

Dispersal of *Amblyseius swirskii* (Acari: Phytoseiidae) on High-Tunnel Bell Peppers in Presence or Absence of *Polyphagotarsonemus latus* (Acari: Tarsonemidae)

L. Lopez^{1,2}, H. A. Smith³, M. A. Hoy¹, and R. D. Cave⁴

¹1881 Natural Area Drive, Entomology and Nematology Department, University of Florida, Gainesville, FL 32611, USA,

²Corresponding author e-mail: lorelopezq.257@ufl.edu, ³4625 Co Rd 672, Gulf Coast Research and Education Center (GCREC), University of Florida, Wimauma, FL 33598, USA, and ⁴2199 South Rock Road, Indian River Research and Education Center (IRREC), University of Florida, Fort Pierce, FL, 34945, USA

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Abstract

Amblyseius swirskii Athias-Henriot (Acari: Phytoseiidae) is a predatory mite used to control thrips (Thysanoptera), whiteflies (*Bemisia tabaci* Genn., Hemiptera: Aleyrodidae), and broad mites (BMs) (*Polyphagotarsonemus latus* Banks, Acari: Tarsonemidae). Dispersal of *A. swirskii*, using the ornamental pepper “Explosive Ember” as a banker plant was evaluated for control of BMs in high-tunnel peppers. Open-canopy plants (5 weeks old) versus closed-canopy plants (10-weeks old) were used to evaluate the effect of plant connectedness in *A. swirskii* dispersal, in the presence (two females per plant) and absence of BMs. Plots consisted of a single central banker plant and four bell peppers extending linearly north and south. Sets of all treatments were destructively sampled 1, 4, and 7 days after releasing *A. swirskii*. Within 24 h, *A. swirskii* dispersed four plants away from the banker plants (1 m), regardless of the state of the canopy. Canopy connectedness did increase the presence of *A. swirskii* on the crop plants. Predatory mite numbers on closed-canopy treatments doubled within the 7-day sampling period, whereas no significant increase was observed on open-canopy treatments. The presence of BMs had no significant effect on the movement of *A. swirskii*. The results suggest further experiments with *A. swirskii* and banker plants for control of BMs is warranted.

Key words: biological control, predatory mite, dispersal capacity, Acari, Phytoseiidae

The predatory mite *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) became one of the most successful biocontrol agents in protected agriculture after its introduction into the market in 2005 (Calvo et al. 2015). It is an effective predator of major pests in Florida bell pepper production, such as thrips (Thysanoptera) and broad mites (BMs) (*Polyphagotarsonemus latus* Banks, Acari: Tarsonemidae), and less frequent pests such as sweetpotato whiteflies (WFs) (*Bemisia tabaci* Genn., MEAM1, Hemiptera: Aleyrodidae) (Xu and Enkegaard 2010, Onzo et al. 2012, Ozores-Hampton et al. 2014, Buitenhuis et al. 2015).

BMs attacking bell peppers can be found in protected structures, including high tunnels, causing the development of stunted plants that produce small and poor-quality fruits or no fruit (Ibrahim and Low 1998, Jovicich et al. 2004). Research on *A. swirskii* has shown it is successful controlling BMs (Van Maanen et al. 2010, Onzo et al. 2012), but only few studies have assessed its performance under field conditions (Abou-Awad et al. 2014a,b).

Several studies have demonstrated that augmentative releases of *A. swirskii* significantly improve control of *Frankliniella occidentalis* Pergande (Thysanoptera: Thripidae) and *B. tabaci*, in sweet pepper,

cucumber, eggplant, melon, and zucchini crops grown in commercial greenhouses when good coverage is achieved (Calvo et al. 2008, 2011, 2012). Buitenhuis et al. (2015) showed that one *A. swirskii* release sachet must be used on every plant to achieve good coverage in greenhouse-grown chrysanthemums. When using *A. swirskii* bran product, predatory mites should be ideally added to every plant in the crop to ensure pest suppression. However, augmentative releases of natural enemies by bran product or sachets on every plant requires the frequent purchase of large amounts of commercial predatory mites, which can be expensive and labor intensive (Collier and Van Steenwyk 2004, Frank 2010).

The ability of a predatory mite to suppress pests is strongly influenced by its capacity to disperse from the release site and seek prey throughout the crop (Pratt and Croft 2000, Skirvin and Fenlon 2003; Buitenhuis et al. 2010; Parolin et al. 2014). Because they cannot fly, adequate coverage with augmentative releases of *A. swirskii* is determined by its ambulatory dispersal capacity. Thus, plant connectivity is one of the most important factors to consider when introducing predatory mites into cropping systems (Buitenhuis et al.

2015). Spacing between plants or containers can result in the loss of predatory mites that walk down the plant or container trying to reach neighboring plants. A closed canopy created when the leaves of neighboring plants are in contact is an ideal situation for predatory mite dispersal, but canopy connectivity varies according to the stage and age of the crop (Kumar et al. 2015). In Florida high tunnel pepper production, plants are grown in rows of contiguous pots or bags that are in contact with each other. This contact provides a plant-to-plant bridge for predatory mites in early stages of crop production before the foliage of adjacent plants is sufficiently abundant to overlap. The success of early releases of *A. swirskii* is dependent on the predator's ability to take advantage of these bridges.

Strategies aiding introduction of generalist predators such as *A. swirskii* in agroecosystems include the use of release sites or release plants that provide shelter and some type of food (prey, pollen, or nectar) to enhance survival and reproduction when the target pest is not yet present (Kumar et al. 2015). Non-crop banker plants hosting large numbers of *A. swirskii* have been used as release site and have been evaluated as a potentially more cost effective technique that reduces or eliminates the need for multiple releases (Collier and Van Steenwyk 2004; Huang et al. 2011; Parolin et al. 2012; Xiao et al. 2012; Kumar et al. 2015).

Most research on *A. swirskii* control over BMs and its ambulatory dispersal has been conducted in laboratories and greenhouses. There is no information regarding *A. swirskii* dispersal or the level of plant protection provided by *A. swirskii* under high-tunnel bell pepper culture when diverse prey is available. Therefore, experiments were conducted to 1) evaluate the dispersal of *A. swirskii* from release plants to neighboring bell pepper plants at different ages and different phenology (i.e. number of leaves, canopy connectedness, and presence of flowers) under high tunnels, 2) determine the influence of prey presence (i.e. BMs artificially introduced) on *A. swirskii* movement from plant to plant, and 3) monitor the abundance of naturally occurring alternative prey for *A. swirskii* (e.g. WFs and thrips).

Materials and Methods

Study Site and Pepper Plants

Four field trials were conducted in November, December 2013, February, and March 2014 at the University of Florida's Gulf Coast Research and Education Center (GCREC), Wimauma, FL. Experiments were carried out in a high tunnel (Tunnel Tech, Tillsonburg, Ontario, Canada) 8.5- × 5- × 61-m (width × height × length). Temperature and relative humidity (RH) were measured inside the high tunnel using a HOBO data logger (Onset Co., Bourne, MA, USA) placed 60 cm above the ground.

The ornamental pepper 'Explosive Ember' (Ball Horticultural Co., Chicago, IL, USA) and determinate bell pepper 'Revolution' (Harris Moran Co., Modesto, CA, USA) were sown in cell plug trays containing potting mix (Fafard 2 mix; Fafard, Agawam, MA, USA) in a greenhouse ($25 \pm 2^\circ\text{C}$, $40 \pm 20\%$ RH). Seedlings were transplanted four weeks after sowing into 4.5-L plastic pots, using pine bark as growing medium with 15 g of slow release fertilizer per plant (Osmocote 14-14-14; Scotts, Marysville, OH, USA), and drip irrigated.

Experimental Design

Five-week-old bell pepper plants (9 ± 2 leaves per plant and 0 flowers) were used to test movement of *A. swirskii* when pots, but not leaves, were touching (open canopy). Ten-week-old bell pepper plants (27 ± 9 leaves per plant and 2 ± 1 flowers per plant) were used to test mite movement when both pots and leaves were touching (closed canopy). Each canopy state was assessed in the presence

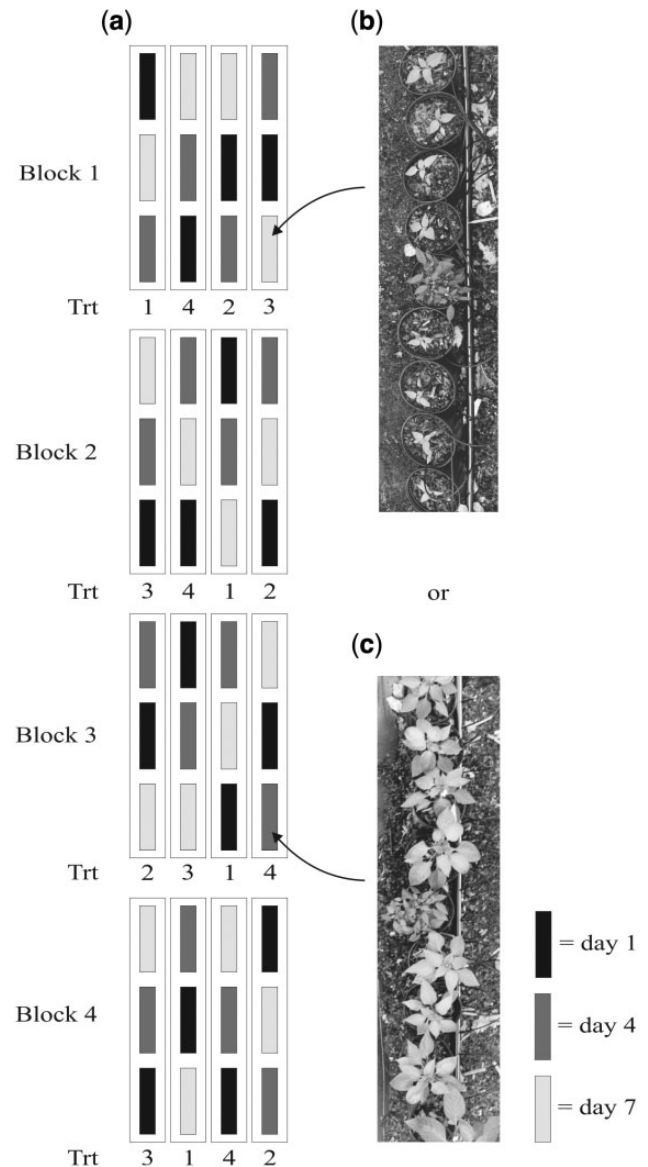


Fig. 1. Experimental design. (a) Plots were arranged among four blocks (replicates) under the high tunnel. Each block consisted of four groups of three plots, each group representing one treatment (Trt), and each plot corresponding to one of three sampling days after release of *A. swirskii*. Randomization was changed at the beginning of each trial. (b) Pepper plant distribution within plots of the open-canopy treatments. (c) Pepper plant distribution within plots of the closed-canopy treatments.

and absence of BMs. Treatments were 1) Open canopy + BM, 2) Open canopy, 3) Closed canopy + BM, 4) Closed canopy.

Each treatment combination was arranged among four blocks (replicates). Each block consisted of four groups of three plots, each group representing one treatment, and each plot corresponding to one of three sampling days for a total of 48 plots per trial (Fig. 1a). Suspended polypropylene curtains were placed to minimize movement of insects and mites between treatments. No pesticides were applied before or during the experiments.

Plots consisted of a single row of nine plants with one release plant placed in the center and four bell pepper plants extending linearly north and south (plot area $\sim 0.7 \text{ m}^2$), plant position 1 being adjacent to the release plant and plant position 4 being the farthest from the release plant (Fig. 1b and c). Ornamental peppers (8–10

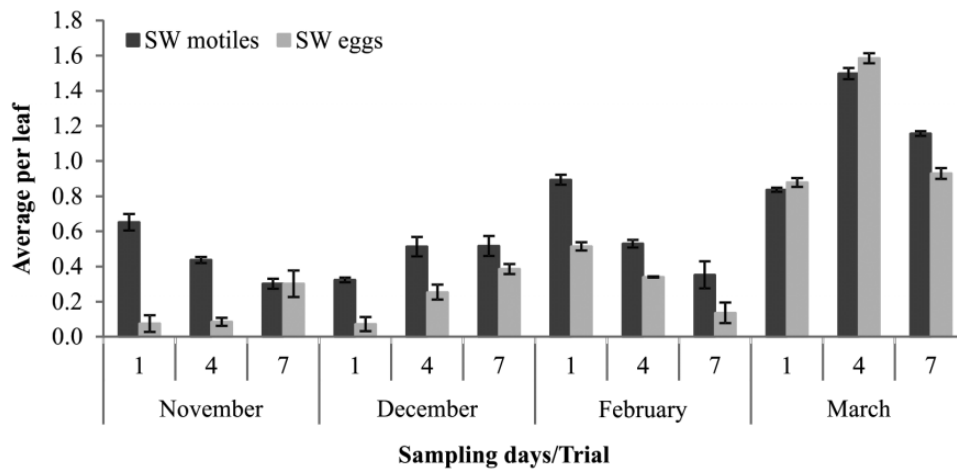


Fig. 2. Mean number and SEM of *A. swirskii* (SW) eggs and motiles found on 'Explosive Ember' release plants 1, 4, and 7 days after release in the November, December, February, and March trials. Untransformed data are presented.

weeks old) were used as release plants (131 ± 58 leaves per plant and 21 ± 15 flowers per plant).

The top third of bell pepper plants (9 ± 2 leaves per plant) were checked for mites and insects because this is the area where most *A. swirskii* and BMs ($\sim 75\%$) were found in previous studies (Abou-Awad et al. 2014a,b; Lopez 2014). Numbers of eggs of *A. swirskii* and BMs per leaf were recorded. Nymphs and adult males and females of both mite species per leaf were recorded together as motiles. Naturally occurring pests, such as thrips and WFs, and naturally occurring predators found on peppers were recorded and identified to species when possible. On days 1, 4, and 7 after placement of the release plants in the tunnel (day 0), all pepper plants (including the ornamental peppers) from one randomly chosen plot of each treatment in each block (Fig. 1a) were cut at the base of the stem, placed separately in plastic bags, and refrigerated prior to counting mites and insects under the stereoscope. By day 7, all plots were sampled. Bell Pepper Plant Infestation and *A. swirskii* Release

Treatments receiving BMs were infested from a colony maintained at the GCREC by securing one leaf strip (0.5×0.5 cm) with two adult female BMs per strip on each bell pepper plant using 100% egg albumin as glue immediately after the potted plants were moved to the high tunnel.

Three days after bell pepper plants were inoculated with BMs, ornamental pepper release plants were treated with 1.5 g of bran containing ~ 200 (± 42) predatory mites from a single tube of *A. swirskii* in loose bran used the day of arrival for each of the four trials. The release rate used was based on the rate recommended for high levels of pest infestations ($100\text{--}250$ mites/m², BioBest 2013, Koppert Biological Systems 2013). Ornamental peppers were placed under the tunnel 24 h after treatment with *A. swirskii*.

Statistical Analysis

The high-tunnel experiments were arranged in a split-split plot design. Three factors were compared: 1) trials (November, December, February, and March), 2) treatment combination (Open canopy + BM, Open canopy, Closed canopy + BM, Closed canopy), and 3) plant position (first, second, third, or fourth plant away from the release plant). There were three levels for each factor combination determined by sampling day: 1, 4, and 7 days after release of *A. swirskii* (Fig. 1a). All data obtained were square-root transformed to meet assumptions of normality. Because release plants were treated equally in all plots (contrary to bell peppers), numbers of *A. swirskii* recorded

on the ornamental peppers were analyzed separately using a one-way analysis of variance (ANOVA) to determine differences in dispersal among trials ($P < 0.05$), followed by a Tukey's mean separation test.

Six response variables measured in the bell peppers were analyzed: numbers of *A. swirskii* eggs and motiles, BM eggs and motiles, sweetpotato WF eggs, and thrips (immatures and adults counted together). To identify any relationship between variables, Pearson's correlation coefficient (r) was calculated. A factorial ANOVA was conducted using data from bell pepper plants to identify interactions among trials, treatment combinations, sampling days, and plant positions ($P < 0.05$), followed by a Tukey's mean separation test when appropriate. Data were analyzed using SAS 9.3 (SAS Institute Inc., 2011) and Statistica 9 (Statsoft 1995).

Results

A. swirskii Dispersal from the Release Plants

Twenty-four hours after release, an average of $24 \pm 0.1\%$ (49 mites per plant or 1.78 mites per leaf) of the released *A. swirskii* (200 ± 42 individuals or 1.5 individuals per leaf) was found per release plant. There was a significant trial-by-sampling day interaction for *A. swirskii* eggs and motiles recorded on the release plants ($F_{6,141} = 5.26$; $P < 0.001$ and $F_{6,141} = 3.45$; $P = 0.003$). The highest numbers were obtained in the March trial by day 4 (Fig. 2), an average of one *A. swirskii* egg every three leaves and one motile every four leaves (0.4 ± 0.1 and 0.3 ± 0.04 per leaf, respectively). The lowest *A. swirskii* numbers on release plants were recorded in the December trial by day 1 (Fig. 2), an average of one egg every 67 leaves and one motile every 17 leaves (0.02 ± 0.01 and 0.1 ± 0.02 per leaf, respectively). No significant differences among treatments (state of the canopy and presence or absence of BMs) were found for *A. swirskii* eggs and motiles recorded on the release plants over all trials.

No naturally occurring predators or BMs were observed on release plants within the seven-day sampling period. Adults of *Frankliniella bispinosa* Morgan (Thysanoptera: Thripidae) and immatures stages of sweetpotato WFs (each 1 ± 1 per plant) were observed on six ($\sim 3\%$) of the 192 ornamental peppers used.

The Effect of Canopy Connectedness on *A. swirskii* and BMs

There was a significant trial-by-treatment interaction for numbers of *A. swirskii* eggs ($F_{9,717} = 18.74$, $P < 0.0001$), *A. swirskii* motiles

Table 1. Mean number (\pm SEM) of *A. swirskii* eggs (SW eggs), *A. swirskii* motiles (SW motiles), BM eggs, BM motiles, WF eggs, and thrips per bell pepper leaf sampled in each treatment over a seven-day period

	Treatment	SW eggs	SW motiles	BM eggs	BM motiles	WF eggs	Thrips
November	Open + BM	0.012 \pm 0.012b	0.017 \pm 0.004b	0.353 \pm 0.145a	0.391 \pm 0.125a	0.639 \pm 0.110ab	0.218 \pm 0.063
	Open	0.018 \pm 0.006b	0.025 \pm 0.009b	0.009 \pm 0.009c	0.009 \pm 0.005b	0.808 \pm 0.186a	0.145 \pm 0.068
	Closed + BM	0.242 \pm 0.099a	0.266 \pm 0.036a	0.124 \pm 0.057b	0.123 \pm 0.044b	0.276 \pm 0.011bc	0.100 \pm 0.025
	Closed	0.233 \pm 0.119a	0.373 \pm 0.082a	0.025 \pm 0.012c	0.015 \pm 0.010b	0.182 \pm 0.019c	0.145 \pm 0.037
December	Open + BM	0.008 \pm 0.005b	0.018 \pm 0.005b	0.367 \pm 0.089a	0.455 \pm 0.172a	0.641 \pm 0.105a	0.008 \pm 0.006
	Open	0.011 \pm 0.006b	0.011 \pm 0.005b	0.005 \pm 0.005b	0.003 \pm 0.002b	0.363 \pm 0.070ab	0.011 \pm 0.002
	Closed + BM	0.182 \pm 0.063a	0.119 \pm 0.038a	0.447 \pm 0.182a	0.387 \pm 0.148a	0.206 \pm 0.029b	0.019 \pm 0.007
February	Open + BM	0.004 \pm 0.002b	0.005 \pm 0.003b	0.486 \pm 0.206a	0.624 \pm 0.108a	0.241 \pm 0.068ab	0.002 \pm 0.002
	Open	0.003 \pm 0.003b	0.007 \pm 0.000b	0.002 \pm 0.002b	0.002 \pm 0.002b	0.309 \pm 0.054a	0.005 \pm 0.003
	Closed + BM	0.112 \pm 0.053a	0.186 \pm 0.098a	0.417 \pm 0.103a	0.418 \pm 0.059a	0.112 \pm 0.009ab	0.016 \pm 0.003
	Closed	0.031 \pm 0.023b	0.080 \pm 0.052ab	0.000 \pm 0.000b	0.018 \pm 0.018b	0.074 \pm 0.016b	0.011 \pm 0.003
March	Open + BM	0.035 \pm 0.018c	0.065 \pm 0.012	0.222 \pm 0.041a	0.354 \pm 0.050a	0.604 \pm 0.118ab	0.020 \pm 0.005
	Open	0.024 \pm 0.011c	0.053 \pm 0.030	0.000 \pm 0.000b	0.000 \pm 0.000b	0.476 \pm 0.020b	0.019 \pm 0.003
	Closed + BM	0.116 \pm 0.038b	0.111 \pm 0.051	0.288 \pm 0.119a	0.350 \pm 0.137a	0.878 \pm 0.123a	0.057 \pm 0.012
	Closed	0.226 \pm 0.111a	0.193 \pm 0.101	0.000 \pm 0.000b	0.001 \pm 0.001b	0.701 \pm 0.143ab	0.106 \pm 0.025

Letters following means within a column indicate significant differences ($P < 0.05$) calculated using Tukey's mean separation test. Untransformed data are presented.

($F_{9,717} = 21.51$, $P < 0.0001$), BM eggs ($F_{9,717} = 19.43$, $P < 0.0001$), BM motiles ($F_{9,717} = 19.52$, $P < 0.0001$), and WF eggs ($F_{9,717} = 9.31$, $P < 0.0001$) on the bell peppers. Thus, data from the four trials is shown separately. Because WF nymphs were found on less than 6% of the bell peppers (0.52 ± 0.98 nymphs per plant) from each trial, only WF eggs were included in the analyses. No trial-by-treatment interaction was found for thrips, but their numbers were analyzed separately as with the rest of the variables for consistency.

The greatest numbers of *A. swirskii* and BMs on bell peppers were observed in the March trial, whereas the lowest were recorded in the February trial (Table 1). The warmest average temperatures and highest RH occurred during the March trial (22.4 °C and 63% RH) and the coldest average temperatures and lowest RH in the February trial (19 °C and 56% RH).

A. swirskii dispersed four bell pepper plants away from the release plants (1 m) within 24 h in all treatments and all trials. The state of the canopy (open vs. closed) had a greater influence on *A. swirskii* movement than the presence of BMs (Fig. 3), in spite of finding significant but low negative correlations between numbers of *A. swirskii* and BMs (November: $r = -0.33$ and March: $r = -0.26$ trials). In all trials, there were significant differences in *A. swirskii* eggs and motiles between open- and closed-canopy treatments, whereas no significant differences were found between treatments with or without BMs (Table 1). High numbers of *A. swirskii* eggs and motiles were observed in all closed-canopy treatments, whereas low numbers of *A. swirskii* eggs and motiles were recorded in all open-canopy treatments from all trials (Table 1). Similarly, statistical differences were observed for *A. swirskii* eggs and motiles at different distances from the release plants in all trials (Table 2). The highest numbers of *A. swirskii* motiles were found on bell peppers in the closed-canopy treatments immediately next to the release plant, regardless of the presence of BMs, in the December, February, and March trials (Fig. 3c and d). Numbers decreased on the bell peppers with increasing distance from the release plant or were unevenly distributed. No clear patterns were observed for *A. swirskii* abundance in the November trial (Fig. 3c and d).

There were significant differences for BM egg and motile numbers between open- and closed-canopy treatments and numbers at

different distances from the release plants in the December and March trials (Table 2). The highest abundance of BM eggs and motiles was recorded in the bell peppers farthest from the release plants in the closed-canopy treatments (Fig. 3c and d). The lowest abundance of BMs was observed in the bell peppers immediately next to the release plant in the open-canopy treatments, as where high numbers of *A. swirskii* were observed (Fig. 3a and b).

A. swirskii and Alternative Prey Interactions

Low numbers of WF eggs were observed in closed-canopy bell peppers across trials (Table 1). Distance from the release plant had a significant effect on WF egg numbers in all trials (Table 2). Abundance of WF eggs on bell peppers increased as distance from the release plant increased, and the highest abundance was always recorded on the most distant bell pepper, where low numbers of *A. swirskii* were recorded (Fig. 3a and b). Significant but low negative correlations between numbers of *A. swirskii* and sweetpotato WFs (November: $r = -0.3$ and December: $r = -0.22$ trials) were observed, suggesting that *A. swirskii* had some effect on WF populations.

WF egg numbers on the closed-canopy plants were significantly different among sampling days in the February trial, being six times higher by day 7 than day 1 (Table 2).

Three thrips species were identified on the bell peppers: Florida flower thrips (*F. bispinosa* Morgan); *Neohydatothrips* sp. (Thysanoptera: Thripidae); and black flower thrips (*Haplothrips gowdeyi* Franklin, Thysanoptera: Phlaeothripidae). There were no treatment effects on thrips abundance in any trial (Table 2). The presence of thrips appeared to be determined by the availability of flowers on the bell peppers. Moreover, *Tetranychus* sp., *Oligonychus* sp., (Acari: Tetranychidae) and one undetermined species of eriophyid were found on fewer than 3% of the plants (1–9, 1–5, and 1–7 mites per trial, respectively) in three of the trials.

Naturally Occurring Predators

Only two predatory mites naturally established on the bell pepper plants, and no effect on *A. swirskii* or BM populations was observed due to their low densities. Females of *Ameroseius* sp. (Acari: Ameroseiidae) were found associated with leaf domatia in fewer than 3% of the bell peppers from each trial (4–12 mites per trial).

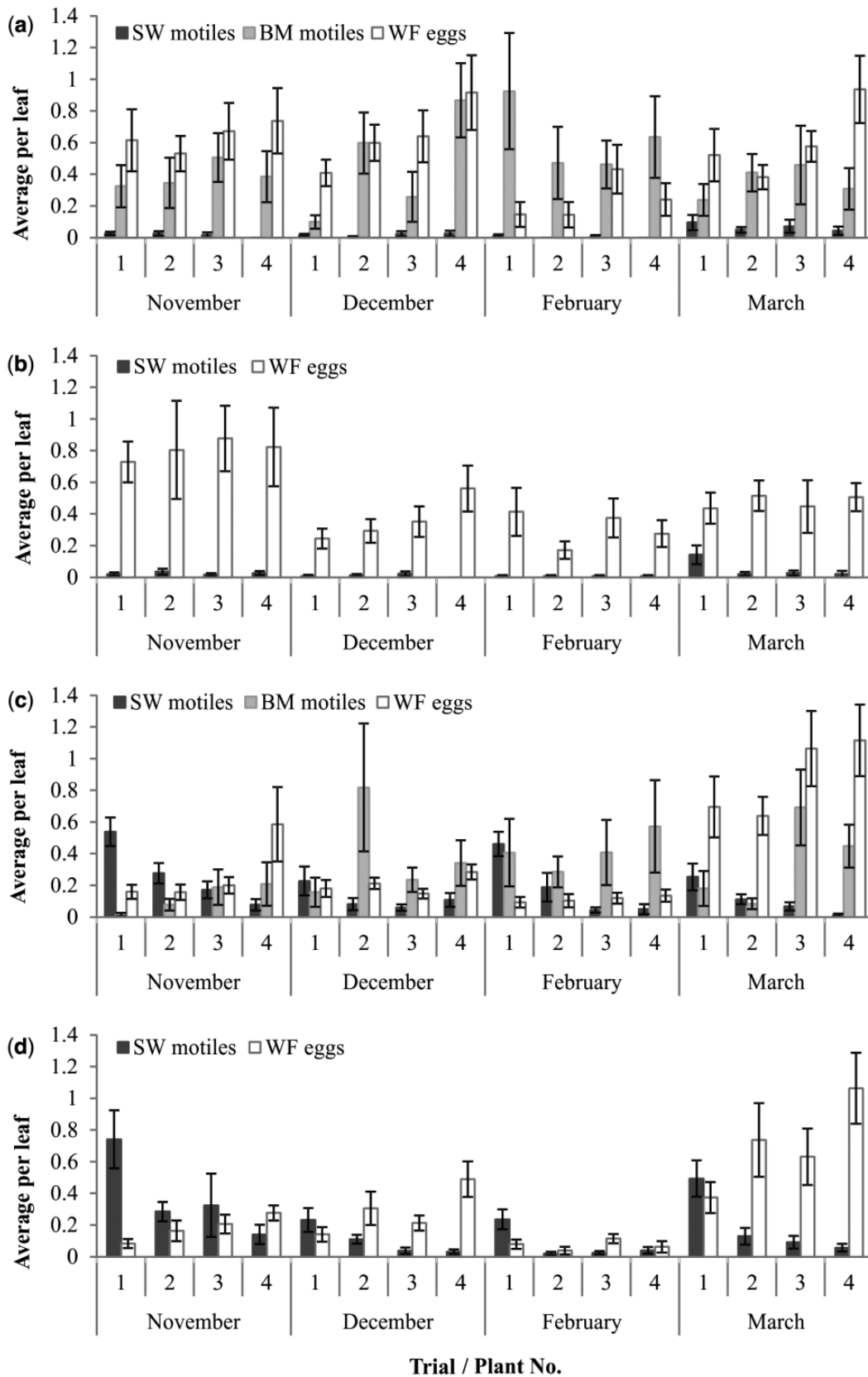


Fig. 3. Mean number and SEM of *A. swirskii* (SW) motiles, BM motiles, and WF eggs found on the first, second, third, and fourth bell pepper plant away from the release plant in all trials. (a) Open canopy + BM, (b) Open canopy, (c) Closed canopy + BM, (d) Closed canopy. Untransformed data are presented.

Table 2. Summary statistics of the ANOVA to identify differences among sampling days (Day), treatments (Trt), plant position (Plant), and interactions for *A. swirskii* (SW), BMs, WFs and thrips numbers per bell pepper leaf

		SW eggs		SW mobiles		BM eggs		BM mobiles		WF eggs		Thrips	
		F-value	P	F-value	P	F-value	P	F-value	P	F-value	P	F-value	P
November	Day	9.85	0.0008a	2.56	0.0976	3.01	0.0682	0.68	0.5149	0.95	0.3996	4.34	0.0245a
	Trt	21.41	0.0002a	22.31	0.0002a	70.89	<0.0001a	27.21	<0.0001a	9.29	0.0040a	0.22	0.8787
	Plant	8.33	<0.0001a	22.62	<0.0001a	1.00	0.3921	1.55	0.2048	3.27	0.0238a	0.66	0.5766
	Day*Trt	1.83	0.1349	0.45	0.8333	6.42	0.0004a	3.09	0.0217a	1.20	0.3367	0.36	0.8959
	Day*Plant	1.50	0.1837	1.81	0.1033	0.22	0.9678	1.44	0.2053	1.31	0.2557	1.11	0.3583
	Trt*Plant	3.50	0.0008a	5.86	<0.0001a	0.41	0.9247	0.39	0.9342	0.99	0.4469	0.76	0.6529
	Day*Trt*Plant	1.75	0.0407a	1.20	0.2710	1.38	0.1543	1.55	0.0863	0.54	0.9323	1.14	0.3234
December	Day	9.78	0.0008a	11.80	0.0003a	2.83	0.0787	1.03	0.3700	0.51	0.6057	0.13	0.8720
	Trt	26.21	<0.0001a	16.62	0.0005a	14.20	0.0009a	18.91	0.0003a	3.89	0.0490a	1.28	0.3367
	Plant	4.20	0.0075a	4.52	0.0050a	3.96	0.0101a	6.82	0.0003a	10.84	<0.0001a	2.10	0.1040
	Day*Trt	2.11	0.0891	1.79	0.1421	1.06	0.4111	0.61	0.7183	0.28	0.9392	0.43	0.8460
	Day*Plant	2.02	0.0679	1.80	0.1047	0.59	0.7328	0.69	0.6574	1.18	0.3221	0.35	0.9048
	Trt*Plant	2.76	0.0059a	2.57	0.0099a	2.20	0.0271a	2.92	0.0038a	0.40	0.9316	1.05	0.4043
	Day*Trt*Plant	1.33	0.1788	1.22	0.2521	0.54	0.9321	0.83	0.6571	1.18	0.2887	1.02	0.4371
February	Day	5.64	0.0098a	4.42	0.0232a	1.27	0.2978	0.49	0.6181	7.81	0.0024a	0.02	0.9793
	Trt	21.37	0.0002a	9.42	0.0039a	23.78	0.0001a	14.24	0.0009a	4.39	0.0365a	1.69	0.2369
	Plant	5.30	0.0019a	22.06	<0.0001a	0.36	0.7794	0.70	0.5489	3.61	0.0156a	0.46	0.7056
	Day*Trt	2.45	0.0539	1.24	0.3206	1.37	0.2656	0.41	0.8600	0.68	0.6621	0.31	0.9232
	Day*Plant	0.49	0.8128	0.07	0.9983	0.93	0.4719	0.40	0.8726	1.01	0.4170	1.63	0.1433
	Trt*Plant	3.86	0.0003a	7.41	<0.0001a	2.28	0.0218a	0.57	0.8149	0.96	0.4758	0.56	0.8191
	Day*Trt*Plant	0.74	0.7601	0.28	0.9980	1.97	0.0169a	2.46	0.0022a	0.62	0.8709	0.62	0.8716
March	Day	10.31	0.0006a	0.90	0.4160	1.63	0.2166	2.71	0.0868	0.22	0.7998	3.57	0.0437a
	Trt	36.90	<0.0001a	3.54	0.0610	18.61	0.0003a	15.98	0.0006a	3.89	0.0490a	3.63	0.0576
	Plant	16.59	<0.0001a	23.12	<0.0001a	2.67	0.0507	2.87	0.0397a	5.79	0.0010a	2.18	0.0943
	Day*Trt	2.82	0.0319a	0.66	0.6775	2.05	0.0977	2.73	0.0362a	0.46	0.8246	0.53	0.7776
	Day*Plant	1.08	0.3745	0.69	0.6510	0.24	0.9618	0.63	0.7006	2.37	0.0343a	0.84	0.5359
	Trt*Plant	3.10	0.0023a	2.59	0.0096a	4.61	<0.0001a	3.03	0.0029a	0.97	0.4662	0.87	0.5501
	Day*Trt*Plant	0.54	0.9307	0.94	0.5330	0.32	0.9960	0.91	0.5570	0.80	0.6877	1.49	0.1044

Square-root transformed data were used for analyses.

^aSignificantly different. Degrees of freedom: 2, 3, 3, 6, 6, 9, and 18 for Day, Trt, Plant, Day*Trt, Day*Plant, Trt*Plant, and Day*Trt*Plant, respectively.

Females of *Lasioseius* sp. (Acari: Ascidae) were found on <2% of the plants from the December and March trials (3 and 15 mites, respectively), sharing the same niche with *A. swirskii*.

Discussion

This is the first evaluation of *A. swirskii* dispersal from ornamental pepper release plants to neighboring bell pepper plants in a high tunnel. Various studies have stated that predatory mites do not migrate more than a plant or two away from their release sites (Skirvin and Fenlon 2003; Buitenhuis et al. 2010; Parolin et al. 2012, 2014). However, our results demonstrated that *A. swirskii* individuals moved four bell pepper plants away from the release plant (1 m), within 24 h in all treatments.

Pratt and Croft (2000) evaluated the dispersal of the generalist phytoseiid *Neoseiulus fallacis* Garman from arborvitae [*Thuja occidentalis* (L.), Cupressaceae] plants in a nursery setting to control *Tetranychus urticae* Koch (Acari: Tetranychidae), but the rate of dispersal was very low (<60 cm away within a week). Similarly, Buitenhuis et al. (2010) evaluated the dispersal of *A. swirskii* in a greenhouse system where one release plant (chrysanthemum) was surrounded by three circles of potted chrysanthemums to test the movement of *A. swirskii* in the presence or absence of western flower thrips (*F. occidentalis* Pergande, Thysanoptera: Thripidae). They did not find any predatory mites in the second circle (60 cm away from the chrysanthemum) 14 days after release and concluded that

A. swirskii had a very low dispersal rate when canopies were not connected.

The most commonly cited factor that limits the movement of biological control agents in outdoor cropping systems is “unfavorable environmental conditions” at the time of release (Collier and Van Steenwyk 2004). Weintraub et al. (2007) reported that dispersal of *N. californicus* is negatively affected by extreme cold and hot temperatures in sweet pepper crops. Abou-Awad et al. (2014a,b) suggested $21^{\circ} \pm 2^{\circ} \text{C}$ is the optimal temperature for development and reproduction of *A. swirskii*. In the present study, the highest numbers of *A. swirskii* were observed in the bell peppers during the March trial, which was the warmest (22.4 °C and 63% RH), and the predatory mite was apparently negatively affected by cold temperatures during the February trial (19 °C and 56% RH, Fig. 3).

As a generalist, *A. swirskii* is an effective predator of multiple prey simultaneously (Calvo et al. 2015, Jansen and Sabelis 2015). Messelink et al. (2010) showed that the presence of thrips and *T. urticae* enhanced WF control by *A. swirskii*, because this generalist predatory mite performs better on a mixed pest diet. This study aimed to determine the influence of BMs (artificially introduced) on *A. swirskii* movement from release plants to neighboring bell peppers. In addition, monitored alternative naturally occurring prey. Although our primary objective was to evaluate dispersal, we did find significant but low negative correlations between numbers of *A. swirskii*, BMs, and sweetpotato WFs. However, the highly variable numbers of *A. swirskii* among open- and closed-canopy treatments, as well as the

lack of an untreated control (no *A. swirskii*) limited our ability to describe the effect of *A. swirskii* on pest populations.

Unlike some studies evaluating the use of release plants and predatory mites (Parolin et al. 2012), bell pepper flowers were not eliminated during the experiment, even though they might have been attractive to pests and predators. High numbers of *A. swirskii* and thrips in closed-canopy treatments might be explained both by container and canopy connectedness, which allowed them to move easily, and the presence of bell pepper pollen. By allowing flowers in the bell peppers with a closed canopy, conditions similar to commercial high-tunnel pepper production systems were maintained. Moreover, the presence of flowers in crop plants and low numbers of pest mites, such as *Tetranychus* sp., *Oligonychus* sp., or eriophyid mites, might serve as alternative food items that might enhance the movement of generalist predators such as *A. swirskii* in times when target pests are not yet detected (Weintraub et al. 2007, Messelink et al. 2010, Xu and Enkegaard 2010, Kumar et al. 2015).

Our results offer useful information regarding the dispersal capacity of *A. swirskii* and the use of release plants for pest management in high-tunnel pepper production. Evaluations of biocontrol agents under commercial production conditions are essential for the development of proper use guidelines. Season temperature variations and variable pest abundance may influence the efficacy of biocontrol agents. Our research demonstrates the high dispersive capacity of *A. swirskii* on high-tunnel pepper under variable growing conditions and its potential as biocontrol agent in bell pepper culture.

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References Cited

- Abou-Awad, B. A., S. M. Hafez, and B. M. Farahat. 2014a. Bionomics and control of the broad mite *Polyphagotarsonemus latus* (Banks) (Acari: Tarsonemidae). Arch. Phytopathol. Plant Protect. 47: 631–641.
- Abou-Awad, B. A., S. M. Hafez, and B. M. Farahat. 2014b. Biological studies of the predacious mite *Amblyseius swirskii*, a predator of the broad mite *Polyphagotarsonemus latus* on pepper plants (Acari: Phytoseiidae: Tarsonemidae). Arch. Phytopathol. Plant Protect. 47: 349–354.
- BioBest. 2013. Technical sheet: Swirskii-System. (http://www.biobest.be/images/uploads/public/8694958177_Swirskii-System_EN.pdf).
- Buitenhuis, R., G. Murphy, L. Shipp, and C. Scott-Dupree. 2015. *Amblyseius swirskii* in greenhouse production systems: a floricultural perspective. Exp. Appl. Acarol. 65: 451–464.
- Buitenhuis, R., L. Shipp, and C. Scott-Dupree. 2010. Dispersal of *Amblyseius swirskii* Athias-Henriot (Acari: Phytoseiidae) on potted greenhouse chrysanthemum. Biol. Control 52: 110–114.
- Calvo, F. J., M. Knapp, Y. M. van Houten, H. Houten, H. Hoogerbrugge, and J. E. Belda. 2015. *Amblyseius swirskii*: what made this predatory mite such a successful biocontrol agent?. Exp. Appl. Acarol. 65: 419–433.
- Calvo, F. J., K. Bolckmans, and J. E. Belda. 2012. Biological control-based IPM in sweet pepper greenhouses using *Amblyseius swirskii* (Acari: Phytoseiidae). Biocontrol Sci. Tech. 22: 1398–1416.
- Calvo, F. J., K. Bolckmans, and J. E. Belda. 2011. Control of *Bemisia tabaci* and *Frankliniella occidentalis* in cucumber by *Amblyseius swirskii*. BioControl 56: 185–192.
- Calvo, F. J., K. Bolckmans, and J. E. Belda. 2008. Controlling the tobacco whitefly *Bemisia tabaci* (Genn.) (Hom.: Aleyrodidae) in horticultural crops with the predatory mite *Amblyseius swirskii* (Athias-Henriot). J. Insect Sci. 8: 11–12.
- Collier, T., and R. Van Steenwyk. 2004. A critical evaluation of augmentative biological control. Biol. Control 31: 245–256.
- Frank, S. D. 2010. Biological control of arthropod pests using banker plant systems: Past progress and future directions. Biol. Control 52: 8–16.
- Huang, N., A. Enkegaard, L. S. Osborne, P. M. J. Ramakers, G. J. Messelink, J. Pijnakker, and G. Murphy. 2011. The banker plant method in biological control. Crit. Rev. Plant Sci. 30: 259–278.
- Ibrahim, Y. B., and T. H. Low. 1998. Life cycle of the broad mite *Polyphagotarsonemus latus* (Banks) (Acari: Tarsonemidae) and its innate proliferating capacity on chilli. Mal. Appl. Biol. 27: 51–56.
- Janssen, A., and M. W. Sabelis. 2015. Alternative food and biological control by generalist predatory mites: the case of *Amblyseius swirskii*. Exp. Appl. Acarol. 65: 413–418.
- Jovicich, E., D. J. Cantliffe, L. S. Osborne, and P. J. Stoffella. 2004. Mite population and damage caused by broad mites (*Polyphagotarsonemus latus* [Banks]) infesting bell pepper (*Capsicum annuum* L.) at different seedling developmental stages. Acta Hort. 659: 339–344.
- Koppert Biological Systems. 2013. Swirskii-Mite. (<http://www.koppert.com/products/products-pests-diseases/products/detail/swirski-mite-1/>).
- Kumar, V., Y. Xiao, C. L. McKenzie, and L. S. Osborne. 2015. Early establishment of the phytoseiid *Amblyseius swirskii* (Acari: Phytoseiidae) on pepper seedlings in a Predator-in-First approach. Exp. Appl. Acarol. 65: 465–481.
- Lopez, L. 2014. Use of *Amblyseius swirskii* for biological control of *Polyphagotarsonemus latus* in high-tunnel pepper production in Florida. (Unpublished master's thesis), University of Florida, Gainesville, FL, USA.
- Messelink, G. J., R. Van Maanen, R. Van Holstein-Saj, M. W. Sabelis, A. Janssen. 2010. Pest species diversity enhances control of spider mites and whiteflies by a generalist phytoseiid predator. BioControl 55: 387–398.
- Onzo, A., A. F. Houedokoho, R. Hanna. 2012. Potential of the predatory mite, *Amblyseius swirskii* to suppress the broad mite, *Polyphagotarsonemus latus* on the gboma eggplant, *Solanum macrocarpon*. J. Insect Sci. 12: 1–11.
- Ozores-Hampton, M., N. S. Boyd, E. J. McAvoy, H. A. Smith, G. E. Vallad. 2014. Pepper production. In G. E. Vallad, J. H. Freeman, and P. J. Dittmar (eds.), Vegetable and small fruit production handbook of Florida, University of Florida, UF/IFAS Extension, Gainesville, FL, USA; (<http://edis.ifas.ufl.edu/pdf/files/cv/cv29200.pdf>).
- Parolin, P., C. Bresch, C. Poncet, N. Desneux. 2014. Introducing the term “Biocontrol Plants” for integrated pest management. Sci. Agric. 71: 77–80.
- Parolin, P., C. Bresch, N. Desneux, R. Brun, A. Bout, R. Boll, C. Poncet. 2012. Secondary plants used in biological control: A review. Int. J. Pest Manage. 58: 91–100.
- Pratt, P. D., B. A. Croft. 2000. Banker plants: evaluation of release strategies for predatory mites. J. Environ. Hort. 18: 211–217.
- SAS Institute Inc. 2011. SAS® (9.3) System Options, Second Edition. Cary, NC, USA. (<http://support.sas.com/documentation/cdl/en/lesyoptsref/64892/HTML/default/viewer.htm#titlepage.htm>).
- Skirvin, D., J. Fenlon. 2003. Of mites and movement: the effects of plant connectedness and temperature on movement of *Phytoseiulus persimilis*. Biol. Control 27: 242–250.
- Statsoft Inc. 1995. Statistical user guide. Complete Statistical System Statsoft. Oklahoma, USA. (<http://www.statsoft.com/textbook/>).
- Van Maanen, R., E. Vila, M. W. Sabelis, A. Janssen. 2010. Biological control of broad mites (*Polyphagotarsonemus latus*) with the generalist predator *Amblyseius swirskii*. Exp. Appl. Acarol. 52: 29–34.
- Weintraub, P. G., S. Kleitman, V. Alchanatis, E. Palevsky. 2007. Factors affecting the distribution of a predatory mite on greenhouse sweet pepper. Exp. Appl. Acarol. 42: 23–35.
- Xiao, Y., P. Avery, J. Chen, C. McKenzie, L. Osborne. 2012. Ornamental peppers as banker plants for establishment of *Amblyseius swirskii* (Acari: Phytoseiidae) for biological control of multiple pests in greenhouse vegetable production. Biol. Control 63: 279–286.
- Xu, X., A. Enkegaard. 2010. Prey preference of the predatory mite, *Amblyseius swirskii* between first instar western flower thrips *Frankliniella occidentalis* and nymphs of the twospotted spider mite *Tetranychus urticae*. J. Insect Sci. 10: 1–11.