadores *Amblyseius swirskii* Athias-Henriot y *Neoseiulus californicus* McGregor (Phytoseiidae) se usan rutinariamente para controlar estas plagas en cultivos especializados de invernadero, y han demuestrado su potencial en ensayos con berenjena y pimiento en campo abierto en Florida. Aquí informamos resultados de experimentos de campo dirigidos a cuatro objetivos específicos: (1) evaluar la efectividad en diferentes plantas hospedadoras, (2) evaluar el tiempo de liberación y el valor de proporcionar alimentos suplementarios para ácaros depredadores en el campo, (3) comparar resultados con mezclas de dos especies de ácaros depredadores en comparación con rotaciones o liberaciones de especies únicas, y (4) para comparar el control obtenido con los ácaros depredadores con el de los plaguicidas estándar. Todos los experimentos se realizaron en berenjena (*Solanum melongena* L.), algunos también incluyeron calabaza calabacín (*Cucurbita pepo* L.), melón cantalupo (*Cucumis melo* L.) o pimienta (*Capsicum annuum* L.).

Se observaron reducciones notables de las plagas objetivo en la mayoría de los casos después de las liberaciones de ácaros depredadores poco después del trasplante. Los ácaros depredadores persistieron durante más tiempo, y el control fue más notable en la berenjena, probablemente debido a las poblaciones de plagas más altas que en otros cultivos. La evidencia de interacciones competitivas entre especies de ácaros sugiere su importancia potencial. Tal competencia se observó cuando ambos ácaros se liberaron en una mezcla, aunque el control de ácaros parecía mejorar cuando los dos depredadores fueron liberados en sucesión. Por el contrario, el ácaro blanco y la mosca blanca se controlaron mejor con liberaciones de *A. swirskii* en solitario. En general, el control biológico fue más efectivo que el control químico para los ácaros anchos, comparable para los ácaros araña pero menos efectivo para las moscas blancas. Estos resultados confirman la efectividad de estos ácaros como agentes de control biológico para varias plagas clave de cultivos de hortalizas.

PALABRAS CLAVE: Ácaros depredadores, control biológico, plagas agrícolas, *Bemisia*, *Polyphagotarsonemus*, *Tetranychus*, *Thrips*, Phytoseiidae.

INTRODUCTION

Fresh market vegetable production is an important industry in Florida, with approximately 75,600 ha harvested in 2012 yielding 2.1 million tons of fresh produce with an estimated monetary value of 1.15 billion US dollars (FDACS 2013). Cucurbit and solanaceous crops predominate, accounting for 71 % of total Florida production, with most cultivated in the open field.

The whitefly *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), broad mite *Polyphagotarsonemus latus* (Banks) (Acari: Tarsonemidae), the spider mites *Tetranychus evansi* (Baker & Pritchard) and *T. urticae* (Koch) (Acari: Tetranychidae), and melon thrips *Thrips palmi* Karny (Thysanoptera: Thripidae) are serious pests of fruiting vegetables. The invasion of Florida by the *B. tabaci* biotype B also known as Middle East Asia Minor 1 (MEAM1, Dinsdale *et al*. 2010) in the late 1980s raised the status of 'silverleaf' whitefly to key pest due to broad host range, high populations, damage potential, and especially virus transmission (Polston *et al*. 1993). Broad mites can cause serious damage in peppers and eggplants including leaf distortion, flower abortion and fruit russeting (Webb *et al*. 2010). Broad mites are phoretic on whiteflies, so the two pests often occur together (Parker & Gerson 1994). Spider mites feed on epidermal cell contents and high infestations reduce net photosynthetic rate and ultimately yield and quality (Meck *et al*. 2013). Melon trips attack many vegetable crops, damaging foliage, especially terminal growth, which may become discolored, stunted and deformed. Fruits may also be scared, deformed or abort (Kawai 1986).

Vegetable pest management in Florida largely relies on insecticides and acaricides. Early soil applications of systemic neonicotinoids are used to reduce whitefly infestation levels and viruses spread, and a variety of pesticides are sprayed to provide additional control of these as well as broad mites and spider mites (Webb *et al*. 2010). However, intensive use of pesticides poses health and environmental risks as well as selecting for resistance in target and non-target pest populations.

Predatory mites of the family Phytoseidae such as *Neoseiulus cucumeris* (Oudemans), *Amblyseius swirskii* Athias-Henriot and *Neoseiulus californicus* (McGregor) are commonly used to control these pests in greenhouse crops (Gerson & Weintraub 2007). *Neoseiulus cucumeris* has been shown to provide effective control of broad mite on greenhouse grown pepper (Weintraub *et al*. 2003; Gerson & Weintraub 2007); *A. swirskii* will feed and develop on whiteflies (Nomikou *et al*. 2001) and controls *B. tabaci* on protected pepper and cucumber crops (Calvo *et al*. 2006, 2011) and broad mite on pepper (van Maanen *et al*. 2010). *Neoseiulus californicus* controls spider mites on pepper (Weintraub & Palevsky 2008) and has also been shown to be effective against broad mites (Peña & Osborne 1996; Jovicich *et al*. 2009).

Although relatively numerous studies have been conducted in greenhouses, little research has been reported for open field crops. However, some promising results have been produced. For example, Stansly and Castillo (2009, 2010) reported superior control of both broad mite and *B. tabaci* with a single release of *A. swirskii* three weeks after transplanting compared to two applications of spiromesifen in open field pepper and eggplant. Also, Kakkar *et al*. (2016) demonstrated significant suppression of *T. palmi* but not the flower inhabiting *Frankliniella schultzei* Trybom following releases of *A. swirskii* on open field cucumber in south Florida. However, control of spider mites, which seek protection from predators under webbing (Messelink *et al*. 2010) was less than satisfactory with *A. swirskii* alone.

Combinations of predatory mite species may be necessary for effective control of these pests (Messelink *et al*. 2010). Stansly and Castillo (2010) found that *N. californicus* persisted for about a month and *A. swirskii* for about 1.5 months when released as a mixture within a week of transplanting in open field eggplant. Whitefly control was limited to two weeks following release, whereas spider mites and broad mites were almost eliminated through eight weeks.

However, two natural enemies sharing the same ecological niche may interact in different and often unpredictable ways (Müller & Brodeur 2002; Çakmak *et al.* 2006). The ability of natural enemies to persist and disperse in the crop often depends on availability of alternate food sources (Nomikou *et al*. 2010). Most plants provide pollen with which both species can survive (Goleva & Zebitz 2013), and some plant species such as pepper also provide floral and extrafloral nectar (Shipp & Ramakers 2004). Both pollen or saprophagous mites such as *Tyrophagus putrescentiae* (Schrank) have been used as alternative diets for Phytoseiidae (Nomikou *et al*. 2010).

We investigated use of the predatory mites, *A. swirskii* and *N. californicus*, either alone or in combination for management of broad mites, spider mites and whiteflies in eggplant, pepper, melon and squash. Host plant effects, influence of alternative food sources on persistence and efficiency for control of these pests, comparisons of mixtures versus rotations of mites, and mites in combination with the entomopathogenic fungus *Metarhizium anisopliae* (Metsch.) and control compared to standard pesticides were evaluated. The overall objective was to advance implementation of more efficient biological control programs in these and other open field crops.

MATERIALS AND METHODS

All trials were conducted at the IFAS/SWFREC research facility near Immokalee, Florida, on single row raised beds 81 cm (32 in) wide, 128 m (420 ft) long and 20 cm (8 in) high. Granular 10-2-10 NPK fertilizer was incorporated before planting at a rate of 121 kg N/ha (100 lbs per acre). Beds were then fumigated with 121 kg/ha 50:50 methyl bromide + chloropicrin, two drip tapes with 20.3 cm (8 in) emitter spacing were laid down and beds were covered with whiteface (fall) or black (spring) polyethylene film mulch. *A. swirskii* and *N. californicus* were provided by Koppert Biological Systems, Howell, MI. Broad mite, whitefly, spider mite and phytoseiid populations were monitored weekly. Generally, eight leaves per plot were sampled, one from the upper and lower parts of four plants, and examined under a dissecting microscope (10×) for broad mite and spider mite eggs, larvae, nymphs and adults, whitefly eggs and nymphs. Predatory mites were counted live and distinguished by body form (flatter for *N. californicus*) and opisthosomal setal length (Z4 and Z5 longer on *A. swirskii*, even for nymphs (Denmark & Evans 2011)). Sampled mites were slide-mounted for detailed assessment under a light microscope (100×) based on the method of Denmark and Evans (2011).

Experiment 1: Eggplant and zucchini squash, fall 2010

This experiment had four objectives: (1) to evaluate efficacy of *A. swirskii* and *N. californicus* released simultaneously immediately prior to or shortly after planting, (2) assess dispersal of predator mites from plots, (3) compare control using these mites with an application of 23.1% spiromesifen (Oberon® 2 SC, Bayer Crop Science, Research Triangle Park, NC), and (4) assess the effect of host plant on biological control using *A. swirskii* and *N. californicus*.

A split-plot randomized complete block design with four replications was used with crop as the whole plot factor. Plants were distributed in four parallel single row beds on 1.8 m (6 ft) between bed centers. Half of each row was planted with seedling 'Black Beauty' zucchini squash, *Cucurbita pepo* (L.), and half with seedling 'Night Shadow' eggplant, *Solanum melongena* L. var. *esculentum*. Plots were assigned to five subplot treatments: (1) release of *A. swirskii* and *N. californicus* in the planting tray immediately before planting (21 Sept.), (2) release of *A. swirskii* and *N. californicus* in the field shortly after planting (22 Sept.), (3) 'dispersal' plots contiguous with release plots, (4) a foliar application of Oberon 2 SC at 0.62 L/ha, and (5) untreated controls isolated by Oberon-treated plants. Each plot contained 20 plants set 60 cm apart (total plot length, 12.8 m). Both species of predacious mite were released simultaneously at approximately 30 mites per plant based on substrate volume. Oberon 2 SC was applied 27 Oct. using a high-clearance sprayer operating at 13.8 bar (200 psi) and 3.7 k/h. Spray was delivered through two vertical booms each fitted with four Albuz® yellow (Coors Tek, Rosevile, MN) hollow-cone nozzles, each nozzle applied 94 L/ha (10 gpa) each for a total of 751 L/ha (80 gpa). The fungicides Quadris Opti® (azoxystrobin + chlorothanonil, Syngenta Crop Protection, Greensboro, NC) was applied 15 and 29 Nov. and Tanos® (famoxadone + cymoxanil, DuPont de Nemours, Wilmington, DE) on 22 Nov. to squash for disease control.

Experiment 2: Eggplant and cantaloupe, spring 2011

The objective of this experiment was to assess the effect of provisioning *A. swirskii* and *N. californicus* with pollen and/or dried fruit mite, *Carpoglyphus lactis* (L.) (Acari: Carpoglyphidae), as alternative foods when released among field pest populations. Treatment effects were assessed on two host plant species: eggplant ('Night Shadow') and 'Athena' cantaloupe, *Cucumis melo* (L.) var. *cantalupensis*. Half of each row was planted to cantaloupe and half to eggplant on 21 Mar. Biological and chemical control was also compared on eggplant.

Each plot again contained 20 plants planted 60 cm apart (total plot length, 12.8 m). Treatments in eggplant arranged in a randomized complete block design (N=4) were as follows: (1) mix of *A. swirskii*, *N. californicus* and *C. lactis*, (2) mix of *A. swirskii* and *N. californicus*, (3) and (4) a soil application of Platinum® SG (75% thiamethoxam) followed by foliar applications of Agri-Flex® (3% abamectin+ 13.9% thiamethoxam) or Agri-Mek® SC (8% abamectin) respectively (all Syngenta Crop Protection, Greensboro, NC), and (5) an untreated control. Treatments in cantaloupe included: (1) *A. swirskii* alone, (2) *C. lactis* alone, (3) mix of *A. swirskii* and *C. lactis*, (4) mix of *A. swirskii* and pollen, and (5) untreated control. We did not release *N. californicus* in cantaloupe because this plant is a suboptimal host for spider mite. Pollen was collected from cattail, *Typha latifolia* L. and kept frozen until use; *C. lactis* originally obtained from Lance Osborne (UF-IFAS-MFREC-Apopka) was reared on Honey Nut Cheerios® (General Mills, Minneapolis, MN). Thirty mites of each predacious species, 0.5 ml of pollen, and 5 ml of *C. lactis* in wheat bran substrate were applied per plant in appropriate plots in the transplant tray at planting (21 Mar.) and in the field a week after planting. Platinum SG was applied to the soil on 8 Apr at 140 g/ha (2 oz/ac) in 120 ml water per plant. Agri-Flex at 0.62 L/ha (8.5 fl oz/ac) and Agri-Mek SC at 0.18 L/ha (2.5 fl oz/ac) were sprayed on plants in pesticide plots on 15 Apr., 12 May and 6 June. We conducted a second release as described above of both predacious mite species on eggplant and *A. swirskii* in cantaloupe on 26 Apr. because of persistent whitefly and spider mite populations. Pests and mites were monitored weekly beginning 5 Apr. as above except that four leaves were sampled from two plants per plot.

Experiment 3: Eggplant, fall 2011

Our objective was to evaluate efficacy of *A. swirskii* and *N. californicus* alone, in rotation and in mixtures. Eggplant ('Zebra') seedlings were transplanted 13 Sep. 60 cm apart in four rows as described above. Each row was considered a replicate and divided into six plots containing 18 plants 60 cm apart separated by a buffer plot with the same number of plants. Treatments were arranged in a randomized complete block design and included: (1) 30 *A. swirskii* per plant, (2) 30 *N. californicus* per plant, (3) a mixture of 30 *A. swirskii* and 30 *N. californicus* per plant, (4) 30 *A. swirskii* released first followed by 30 *N. californicus* one week later, (5) 30 *N. californicus* released first followed by 30 *A. swirskii* one week later, and (6) an untreated control without mite releases. Mites were released 1 Oct. (*A. swirskii* and *N. californicus* released alone and in mixtures of the two species) and 8 Oct. (second species of sequential releases). Buffer were sprayed with Movento® (22.4 % spirotetramat, Bayer CropScience, Research Triangle Park, NC) at 0.37 L/ha (5.0 fl oz/ac) in 563 L/ha (60 gal) water on 3 and 10 Oct. Insects and mites were monitored weekly beginning 26 Sep. by sampling six leaves (three top and three basal) from six randomly selected plants per plot.

Experiment 4: Eggplant and jalapeño pepper, fall 2012

In this experiment, we evaluated control of broad mite, whitefly and spider mite using *A. swirskii* and *N. californicus* alone and mixed on 'Tormenta Jalapeño' pepper, *Capsicum annuum* L. var. *longum*, and 'Classic' eggplant in a split plot design with four replications and whole plot factors completely randomized. Plots consisted of 14 plants set 60 cm apart and 1.8 m between bed centers, each plot separated by a like sized buffer plot treated 8 and 18 Oct. with Movento at 0.37 L/ha (5.0 fl oz/ac) and 3.74 % abamectin (Abba® Ultra, Makhteshim Agan, Raleigh, NC) on 30 Oct. and 25 Nov. Four treatments were randomly assigned to subplots: (1) *A. swirskii* alone, (2) *N. californicus* alone, (3) 1:1 mix of *A. swirskii* and *N. californicus*, and (4) an untreated control. Three weeks after planting when pest populations had been monitored twice, predator mites were released at 50 m^{-2} and 100 m^{-2} for *A. swirskii* and *N. californicus* respectively, based on the Koppert recommendation for 'curative light' (www.koppert.com). Pests and predators were monitored weekly by sampling six leaves (three top and three basal) from six randomly selected plants per plot.

Table 1. Treatments (Tr) and application timing on eggplant for Experiment 5.

			Apr			May					Jun	
Tr	**Product/Formulation**	**Rate**	**11**	**17**	**29**	**6**	**13**	**22**	**23**	**29**	**5**	**12**
1	Untreated Check											
2	Oberon 2 SC	0.73 L/ha	x	x			x	x				x
	Abba Ultra	0.37 L/ha			x	x				x	x	
	JMS Stylet Oil	0.50 %			x	x				x	x	
3	NBZ2166 52 EC	1.1 L/ha	x	x	x	x	x	x		x	x	x
	Induce	0.25 %	x	x	x	x	x	x		x	x	x
4	NBZ2166 52 EC	1.1 L/ha		x		x		x			x	
	Induce	0.25 %		x		x		x			x	
	A. swirskii	Per plot	600									
	N. californicus	Per plot	600						600			
5	*A. swirskii*	Per plot	600									
	N. californicus	Per plot	600						600			

Experiment 5: Eggplant, spring 2014

The objective of this experiment was to compare control of pests on eggplant using pesticides or predatory mites with and without applications of *M. anisopliae.* Greenhouse-raised 'Night Shadow' eggplant seedlings were transplanted 6 Mar., 60 cm apart on two raised beds separated by a row of corn, *Zea mays* L. Each plot contained 16 eggplants with a buffer of five plants incorporated between plots. Plots were assigned in a randomized complete block design with four replications to five treatments: (1) untreated control, (2) standard: weekly rotations of the pesticides Abba Ultra at 0.37 L/ha or Oberon at 0.73 L/ha + 0.5 % JMS Stylet Oil® (JMS Flower Farms Inc, Vero Beach, FL), (3) NBZ: *Metarhizium anisopliae* Strain f52 (NZB2166 52EC, Novozymes, Franklinton, NC) + a non-ionic surfactant (Induce®, Helena Chemical Company, Collierville, TN), (4) rotation: alternate applications of *M. anisopliae* and releases *A. swirskii*, *N. californicus*, and (5) predatory mites alone (Table 1). *Amblyseius swirskii* and *N. californicus*, were released by sprinkling infested bran substrate at an estimated rate of 60 mites of each species onto the center ten plants (Table 1). Buffer plants were sprayed with a rotation of Abba Ultra® at 0.37 L/ha, Oberon at 0.73 L/ha and 12.7 % β cyfluthrin (Baythroid XL®, Bayer CropScience, Research Triangle Park, NC) at 0.21 L/ha on successive spray dates (Table 1) in an attempt to inhibit migration of predatory mites between plots. All stages of spider mites, broad mite, predatory mites, sedentary stages of whitefly (eggs and nymphs) and melon thrips were monitored weekly from 23 Apr. to 16 June by collecting a fully mature mid-canopy leaf from five plants in each plot and examining, under a stereoscopic microscope, ten 3.23 cm^2 discs cut from each leaf. On 21 May and 2 June, all ripe fruit was collected from five plants in each plot. Fruit were weighed and damage by broad mites and thrips rated according to the following scale: no damage = 1, slight calyx damage = 2, severe calyx damage = 3, and scarred fruit = 4.

Analysis

Pest and predator counts per date in Experiments 2, 3 & 5 were evaluated using repeated measures as randomized complete block (RCB) designs by crop and Experiments 1 and 4 were evaluated as repeated measures split-plot RCB designs. All repeated measures analyses specified a variance components covariance structure. Counts were transformed by $\log_{10}(x+0.05)$ as required to normalize. The Mixed procedure was used for analysis of variance specifying the Satterthwaite degrees of freedom approximation in SAS Ver. 9.3 (SAS Institute 2014). Within-experiment pair-wise, Tukey-adjusted treatment comparisons were made using the lsmeans 'factor'/diff adjust=Tukey statement. Block was considered a random factor in all analyses. Correlations of predator and pest counts on each date were conducted with the Corr procedure, specifying the Spearman option (SAS Institute 2014). Predator populations were correlated with target pest populations in the same week or one week later using the "Lag" function in SAS.

Table 2. Mean ± SEM pest and predator counts per plant over 6 weeks in Experiment 1 on eggplant and squash following release of *A. swirskii* and *N. californicus* before planting (tray release) and after planting (field release), dispersion plots adjacent to release plots, control plots isolated by pesticide application plots and pesticide (Oberon) treated plots. Trial was conducted near Immokalee Florida, fall 2010. Means with the same letter in each column per crop are not significantly different (α=0.05).

Eggplant								
Treatment	***A. swirskii***		***N. californicus***		**Whitefly**		**Spider mite**	
Control	0.01 ± 0.01	b	0.02 ± 0.01	a	26.95 ± 3.38	a	2.38 ± 1.14	a
Dispersal	0.02 ± 0.01	ab	0 ± 0	a	17.36 ± 3.93	ab	3.99 ± 2.20	a
Field release	0.09 ± 0.05	a	0.08 ± 0.05	a	16.09 ± 2.75	ab	0.02 ± 0.01	b
Oberon®	0.01 ± 0.01	b	0 ± 0	a	13.80 ± 3.59	b	0.04 ± 0.04	b
Tray release	0.03 ± 0.02	ab	0.04 ± 0.02	a	25.28 ± 4.43	a	0.01 ± 0.01	b

Squash								
Treatment	***A. swirskii***		***N. californicus***		**Whitefly**		**Spider mite**	
Control	0 ± 0	a	0 ± 0	b	8.63 ± 2.06	a	1.19 ± 0.78	a
Dispersal	0.01 ± 0.01	a	0 ± 0	b	6.65 ± 2.90	a	0.23 ± 0.16	a
Field release	0.05 ± 0.04	a	0.13 ± 0.05	a	4.89 ± 1.57	a	0.21 ± 0.12	a
Oberon®	0 ± 0	a	0 ± 0	b	4.36 ± 1.18	a	0.05 ± 0.05	a
Tray release	0 ± 0	a	0.04 ± 0.03	ab	3.77 ± 1.29	a	0.34 ± 0.24	a

RESULTS

Experiment 1: Eggplant and zucchini squash, fall 2010

Numbers of *A. swirskii* were low but greater on eggplant (mean ± SEM: 0.03±0.01) than squash (mean ± SEM: 0.01±0.01) (P=0.034) on which there was no significant treatment effect (P>0.05 for all treatment comparisons). Most *A. swirskii* were found on eggplants receiving the mites the week after transplanting although not significantly more than in dispersal or tray release plots (Table 2). The crop x date interaction was significant ($F_{5,180}$=3.29; P=0.007) with numbers of *A. swirskii* peaking mid-November on eggplant with a lesser peak mid-November on squash (Figs 1A, C). *Neoseiulus californicus* was scarce in both crops with no

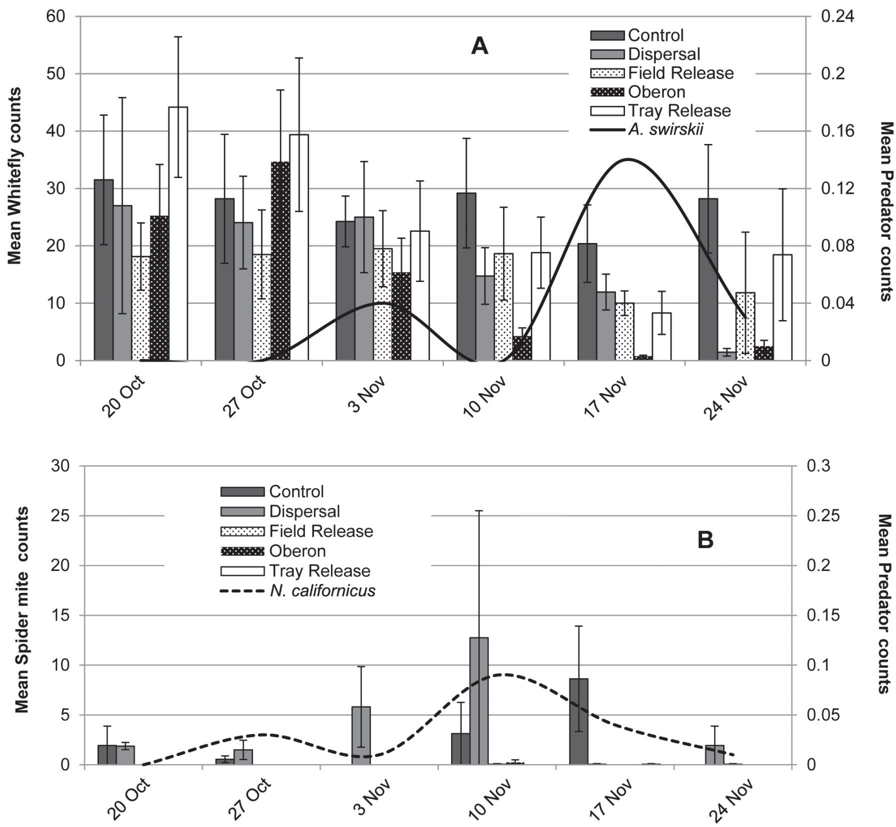


Fig. 1: Mean ± SEM pests and predators per leaf by date for whitefly and spider mite populations and *A. swirskii* and *N. californicus* (mean of all treatments) after mixed releases of *A. swirskii* and *N. californicus* before (in tray) and after planting and applications of Oberon (pesticide) in eggplant (A, B) and squash (C, D).

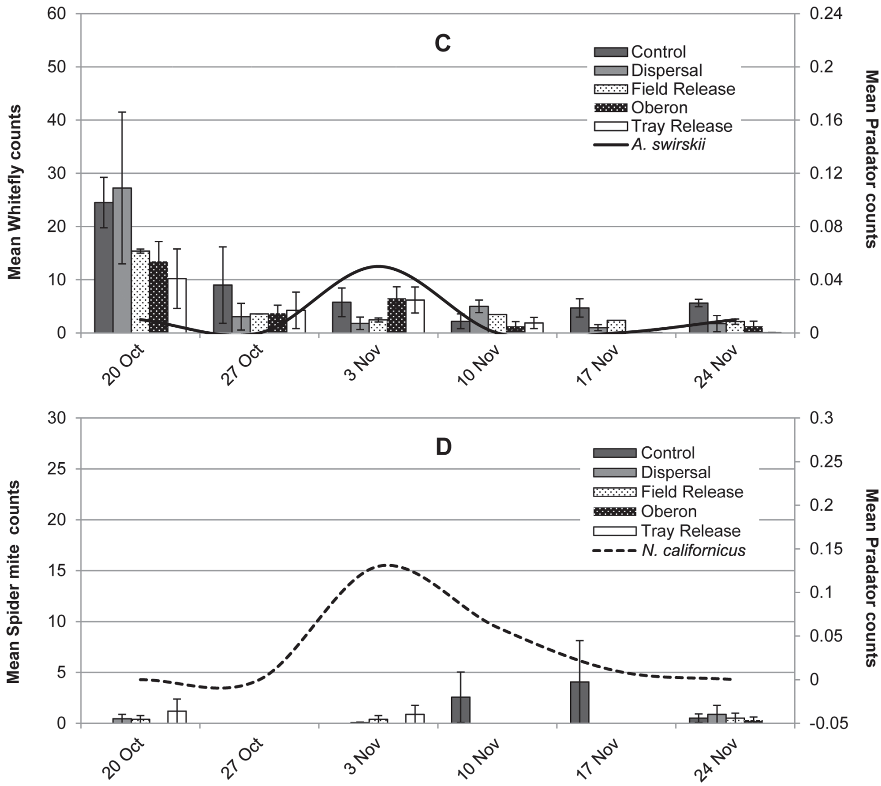


Fig. 1 *(continued)*: Mean ± SEM pests and predators per leaf by date for whitefly and spider mite populations and *A. swirskii* and *N. californicus* (mean of all treatments) after mixed releases of *A. swirskii* and *N. californicus* before (in tray) and after planting and applications of Oberon (pesticide) in eggplant (A, B) and squash (C, D).

treatment effects on eggplant and almost none seen on squash in tray release plots (Table 2). Numbers of *N. californicus* peaked early to mid-November in both crops (Figs 1B, D).

Whitefly was the most abundant pest species in both eggplant and squash followed by spider mite (Fig. 1). Broad mite was absent in both. More whiteflies were found in eggplant than squash ($F_{1,3}$=61.33; P=0.004) with no significant treatment effects in the latter (P>0.05 for all treatment comparisons) (Table 2). Most whiteflies were found on eggplant controls and least on pesticide-treated plants with the dispersal and field release treatments intermediate (Table 2). A date ($F_{1,174}$=14.91; P<0.001) effect and interactions of crop and date ($F_{5,174}$=2.52; P=0.031) were detected. Interactions could be attributed in part to sustained whitefly numbers on control plants in eggplant and decreasing numbers with time in all treatments in squash (Figs 1A, C).

Spider mite populations were low on squash and no treatment effect was noted (P>0.05) in contrast to eggplant ($F_{4,174}$=5.40; P<0.001). Field release, tray release and Oberon reduced spider mite counts on eggplant in equal measure compared to the control and dispersal treatments (Table 2). For plants not receiving pesticide applications, *N. californicus* counts and whitefly numbers one week later were negatively correlated on eggplant (R=-0.268; P=0.038) as were *A. swirskii* and *N. californicus* (R=0.305; P=0.009).

Experiment 2: Eggplant and cantaloupe, spring 2011

Numbers of *A. swirskii* differed by treatment in eggplant ($F_{4,147}$=6.53; P<0.001) with most found on plants receiving the *A. swirskii* + *N. californicus* mix (Table 3). Numbers of *A. swirskii* were not significantly improved overall by addition of *C. lactis* (Table 3). However, a significant interaction of treatment and date was apparent ($F_{36,147}$=1.70; P=0.015) and explained by a peak in *A. swirskii* numbers late May to early June on plants that had received *A. swirskii* + *N. californicus* + *C.*

Table 3. Mean ± SEM pest and predator counts per plant over 11 weeks in Experiment 2 on eggplant and over 7 weeks on cantaloupe following release of predatory mite species individually and as a mixture. Effects on pests and predators were compared to application of the pesticides Agri-Mek® and Agri-Flex® in eggplant. Effects of releases on pests and predators were compared to those of mites provisioned with food (*Carpoglyphus lactis* or pollen) in cantaloupe. Trial was conducted near Immokalee Florida, spring 2011. Means with the same letter in each column per crop are not significantly different (α=0.05).

Eggplant								
Treatment	***A. swirskii***		***N. californicus***		**Whitefly**		**Spider mite**	
Control	0.00±0.00	c	0.00±0.00	c	13.48±2.50	a	34.93±5.70	a
A. swirskii + *N. californicus* + *C. lactis*	0.09±0.03	ab	0.12±0.04	a	8.77±1.59	ab	14.62±5.58	b
A. swirskii + *N. californicus*	0.11±0.03	a	0.09±0.03	ab	8.62±1.49	ab	9.64±2.37	b
Agri-Mek®	0.04± 0.02	bc	0.01±0.01	c	6.56±1.99	b	6.59±1.72	b
Agri-Flex®	0.03±0.02	bc	0.04±0.03	bc	10.91±2.49	ab	15.88±5.06	b

Cantaloupe						
Treatment	***A. swirskii***		**Whitefly**		**Spider mite**	
Control	0.02±0.02	a	22.33±5.79	a	0.07±0.06	a
C. lactis	0.00±0.00	a	19.52±5.55	a	0.12±0.12	a
A. swirskii	0.03±0.02	a	14.05±2.57	a	0.20±0.12	a
A. swirskii + *C. lactis*	0.01±0.01	a	14.02±3.63	a	0.03±0.02	a
A. swirskii + pollen	0.02±0.01	a	13.89±3.07	a	0.11±0.08	a

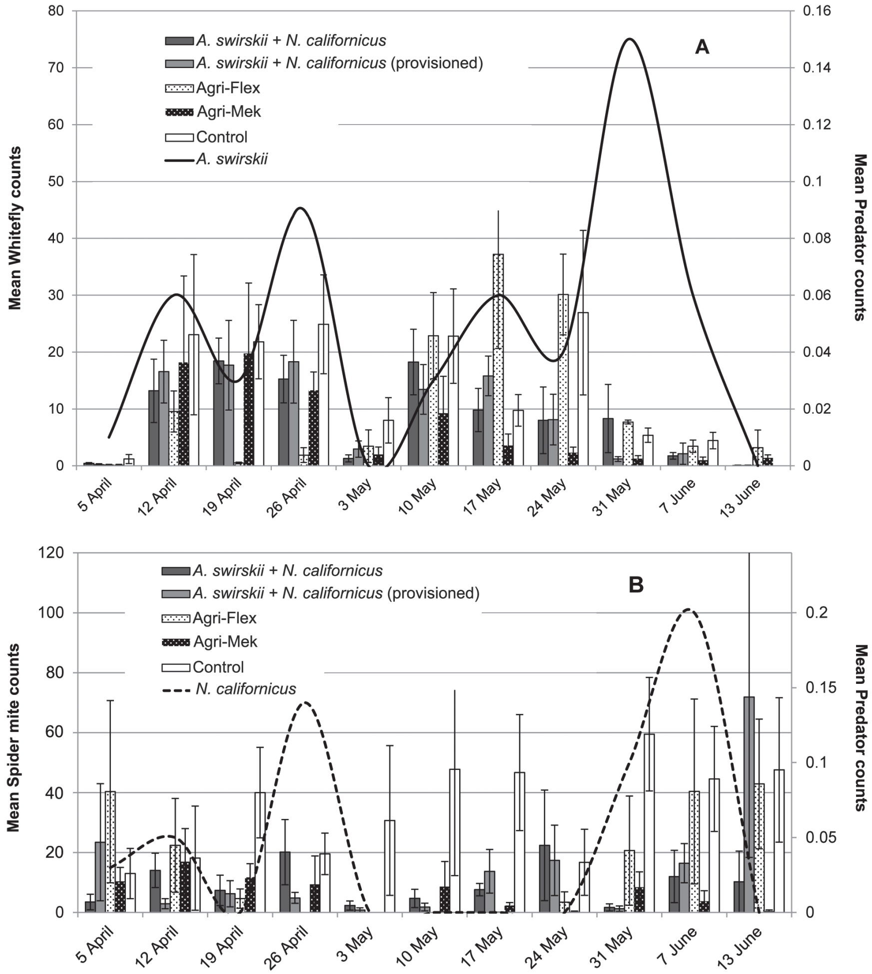


Fig. 2: Mean ± SEM by treatment per leaf by date of (A) whitefly and (B) spider mite and mean *A. swirskii* and *N. californicus* of all treatments after releases of mixes of *A. swirskii* and *N. californicus* supplied with dried fruit mite or applications of pesticides (Agri-Mek and Agri-Flex) in eggplant, and (C) whitefly and (D) spider mite and *A. swirskii* (sum of all treatments) in cantaloupe after release of *A. swirskii* supplied with pollen and dried fruit mite in different treatments.

lactis. Some *A. swirskii* and *N. californicus* were found on buffer plants sprayed with Agri-Mek or Agri-Flex although none were found on untreated plants protected by the buffers (Table 3). Numbers of *A. swirskii* varied by date on eggplant ($F_{10,147}$=3.01; P=0.003) with peaks late April and early June (Fig. 2A). Numbers of *N. californicus* were also influenced by treatment in eggplant ($F_{4,162}$=7.55;

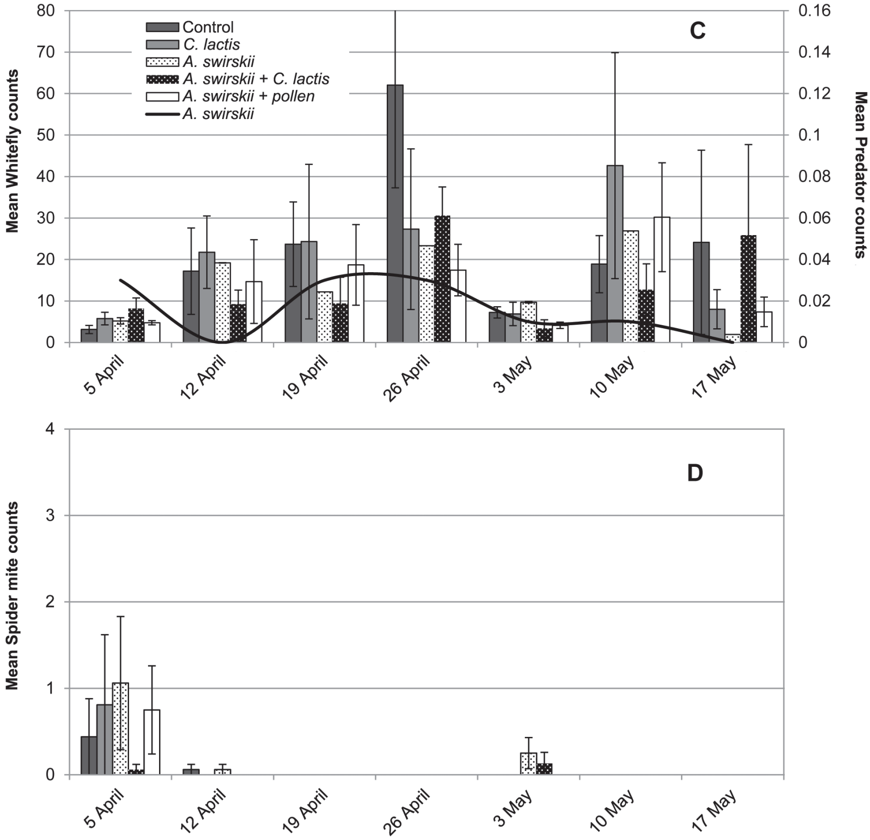


Fig. 2 *(continued)*: Mean ± SEM by treatment per leaf by date of (A) whitefly and (B) spider mite and mean *A. swirskii* and *N. californicus* of all treatments after releases of mixes of *A. swirskii* and *N. californicus* supplied with dried fruit mite or applications of pesticides (Agri-Mek and Agri-Flex) in eggplant, and (C) whitefly and (D) spider mite and *A. swirskii* (sum of all treatments) in cantaloupe after release of *A. swirskii* supplied with pollen and dried fruit mite in different treatments.

P<0.001) with most found where provisioned with *C. lactis* although not significantly so than when with no food supplement (Table 3).

Whitefly numbers were influenced by treatment in eggplant ($F_{4,162}$=3.79; P= 0.006), although the only significant differences were between the control and the Agri-Mek treatments (Table 3). A date effect was also apparent ($F_{10,162}$=15.53; P<0.001) with peak whitefly numbers mid-April in all treatments but Agri-Flex where the peak delayed until late May (Fig. 2A). Spider mite numbers were also influenced by treatment on eggplant ($F_{4,162}$=10.53; P<0.001), being greatest in control plots with no differences among remaining treatments (Table 3). No broad mite was seen.

Cantaloupe matured and died faster than eggplant and sampling of this crop was completed 17 May. The few spider mites peaked early April and whiteflies late April (Figs 2C, D). No significant treatment effects were found (P>0.05 for all treatment comparisons) for whitefly ($F_{4,102}$=0.73; P=0.574) or spider mite counts ($F_{4,105}$=0.71; P=0.584) (Table 3).

For plants without pesticide applications, negative correlations of *A. swirskii* and *N. californicus* counts and whitefly numbers after one week were found (R= -0.224; P=0.014 and R=-0.209; P=0.022, respectively) on eggplant but not on cantaloupe (P>0.05).

Experiment 3: Eggplant, fall 2011

Numbers of *A. swirskii* and *N. californicus* peaked 1 Nov. (Figs 3A and 3B respectively); *N. californicus* then virtually disappeared in late January to reappear later in concert with spider mite populations. Overall, numbers of *A. swirskii* and *N. californicus* were negatively correlated (R=-0.198; P<0.001). Counts of *A. swirskii* differed by treatment ($F_{6,333}$=20.90; P<0.001) with most found on eggplants receiving only *A. swirskii* and fewest on the control and plants receiving *N. californicus* alone or Movento (Table 4). More were found where *A. swirskii* was released before *N. californicus*, than the reverse order, with the mixture intermediate. Similar results were seen in abundance of *N. californicus* ($F_{6,333}$=14.89; P<0.001), with more seen where this species was released alone than where released first, which was not significantly different from the mixture (Table 4). No more were found where *A. swirskii* was released first than in the three treatments, where *N. californicus* was not released at all.

Whitefly numbers varied by date ($F_{15,333}$=35.83; P<0.001) with most observed through 19 Oct. followed by a rapid decline (Fig. 3A). Numbers of *A. swirskii* and whiteflies were negatively correlated (R=-0.215; P<0.001). A significant treatment effect on whitefly numbers was found ($F_{6,333}$=2.22; P=0.041, with more on plants receiving *N. californicus* then *A. swirskii* than those treated with Movento (Table 4). All other treatments were intermediate with no other significant differences.

Spider mites also peaked early, dropped precipitously by 1 Nov., and remained low until a moderate rise mid-February (Fig. 3B). Both whitefly and spider mite counts were greatest when predator numbers were lowest for the most part. Counts for *A. swirskii* and spider mite numbers lagged one week were negatively correlated (R=-0.276; P<0.001). Treatment effects on spider mite counts were significant ($F_{6,333}$=5.40; P<0.001) with fewest seen on plants receiving *N. californicus* a week before *A. swirskii*, although significantly different only from the untreated control (Table 4).

Broad mites appeared relatively late in the trial, with most seen from late October through November, and almost none after mid-January (Fig. 3C). Treatment effects were significant ($F_{6,333}$=6.52; P<0.001), with fewest on plants receiving any combination of predacious mite and most on Movento-treated plants; the untreated

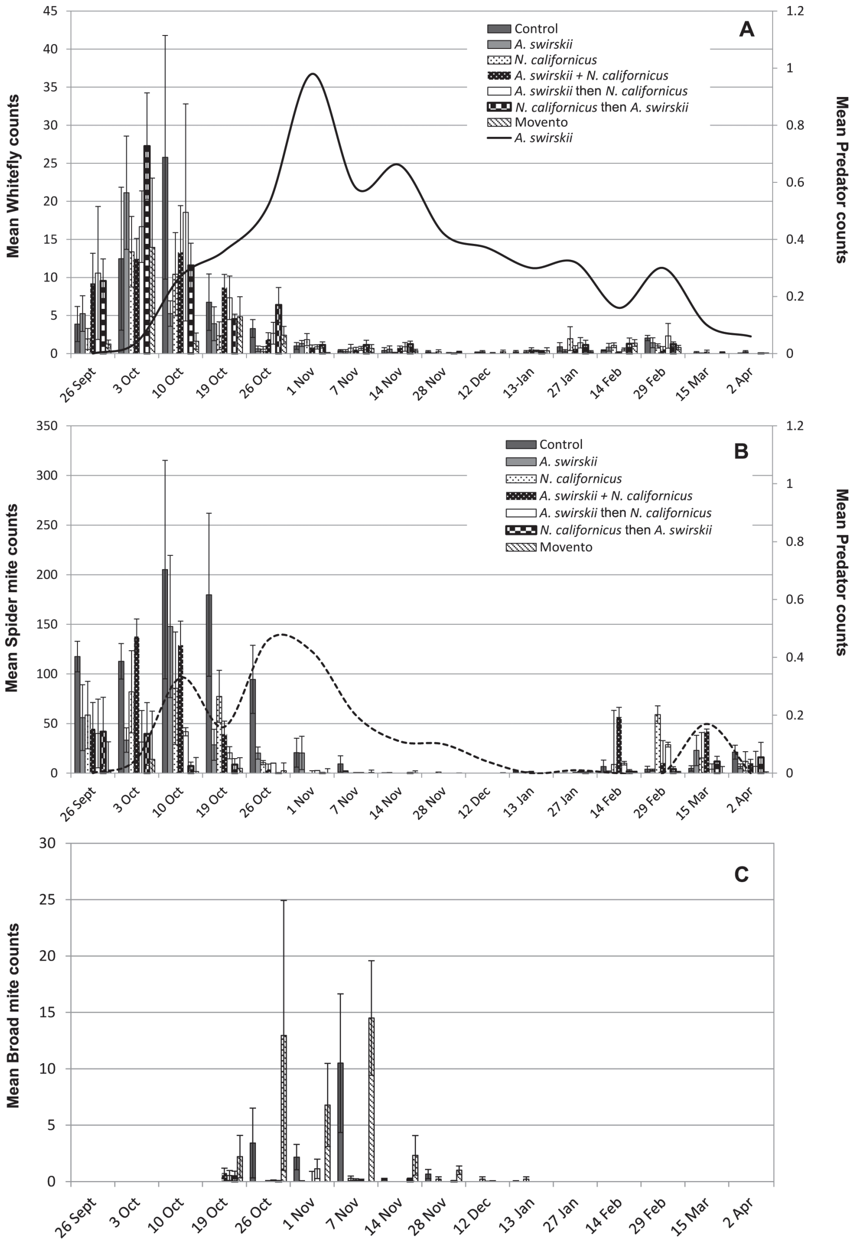


Fig. 3: Mean ± SEM per leaf by date of (A) whitefly, (B) spider mite and (C) broad mite in eggplant after release of predaceous mites alone, in mixtures or in sequence.

Table 4. Mean ± SEM pest and predator counts in Experiment 3 over 24 weeks after release of *A. swirskii* and *N. californicus* as single species, combined or in sequence, and application of the pesticide Movento® in experimental plots of eggplant. Trial was conducted near Immokalee Florida, fall 2011. Means with the same letter in each column are not significantly different (α=0.05).

Treatment	*A. swirskii*		*N. californicus*		Broad mite		Whitefly		Spider mite	
Control	0.08 ± 0.02	d	0.02 ± 0.01	c	1.06 ± 0.50	ab	3.61 ± 1.33	ab	48.65 ± 11.61	a
A. swirskii	0.90 ± 0.17	a	0.00 ± 0.00	c	0.00 ± 0.00	b	2.58 ± 0.79	ab	21.42 ± 6.50	b
N. californicus	0.04 ± 0.01	d	0.49 ± 0.12	a	0.06 ± 0.03	b	2.27 ± 0.63	ab	25.67 ± 8.08	ab
A. swirskii + *N. californicus*	0.47 ± 0.12	bc	0.10 ± 0.04	bc	0.06± 0.04	b	3.10 ± 0.73	ab	29.66 ± 7.84	ab
A. swirskii then *N. californicus*	0.56 ± 0.09	b	0.03 ± 0.02	c	0.12 ± 0.06	b	3.94 ± 1.22	ab	12.40 ± 3.26	b
N. californicus then *A. swirskii*	0.18 ± 0.03	cd	0.20 ± 0.06	b	0.05 ± 0.03	b	4.17 ± 0.99	a	8.21 ± 3.20	b
Movento®	0.14 ± 0.03	d	0.05 ± 0.02	c	2.49 ± 0.95	a	1.79 ± 0.68	b	16.84 ± 4.73	b

control being intermediate (Table 4). Broad mite numbers reached a mean of 10.5 per leaf on untreated plants and 13 per leaf on plants treated with Movento by 7 Nov. (Fig. 3C).

Experiment 4: Eggplant and jalapeño pepper, fall 2012

Numbers of *A. swirskii* peaked on eggplant mid-October, again in mid November and were increasing again at the end of the trial in December (Fig. 4A).

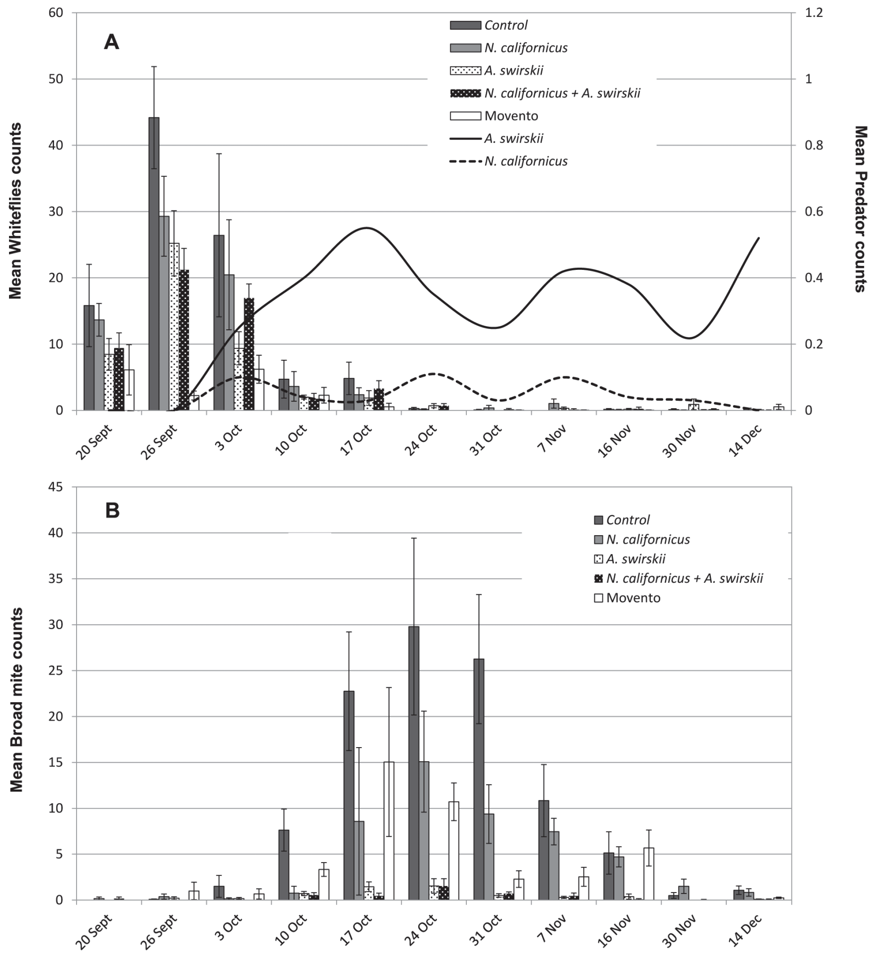


Fig. 4: Mean ± SEM per leaf of (A) whitefly, (B) broad mite and mean *A. swirskii* and *N. californicus* (sum of all treatments), after releases of *A. swirskii* and *N. californicus* alone and combined or applications of a pesticide (Movento) on eggplant and (C) whitefly, and (D) broad mite on pepper.

Trends were similar in pepper but without the increase in December (Fig. 4C). Numbers of *N. californicus* were negatively correlated with *A swirskii* on eggplant (R=-0.263; P < 0.001) and virtually non-existent in pepper. A significant treatment effect ($F_{4,330}$=37.55; P<0.001) and interaction of treatment and crop (P<0.001) was seen on eggplant. Most *A. swirskii* on eggplant and the few found in pepper were on plants receiving *A. swirskii* alone or in mixture (Table 5).

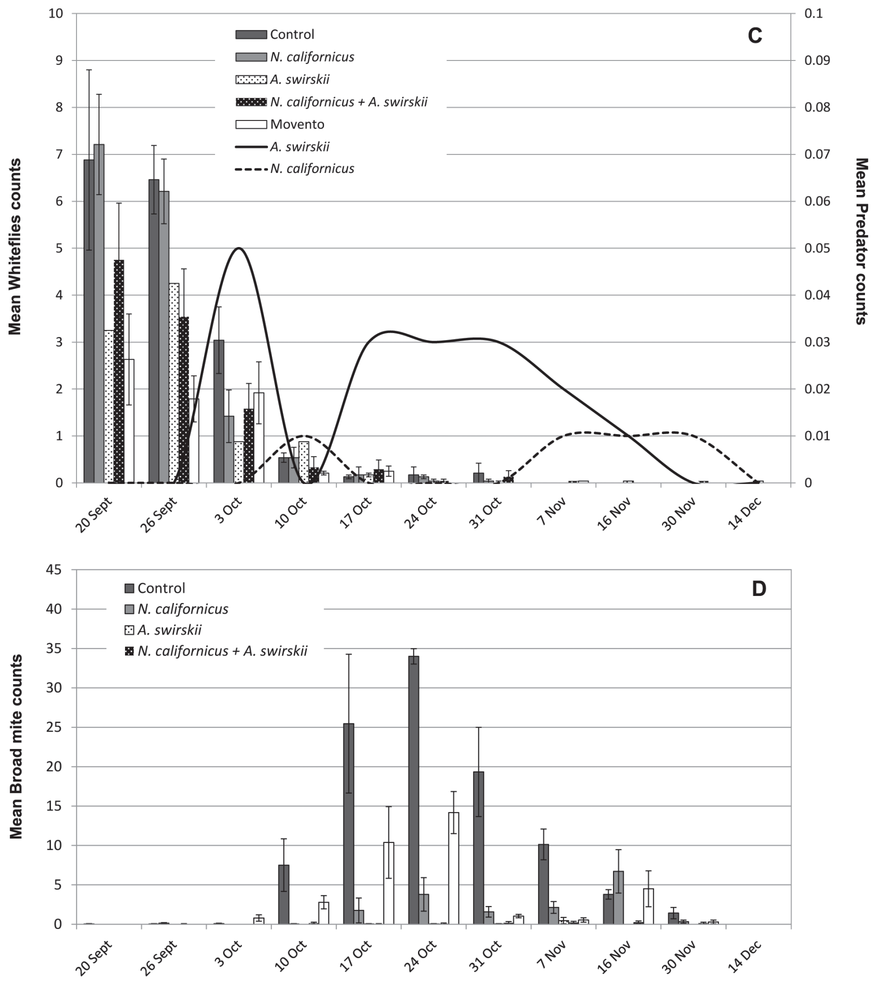


Fig. 4 *(continued)*: Mean ± SEM per leaf of (A) whitefly, (B) broad mite and mean *A. swirskii* and *N. californicus* (sum of all treatments), after releases of *A. swirskii* and *N. californicus* alone and combined or applications of a pesticide (Movento) on eggplant and (C) whitefly, and (D) broad mite on pepper..

Table 5. Mean ± SEM pest and predator counts over 11 weeks following the release of predatory mites as single species or mixed species, and application of the pesticide Movento® in experimental plots of eggplant and pepper. Trial was conducted near Immokalee Florida, fall 2012. Means with the same letter in each crop and column are not significantly different (α=0.05).

Eggplant										
Treatment	***A. swirskii***		***N. californicus***		**Broad mite**		**Whitefly**		**Spider mite**	
Control	0.16 ± 0.05	b	0.00 ± 0.00	-	9.59 ± 2.02	a	8.78 ± 2.47	a	3.20 ± 1.64	a
A. swirskii	0.68 ± 0.11	a	0.00 ± 0.00	-	0.48 ± 0.12	c	4.47 ± 1.22	a	0.01 ± 0.01	b
N. californicus	0.05 ± 0.03	b	0.21 ± 0.05	a	4.45 ± 1.11	b	6.48 ± 1.71	a	0.02 ± 0.02	b
A. swirskii + *N. californicus*	0.55 ± 0.09	a	0.01 ± 0.01	b	0.37 ± 0.10	c	4.91 ± 1.17	a	0.06 ± 0.04	b
Movento®/Abba	0.08 ± 0.03	b	0.00 ± 0.00	-	3.77 ± 1.00	b	1.66 ± 0.50	b	0.05 ± 0.05	b

Pepper								
Treatment	***A. swirskii***		***N. californicus***		**Broad mite**		**Whitefly**	
Control	0.00 ± 0.00	-	0.00 ± 0.00	-	9.25 ± 1.95	a	1.58 ± 0.43	a
A. swirskii	0.04 ± 0.01	a	0.04 ± 0.01	a	0.05 ± 0.04	c	0.87 ± 0.23	a
N. californicus	0.00 ± 0.00	-	0.00 ± 0.00	-	1.50 ± 0.44	b	1.43 ± 0.40	a
A. swirskii + *N. californicus*	0.03 ± 0.02	a	0.03 ± 0.02	a	0.09 ± 0.03	c	4.91 ± 1.17	a
Movento®/Abba	0.00 ± 0.00	-	0.00 ± 0.00	-	3.14 ± 0.84	b	1.66 ± 0.50	a

Broad mite counts were also greater on eggplant (mean ± SEM: 3.73±0.55) than pepper (mean ± SEM: 2.81 ± 0.49) ($F_{1,3}$=18.05; P=0.024) although numbers decreased rapidly in both crops following release of *A. swirskii* three weeks after planting (Figs 4B, D). In both crops, fewest broad mites were found on plants receiving *A. swirskii* alone or with *N. californicus*, whereas most were found in control plots. Intermediate numbers were seen where *N. californicus* was released alone or Movento sprayed (Table 5). Broad mite numbers on eggplant were negatively correlated with *A. swirskii* (R=-0.223; P=0.005).

Whiteflies peaked in early October, decreasing later in the year and were more numerous in eggplant (mean ± SEM: 5.26 ± 0.71) than pepper (mean ± SEM: 1.10±0.14). Numbers of *A. swirskii* and whiteflies were negatively correlated on eggplant (R=-0.228; P<0.002). Treatment effects were significant in eggplant ($F_{4,324}$=14.94; P<0.001) as was the interaction of treatment and crop (P<0.001). Only Movento-treated plants had significantly (P<0.05) fewer whiteflies than the control, with no significant treatment effects in pepper (Table 5). Spider mites were essentially absent from pepper and scarce in eggplant except on control plants where significantly more were seen than all other treatments (P<0.05) (Table 5).

Experiment 5: Eggplant, spring 2014

The only predatory mite species present throughout the trial was *A. swirskii*. *Neoseiulus californicus* was present in low numbers initially, but absent by the third week. *Amblyseius swirskii* eventually migrated to all plots despite the insecticide barrier applied to buffer plants. Nevertheless, most were found on plants treated with the rotation of NBZ (*M. anisopliae*) and the mite mixture, which was significantly greater than mites alone (Table 6). A significant effect of date ($F_{9,147}$=10.68; P<0.001) and interaction of treatment and date ($F_{36,147}$=2.32; P<0.001) were also detected. Numbers of *A. swirskii* peaked in May (Fig. 5A) primarily on mite-treated plants with or without NBZ.

Treatments significantly affected broad mite numbers ($F_{4,162}$=8.06; P<0.001), with fewest found on plants receiving mites alone or the standard miticides (Table 6). Numbers were generally low with most broad mites seen in control plots late April (Fig. 5B).

A treatment effect on whitefly numbers was also apparent ($F_{4,162}$=4.71; P<0.001). Greatest reductions occurred on plants receiving predacious mites rotated with NBZ, although not significantly different from the miticide standard (Table 6). A significant negative correlation was seen between counts of *A. swirskii* and whiteflies lagged by one week (R=-0.345, P<0.001).

All treatments except mites alone reduced spider mite numbers compared to the control (Table 6). Fewest spider mites were seen using the chemical standard but not significantly so compared to the NBZ treatment. The interaction of treatment and date was significant ($F_{40,162}$=1.96; P=0.002), with the spider mites peaking in late May, primarily in control plots (Fig. 5C). Likewise, all treatments except mite releases alone significantly reduced melon thrips ($F_{4,165}$=8.97; P<0.001), with most

Table 6. Mean ± SEM pest and predator counts over 11 weeks on eggplant assigned in a randomized complete block design to 4 replications of 5 treatments: (1) untreated control, (2) *M. anisopliae*, (3, 4) *M. anisopliae* + releases of the predatory mites, (4) predatory mites alone, and (5) weekly applications of pesticides. Trial was conducted near Immokalee Florida, spring 2012. Means with the same letter in each crop and column are not significantly different (α=0.05).

Treatment	***A. swirskii***		**Broad mite**		**Whitefly**		**Spider mite**		**Melon thrips**	
Control	0.44 ± 0.10	d	0.18 ± 0.07	a	18.72 ± 2.43	a	86.15 ± 24.50	a	2.84 ± 0.49	a
NBZ	1.02 ± 0.19	c	0.05 ± 0.02	ab	17.51 ± 1.79	ab	2.77 ± 0.89	bc	2.02 ± 0.42	b
Rotation	3.54 ± 0.41	a	0.09 ± 0.03	ab	11.19 ± 2.52	c	7.50 ± 1.75	b	1.73 ± 0.38	bc
A. swirskii	1.94 ± 0.30	b	0.01 ± 0.01	b	18.75 ± 5.42	a	24.71 ± 7.93	a	2.08 ± 0.44	ab
Standard	0.83 ± 0.16	cd	0.00 ± 0.00	b	14.16 ± 2.18	bc	0.65 ± 0.17	c	0.85 ± 0.24	c

found on control plants and fewest on plants receiving the pesticide standard treatment though not different from the rotation of NBZ and mites (Table 6).

Reductions in thrips populations on pesticide-treated plants began 30 Apr., and later on rotation treated plants in mid-May, commensurate with the buildup of *A. swirskii* populations (Fig. 5D). For plants without pesticide application, *A. swirskii* and lagged thrips numbers were negatively correlated (R=-0.427; $P<0.001$).

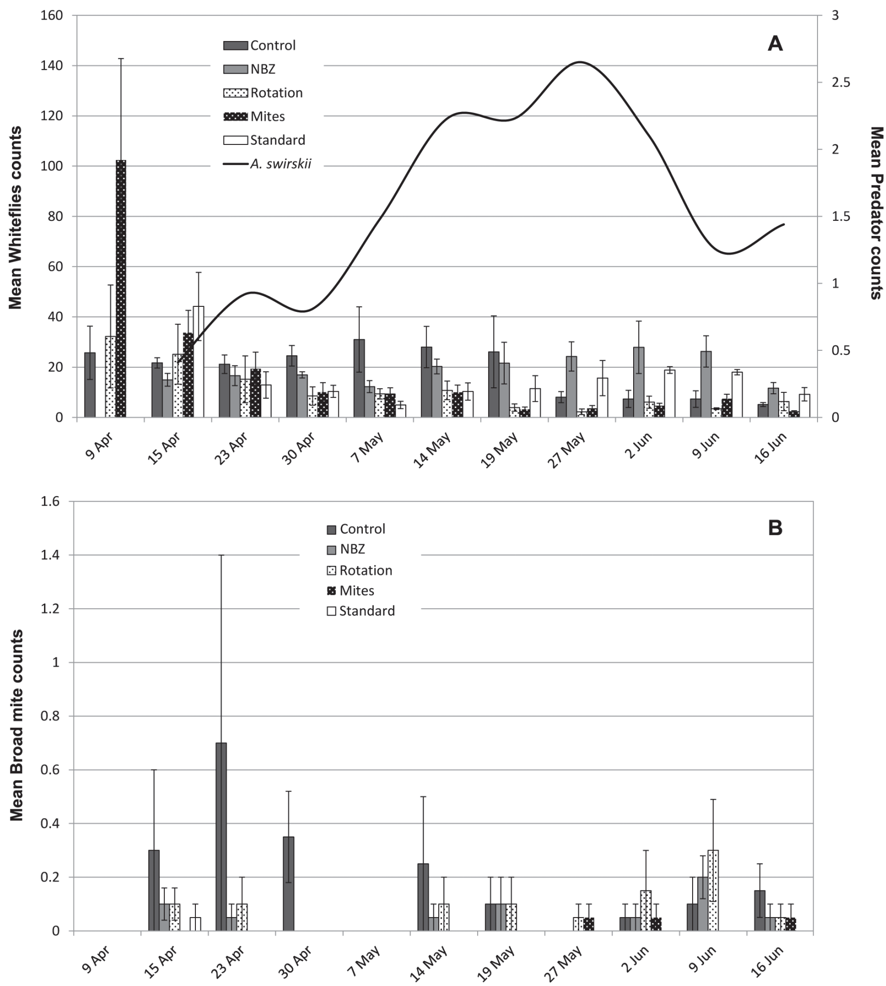
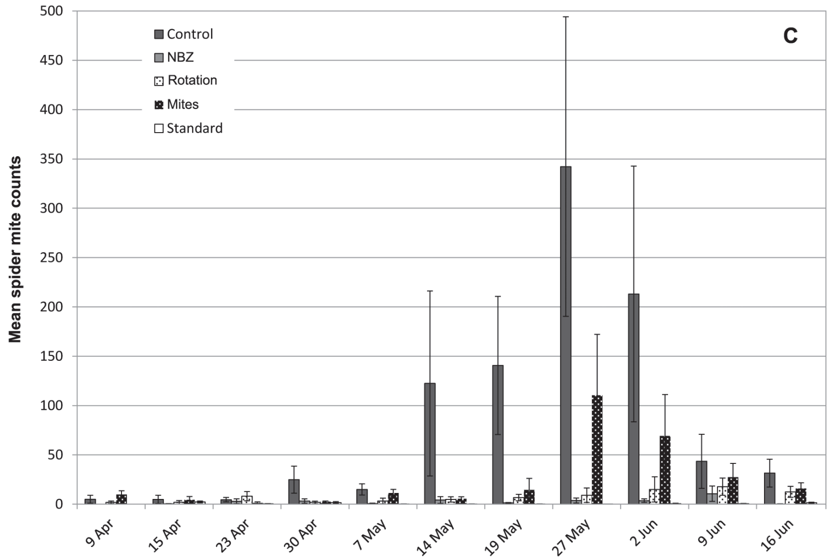


Fig. 5: Mean ± SEM pests and predators per leaf by date of (A) whitefly and mean *A. swirskii* (all treatments), (B) broad mite, (C) spider mite, and (D) melon thrips in eggplant treated with a pesticide standard, NBZ: *M. anisopliae*, rotation of *M. anisopliae* and releases of the predatory mites, *A. swirskii*, *N. californicus*, and *Neoseiulus longispinosus*, predatory mites alone and an untreated control.



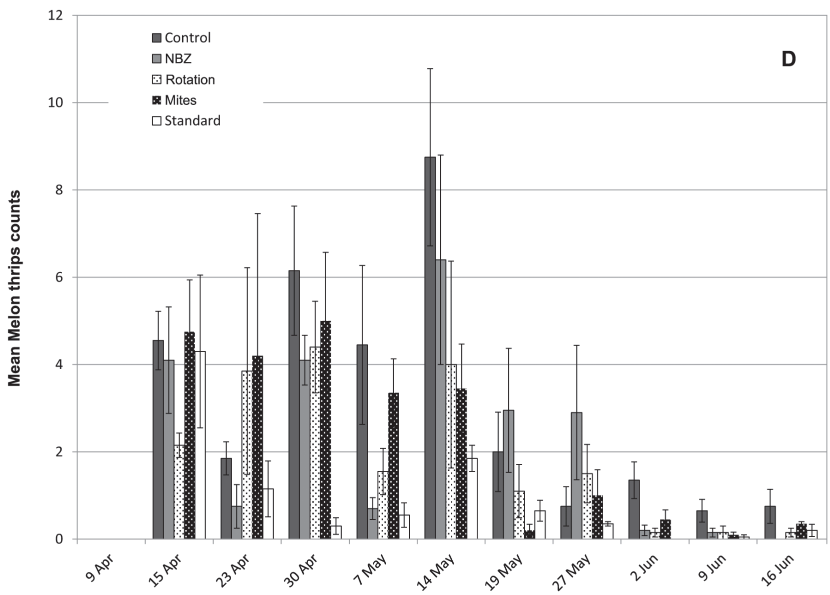


Fig. 5 *(continued)*: Mean ± SEM pests and predators per leaf by date of (A) whitefly and mean *A. swirskii* (all treatments), (B) broad mite, (C) spider mite, and (D) melon thrips in eggplant treated with a pesticide standard, NBZ: *M. anisopliae*, rotation of *M. anisopliae* and releases of the predatory mites, *A. swirskii*, *N. californicus*, and *Neoseiulus longispinosus*, predatory mites alone and an untreated control.

Table 7. Mean ± SEM eggplant damage ratings (no damage=1, slight calyx damage=2, severe calyx damage=3, and scarred fruit=4) and mass (kg) per fruit for eggplant assigned in a randomized complete block design to 4 replications of 5 treatments: (1) untreated control, (2) weekly applications of pesticides, (3) *M. anisopliiae*, (4) *M. anisopliiae* + releases of the predatory mites, and (5) predatory mites alone. Trial was conducted near Immokalee Florida, spring 2012. Means with the same letter in each column are not significantly different (α=0.05).

Treatment	Damage rating		Harvested mass (kg/fruit)	
Control	2.57 ± 0.21	a	0.48 ± 0.01	a
M. anisopliae	2.20 ± 0.14	a	0.49 ± 0.04	a
M. anisopliae rotated with mites	2.55 ± 0.17	a	0.50 ± 0.02	a
Mites alone	2.42 ± 0.20	a	0.47 ± 0.02	a
Standard	1.54 ± 0.09	b	0.48 ± 0.02	a

Fruit damage, primarily russeting of calices, was significantly reduced on plants treated with the chemical standard compared to other treatments (Table 7) although harvested masses did not differ by date ($F_{1,3}$=0.18; P=0.702) or treatment ($F_{4,24}$=0.20; P=0.938) (Table 7).

DISCUSSION

Five field trials were conducted to evaluate the use of phytoseiid mites for management of whiteflies, thrips, broad mites and spider mites in open field solanaceous and cucurbit vegetable crops. Specific objectives were to (1) assess host plant effects, (2) assess release time and the value of providing supplemental food for predacious mites in the field, (3) compare results with mixtures of two predacious mite species compared to rotations or single species releases, and (4) compare control obtained with predacious mites to that of standard pesticides.

Host plant effects

Eggplant is an excellent host for all three pests evaluated as well as melon thrips included in the last experiment. Therefore, all experiments included eggplant as one or the only crop. Results on eggplant were compared to zucchini in Experiment 1, to cantaloupe in Experiment 2 and to jalapeño pepper in Experiment 4. Eggplant generally sustained higher numbers of predacious mites than squash, cantaloupe or pepper. This corresponded to generally higher numbers of whiteflies and spider mites on control plants. Eggplant is a preferred host of spider mites (van den Boom *et al*. 2003) and *B. tabaci* (Hilje *et al*. 2001). Spider mites were essentially absent from pepper. Attractiveness of host plants to these pests wanes with age (Hilje *et al*. 2001), and squash and cantaloupe matured and declined more quickly than eggplant. Spider mite and phytoseiid numbers were also greater on eggplant than cantaloupe. Thus, differences in predacious mite numbers on different host plants were likely due primarily to differences in pest populations.

Release time and supplemental food

No differences were seen in number of predacious mites recovered or spider mite control from release of a mixture of *A. swirskii* and *N. californicus* on eggplant seedlings before or after transplanting (Table 2). Releasing in the seedling tray prior to transplanting would be labor-saving but requires further evaluation. Similarly, supplemental provisioning with *C. lactis* did not significantly enhance the number of predacious mites or spider mite control on eggplant (Table 3).

Messelink *et al*. (2008) found that a subsequent numerical response by the predatory mites more than compensated for initially reduced predation on thrips and whiteflies when both pests were present. However, *C. lactis* probably did not persist long enough in our experiment to elicit a numerical response (Table 3). Nomikou *et al*. (2010) found a 5-fold increase in numbers of *A. swirskii* and an 8-fold decrease in *B. tabaci* on cucumber plants provided with cattail pollen presented in vials suspended from the leaves. Cattail pollen has been shown to enhance predator mite populations and subsequent pest management in greenhouse vegetable crops (Pijnakker *et al*. 2016) although we did not see the effect in field-grown cantaloupe. The lack of any effect of pollen on cantaloupe may simply reflect low populations of pests and consequently *A. swirskii*. However, the apparent ability of both mites, especially *A. swirskii*, to persist on eggplant following release on young seedlings suggests that some source of food was available. The possibility that windblown pollen caught by the densely pilose eggplant leaves may sustain predacious mites in the open field until flowering deserves further study.

Mixtures, rotations or single species releases

Predacious mite populations were greatest in Experiment 3 on eggplant when each species was released alone > released first > released together > released second (Table 4). Counts of *N. californicus* and *A. swirskii* were negatively correlated in this and the subsequent experiment (4). However, no significant effect was seen on target pest populations. In contrast, no difference in *A. swirskii* numbers was seen whether *A. swirskii* was released on eggplant alone or mixed with *N. californicus*, although more of the latter were found when it was released alone (Table 5). Predacious mites on pepper were too low to compare in the companion trial, and significant treatment effects were only seen on broad mite on either crop, with best control where *A. swirskii* was released regardless of whether *N. californicus* was included.

These results suggest a degree of intraguild predation between the two predacious mite species. Buitenhuis *et al*. (2010) found greater predation by *A. swirskii* on *N. cucumeris* than vice versa. Both predacious mites, preferred, developed faster and survived better on intra-guild larvae in bean leaf disk bioassays than on larvae of the thrips *Frankliniella occidentalis*. Çakmak *et al*. (2006) also found evidence of intraguild predation between *N. californicus* on *Phytoseiulus persimilis* (Athias-Henriot), although attenuated by the presence of shared prey (*T. urticae*). Indeed, a diversity of prey may have a beneficial effect on pest control (Messelink *et al*.

2008, 2010). Rosenheim *et al*. (1995) predicted disruption of biological control from intraguild predation among predatious mites. We saw that intraguild predation could reduce populations of one or both of two released phytoseiids, but with little or no effect on biological control in the short term context of a vegetable crop (Table 4). Our results suggest that both predacious mites should be released where spider mites are expected to be the main pest, whereas *A. swirskii* alone would be the best choice to control whitefly and broad mite.

Finally, rotation with *M. anisopliae* actually increased populations of *A. swirskii* as well as reducing numbers of whiteflies and spider mites compared to release of *A. swirskii* alone. Midthassel *et al*. (2016) found *A. swirskii* to be largely compatible with *Beauveria bassiana* even though the mite was somewhat susceptible to the fungus. While we do not have specific information on direct effects of *M. anisopliae* on *A. swirskii*, our results would indicate that the two can be used together for whitefly and spider mite control.

Biological *vs* chemical control

In general, pesticides provided better control of whiteflies than *A. swirskii* (Tables 2–5), similar control of spider mites compared to both mites (Tables 2–5), and less control of broad mites than *A. swirskii* (Tables 4, 5). Abamectin is considered harmful to both *A. swirskii* and *N. californicus* and spiromesifen is considered moderately harmful and very persistent against *A. swirskii* (Poletti *et al*. 2007; Audenaert *et al*. 2013; Koppert 2015). Increased spider mite densities in cotton were attributed to effects of foliar-applied thiamethoxam on natural enemies (Smith *et al*. 2013). In addition, neonicotinoids can cause increased fecundity in spider mites through a hormoligant effect (James & Price 2002). Given these incompatibilities and the effectiveness of early season releases of predacious mites to control the target pests, reserving pesticides for late season control if necessary could be an effective strategy for combining biological and chemical control in these crops.

Most published information on use of predacious mites for control of vegetable pests comes from laboratory or greenhouse studies. Nevertheless, most vegetable crops are still grown in the open field although this is the least controllable environment for experimentation. Early establishment is key to success as in greenhouses. Yet, the details of best management practices will depend, in part, on the crop type, pest and disease incidence, interactions with crop protection chemicals, environmental conditions and all the other variables of open field horticulture. Our results demonstrate the potential of phytoseiid predators for management of whiteflies, mites and thrips in many open field vegetable crops excluding tomato to which *N. californicus* and *A. swirskii* are maladapted (Koller *et al*. 2007; Buitenhuis *et al*. 2014). The advantages of this approach are becoming ever more evident as are the drawbacks of total dependence on pesticides. Successful integration of biological control into open field vegetable production will ultimately depend on the experience and expertise of growers and crop protection specialists.

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REFERENCES

Audenaert, J., Vissers, M. & Gobin, B. 2013. Testing side-effects of common pesticides on *A. swirskii* under greenhouse circumstances. *Communications in Agricultural and Applied Biological Sciences* **79** (2): 207–210. https://www.ncbi.nlm.nih.gov/pubmed/26084099

Buitenhuis, R., Shipp, L. & Scott-Dupree, C. 2010. Intra-guild vs extra-guild prey: effect on predator fitness and preference of *Amblyseius swirskii* (Athias-Henriot) and *Neoseiulus cucumeris* (Oudemans) (Acari: Phytoseiidae). *Bulletin of Entomological Research* **100** (2): 167–173. https://doi.org/10.1017/S0007485309006944

Buitenhuis, R., Shipp, L., Scott-Dupree, C., Brommit, A. & Lee, W. 2014. Host plant effects on the behaviour and performance of *Amblyseius swirskii* (Acari: Phytoseiidae). *Experimental and Applied Acarology* **62** (2): 171–180. https://doi.org/10.1007/s10493-013-9735-1

Çakmak, I., Janssen, A. & Sabelis, M.W. 2006. Intraguild interactions between the predatory mites *Neoseiulus californicus* and *Phytoseiulus persimilis*. *Experimental and Applied Acarology* **38** (1): 33–46. https://doi.org/10.1007/s10493-005-6247-7

Calvo, F.J., Bolckmans, K. & Belda, J.E. 2011. Control of *Bemisia tabaci* and *Frankliniella occidentalis* in cucumber by *Amblyseius swirskii*. *BioControl* **56** (2): 185–192. https://doi.org/10.1007/s10526-010-9319-5

Calvo, J., Fernández, P., Bolckmans, K. & Belda, J.E. 2006. *Amblyseius swirskii* (Acari: Phytoseiidae) as a biological control agent of the tobacco whitefly *Bemisia tabaci* (Hom.: Aleyrodidae) in protected sweet pepper crops in Southern Spain. *IOBC/WPRS Bulletin* **29**: 77–82.

Denmark, H.A. & Evans, G.A. 2011. *Phytoseiidae of North America and Hawaii: (Acari, Mesostigmata)*. Indira Publishing House, West Bloomfield, USA, 451 pp.

Dinsdale, A., Cook, L., Riginos, C., Buckley, Y.M. & De Barro, P. 2010. Refined global analysis of *Bemisia tabaci* (Hemiptera: Sternorrhyncha: Aleyrodoidea: Aleyrodidae) mitochondrial cytochrome oxidase 1 to identify species level genetic boundaries. *Annals of the Entomological Society of America* **103** (2): 196–208. https://doi.org/10.1603/AN09061

Florida Department of Agriculture and Consumer Services [FDACS]. 2013. 2013 Vegetables, melons and berries. *In*: Ewing, J. (Ed.), *2013 Florida agriculture by the numbers*. FDACS, Tallahassee, FL, USA, pp. 78–96. https://www.nass.usda.gov/Statistics_by_State/Florida/Publications/Annual_Statistical_Bulletin/FL_Agriculture_Book/2013/2013%20FL%20Ag%20by%20the%20Numbers.pdf

Gerson, U. & Weintraub P.G. 2007. Mites for the control of pests in protected cultivation. *Pest Management Science* **63** (7): 658–676. https://doi.org/10.1002/ps.1380

Goleva, I. & Zebitz, C.P.W. 2013. Suitability of different pollen as alternative food for the predatory mite *Amblyseius swirskii* (Acari, Phytoseiidae). *Experimental and Applied Acarology* **61** (3): 259–283. https://doi.org/10.1007/s10493-013-9700-z

Hilje, L., Costa, H.S. & Stansly, P.A. 2001. Cultural practices for managing *Bemisia tabaci* and associated viral diseases. *Crop Protection* **20** (9): 801–812. https://doi.org/10.1016/S0261-2194(01)00112-0

James, D.G. & Price, T.S. 2002. Fecundity in twospotted spider mite (Acari: Tetranychidae) is increased by direct and systemic exposure to imidacloprid. *Journal of Economic Entomology* **95** (4): 729–732.
https://doi.org/10.1603/0022-0493-95.4.729

Jovicich, E., Cantliffe, D.J., Osborne, L.S., Stoffella, P.J., Simonne, E.H., Mason, P.G. &. David, R. 2009. Release of *Neoseiulus californicus* on pepper transplants to protect greenhouse-grown crops from early broad mite (*Polyphagotarsonemus latus*) infestations. *In*: Mason, P.G., Gillespie, D.R. & Vincent, C. (Eds.), *Proceedings of the Third International symposium on biological control of arthropods*. USDA Forest Service, Christchurch, New Zealand, pp. 347–353.

Kakkar, G., Kumar, V., Seal, D.R., Liburd, O.E. & Stansly, P.A. 2016. Predation by *Neoseiulus cucumeris* and *Amblyseius swirskii* on *Thrips palmi* and *Frankliniella schultzei* on cucumber. *Biological Control* **92**: 85–91.
https://doi.org/10.1016/j.biocontrol.2015.10.004

Kawai, A. 1986. Studies on population ecology of *Thrips palmi* Karny. X. Differences in population growth on various crops. *Japanese Journal of Applied Entomology and Zoology* **30** (1): 7–11. [in Japanese, English abstract]
https://doi.org/10.1303/jjaez.30.7

Koller, M., Knapp, M. & Schausberger, P.P. 2007. Direct and indirect adverse effects of tomato on the predatory mite *Neoseiulus californicus* feeding on the spider mite *Tetranychus evansi*. *Entomologia Experimentalis et Applicata* **125** (3): 297–305.
https://doi.org/10.1111/j.1570-7458.2007.00625.x

Koppert. 2015. *The Koppert Side effects database*. https://www.koppert.com/side-effects.

Meck, E.D., Kennedy, G.G. & Walgenbach, J.F. 2013. Effect of *Tetranychus urticae* (Acari: Tetranychidae) on yield, quality, and economics of tomato production. *Crop Protection* **52**: 84–90.
https://doi.org/10.1016/j.cropro.2013.05.011

Messelink, G.J., van Maanen, R., van Steenpaal, S.E.F. & Janssen, A. 2008. Biological control of thrips and whiteflies by a shared predator: two pests are better than one. *Biological Control* **44** (3): 372–379.
https://doi.org/10.1016/j.biocontrol.2007.10.017

Messelink, G.J., Van Maanen, R., Van Holstein-Saj, R., Sabelis, M.W. & Janssen, A. 2010. Pest species diversity enhances control of spider mites and whiteflies by a generalist phytoseiid predator. *BioControl* **55** (3): 387–398.
https://doi.org/10.1007/s10526-009-9258-1

Midthassel, A., Leather, S.R., Wright, D.J. & Baxter, I.H. 2016. Compatibility of *Amblyseius swirskii* with *Beauveria bassiana*: two potentially complimentary biocontrol agents. *BioControl* **61** (4): 437–447.
https://doi.org/10.1007/s10526-016-9718-3

Müller, C.B. & Brodeur, J. 2002. Intraguild predation in biological control and conservation biology. *Biological Control* **25** (3): 216–223.
https://doi.org/10.1016/S1049-9644(02)00102-0

Nomikou, M., Janssen, A., Schraag, R. & Sabelis, M.W. 2001. Phytoseiid predators as potential biological control agents for *Bemisia tabaci*. *Experimental and Applied Acarology* **25** (4): 271–291.
https://doi.org/10.1023/A:1017976725685

Nomikou, M., Sabelis, M.W. & Janssen, A. 2010. Pollen subsidies promote whitefly control through the numerical response of predatory mites. *BioControl* **55** (2): 253–260.
https://doi.org/10.1007/s10526-009-9233-x

Parker, R. & Gerson, U. 1994. Dispersal of the broad mite, *Polyphagotarsonemus latus* (Banks) (Heterostigmata: Tarsonemidae), by the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood) (Homoptera: Aleyrodidae). *Experimental and Applied Acarology* **18** (10): 581–585.
https://doi.org/10.1007/BF00051720

Peña, J.E. & Osborne, L. 1996. Biological control of *Polyphagotarsonemus latus* (Acarina: Tarsonemidae) in greenhouses and field trials using introductions of predacious mites (Acarina: Phytoseiidae). *Entomophaga* **41** (2): 279–285.
https://doi.org/10.1007/BF02764253

Pijnakker, J., Arijs, Y., de Souza, A., Cellier, M. & Wäckers, F. 2016. The use of *Typha angustifolia* (cattail) pollen to establish the predatory mites *Amblyseius swirskii*, *Iphiseius degenerans*, *Euseius ovalis* and *Euseius gallicus* in glasshouse crops. *IOBC-WPRS Bulletin* **120**: 47−54.

Poletti, M., Maia, A.H.N. & Omoto, C. 2007. Toxicity of neonicotinoid insecticides to *Neoseiulus californicus* and *Phytoseiulus macropilis* (Acari: Phytoseiidae) and their impact on functional response to *Tetranychus urticae* (Acari: Tetranychidae). *Biological Control* **40** (1): 30–36.
https://doi.org/10.1016/j.biocontrol.2006.09.001

Polston, J.E., Hiebert, E., McGovern, R.J., Stansly, P.A. & Schuster, D.J. 1993. Host range of tomato mottle virus, a new geminivirus infecting tomato in Florida. *Plant Disease* **77**: 1181–1184.
https://doi.org/10.1094/PD-77-1181

Rosenheim, J.A., Kaya, H.K., Ehler, L.E., Marois, J.J. & Jaffee, B.A. 1995. Intraguild predation among biological-control agents: theory and evidence. *Biological Control* **5** (3): 303–335.
https://doi.org/10.1006/bcon.1995.1038

SAS Institute. 2014. *SAS Version 9.3*. Cary, NC, USA. https://www.sas.com.

Shipp, J.L. & Ramakers, P.M.J. 2004. Biological control of thrips on vegetable crops. *In*: Heinz, K.M., Van Driesche, R.G. & Parrella, M.P. (Eds.), *Biocontrol in protected culture*. Ball Publishing, Batavia, IL, USA, pp. 265–276.

Smith, J.F., Catchot, A.L., Musser, F.R. & Gore, J. 2013. Effects of aldicarb and neonicotinoid seed treatments on twospotted spider mite on cotton. *Journal of Economic Entomology* **106** (2): 807–815.
https://doi.org/10.1603/EC10125

Stansly, P.A. & Castillo, J.A. 2009. Control of broad mite *Polyphagotarsomeus latus* and the whitefly *Bemisia tabaci* in open field pepper and eggplant with predaceous mites. *In*: Castane, C. & Perdikis, D. (Eds.), *Proceedings of the working group, Integrated Control in Protected Crops, Mediterranean climate*. *IOBC/WPRS Bulletin* **49**: 145–152.

———2010. Control of broad mites, spider mites, and whiteflies using predaceous mites in open-field pepper and eggplant. *Procceding of Florida State Horticulture Society* **122**: 253–257.
https://fshs.org/proceedings-o/2009-vol-122/FSHS%20vol.%20122/253-257.pdf

van den Boom, C.E.M.., Beek, T.A. & Dicke, M. 2003. Differences among plant species in acceptance by the spider mite *Tetranychus urticae* Koch. *Journal of Applied Entomology* **127** (3): 177–183.
https://doi.org/10.1046/j.1439-0418.2003.00726.x

van Maanen, R., Vila, E., Sabelis, M.W. & Janssen, A. 2010. Biological control of broad mites (*Polyphagotarsonemus latus*) with the generalist predator *Amblyseius swirskii*. *Experimental and Applied Acarology* **52** (1): 29–34.
https://dx.doi.org/10.1007%2Fs10493-010-9343-2

Webb, S.E., Stansly, P.A., Schuster, D.J. & Funderburk, J.E. 2010. Insect management for tomatoes, peppers, and eggplant. *UF-IFAS Extension Bulletin* **ENY-461**: 1–68.
http://edis.ifas.ufl.edu/in169 (accessed 9 June 2018)

Weintraub, P. & Palevsky, E. 2008. Evaluation of the predatory mite, *Neoseiulus californicus*, for spider mite control on greenhouse sweet pepper under hot arid field conditions. *Experimental and Applied Acarology* **45** (1–2): 29–37.
https://doi.org/10.1007/s10493-008-9169-3

Weintraub, P.G., Kleitman, S., Mori, R., Shapira, N. & Palevsky, E. 2003. Control of the broad mite (*Polyphagotarsonemus latus* (Banks)) on organic greenhouse sweet peppers (*Capsicum annuum* L.) with the predatory mite, *Neoseiulus cucumeris* (Oudemans). *Biological Control* **27** (3): 300–309.
https://doi.org/10.1016/S1049-9644(03)00069-0