Biological Control 58 (2011) 239–247

Contents lists available at ScienceDirect

Biological Control

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

Establishment of papaya banker plant system for parasitoid, *Encarsia sophia* (Hymenoptera: Aphilidae) against *Bemisia tabaci* (Hemiptera: Aleyrodidae) in greenhouse tomato production

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ARTICLE INFO

Article history:
Received 7 October 2010
Accepted 6 June 2011
Available online 13 June 2011

Keywords:
Banker plant system
Biological control
Tomato
Papaya plant
Bemisia tabaci
Trialeurodes variabilis
Encarsia sophia

ABSTRACT

The silverleaf whitefly, *Bemisia tabaci* biotype B (Gennadius) (Hemiptera: Aleyrodidae), is a key pest of tomato (*Solanum lycopersicum* L.) and other vegetable crops worldwide. To combat this pest, a non-crop banker plant system was evaluated that employs a parasitoid, *Encarsia sophia* (Girault & Dodd) (Hymenoptera: Aphelinidae) with whitefly, *Trialeurodes variabilis* (Quaintance) (Hemiptera: Aleyrodidae), as an alternative host for rearing and dispersal of the parasitoid to the target pest. (a) Multi-choice and no-choice greenhouse experiments were conducted to determine host specificity of *T. variabilis* to papaya (*Carica papaya* L.) and three vegetable crops including tomato, green bean (*Phaseolus vulgaris* L.), and cabbage (*Brassica oleracea* L.). The result showed that papaya was an excellent non-crop banker plant for supporting the non-pest alternative host, *T. variabilis*, whose adults had a strong specificity to papaya plants for feeding and oviposition in both multi-choice and no-choice tests. (b) The dispersal ability of *E. sophia* was investigated from papaya banker plants to tomato and green bean plants infested with *B. tabaci*, as well as to papaya control plants infested with *T. variabilis*; and (c) the percent parasitism by *E. sophia* on *T. variabilis* reared on papaya plants and on *B. tabaci* infested on tomato plants was also evaluated. These data proved that *E. sophia* was able to disperse at least 14.5 m away from papaya plants to target tomato, bean or papaya control plants within 48–96 h. Furthermore, *E. sophia* was a strong parasitoid of both *T. variabilis* and *B. tabaci*. There was no significant difference in percent parasitism by *E. sophia* on *T. variabilis* (36.2–47.4%) infested on papaya plants or *B. tabaci* (29–45.9%) on tomato plants. Thus, a novel banker plant system for the potential management of *B. tabaci* was established using papaya as a non-crop banker plant to support a non-pest alternative host, *T. variabilis* for maintaining the parasitoid to control *B. tabaci*. The established banker plant system should provide growers with a new option for long-term control of *B. tabaci* in greenhouse vegetable production. Ongoing studies on the papaya banker plant system are being performed in commercial greenhouses.

1. Introduction

The demand for fresh vegetables has significantly increased over the last 20 years in the US (Nzaku and Houston, 2009). Tomato (*Lycopersicon esculen*turn Mill.) is one of the most important fresh vegetables (Van Sickle, 2008). In addition to field production, greenhouse tomato production has rapidly increased since 2005, accounting for 37% of the total fresh market volume in the US (Cook and Calvin, 2005). In 2007, Florida topped the nation in tomato production and produced 0.65 billion kg of fresh tomatoes with a total value of $464 million (Van Sickle, 2008). Tomato production, however, has been increasingly threatened by the silverleaf whitefly, *Bemisia tabaci* B biotype (Gennadius) (Homoptera: Aleyrodidae), one of the most devastating tomato pests and plant virus vectors throughout the southern US.

B. tabaci is a polyphagous pest that has become a worldwide problem in more than 500 plant species across 74 families (Perring et al., 1993). *B. tabaci* can damage plants by producing honeydew which promotes the growth of sooty mold or by transmitting plant viruses through sap feeding (Hilje et al., 2001). It is a vector of 70 plant viruses in tropical and subtropical countries (Hunter and Poston, 2001). In Florida, the most damaging is tomato yellow leaf curl virus (Schuster and Stansly, 2009). The current number of

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doi:10.1016/j.biocontrol.2011.06.004

whitefly biotypes described for this species exceed 20 with two most invasive the B and Q biotypes (Perring et al., 1993). The Q biotype is extremely problematic to agricultural production because it has a high propensity to develop resistance to insect growth regulators (IGRs) (Horowitz et al., 2003) and neonicotinoid insecticides (Horowitz et al., 2004; Nauen and Denholm, 2005). During the past 5 years, biotype Q has been detected in 25 states across the country, including Florida (McKenzie et al., 2009).

Insecticides are the most common method used for controlling *B. tabaci*. However, intensive use of insecticides has resulted in reduced susceptibility of *B. tabaci* (Palumbo et al., 2001; Schuster and Stansly, 2009). With the increasing awareness of sustainable farming, management of *B. tabaci* through biological control has gained in popularity over the last decade. Among the natural parasitoids evaluated, those from the genera, *Encarsia* and *Eretmocerus* (Hymenoptera: Aphelinidae), have achieved some degree of success in both protected and field production environments (Gerling et al., 2001; Oliveira et al., 2001; Stansly et al., 2004, 2005). Stansly et al. (2005) found that the control of biotype Q by *Eretmocerus mundus* appeared to be more effective in pepper than in tomato plants. However, effective biological control must have parasitoid populations established in time to suppress pest populations, otherwise, pesticides had to be applied to suppress populations below the threshold levels.

Another derivation of biological control is to explore the potential of banker plant systems (Osborne et al., 2005; Frank, 2010). Banker plant systems consist of a plant that directly or indirectly provides resources, such as food or prey, to natural enemies that are deliberately released within a cropping system. The goal is to provide preventative, long-term suppression of arthropod pests (Osborne et al., 2005; Frank, 2010). Compared to augmentative or conservation biological control, banker plant systems have received relatively little attention (Frank, 2010) and only limited literature is currently available. The first banker plant system developed in 1977 employed the parasitoid, *Encarsia formosa* Gahan (Hymenoptera: Aphelinidae) to suppress the whitefly, *Trialeurodes vaporariorum* Westwood (Homoptera: Aleyrodidae), in greenhouse tomatoes (Stacey, 1977). The flaw of this system, however, was apparent in that tomato plants were used as both crops and banker plants, which posed great risk for pest control and resulted in poor grower adoption. Consequently, the search for non-crop banker plants infested with non-pest alternative prey and suitable parasitoids continues.

It was reported that papaya (*Carica papaya* L.) is a host of the relatively host specific whitefly, *Trialeurodes variabilis,* (Quaintance) (Hemiptera: Aleyrodidae) (Lourencao et al., 2007), which was reported to be highly parasitized by the parasitoid, *Encarsia sophia* (Girault & Dodd) (Hymenoptera: Aphelinidae) (Gerling et al., 2001; Antony et al., 2003; Giorgini and Baldanza, 2004). *E. sophia* is a cosmopolitan parasitoid of whitefly pests (Giorgini and Baldanza, 2004) and was found to be a dominant parasitoid of *B. tabaci* worldwide (Osborne et al., 1990). Furthermore, *E. sophia* proved to be strong capability of host-feeder compared to other parasitoids (Zang and Liu, 2007). Therefore, evaluating papaya plants for their potential to maintain *E. sophia* through supporting alternative hosts coupled with determining the dispersal capacity and percent parasitism could be the cornerstones for developing a successful banker plant system for controlling *B. tabaci* in greenhouse tomato production.

Our overall goal in this study was to establish a papaya-based banker plant system for potentially managing *B. tabaci* in greenhouse tomatoes, as originally proposed by Osborne et al. (1990). The specific objectives were to (a) determine if papaya is a non-crop banker plant specifically preferred by an alternative non-pest insect host, *T. variabilis*; (b) investigate the dispersal ability and behavior of *E. sophia* between papaya, tomato, green bean, and cabbage plants in greenhouses; and (c) evaluate the percent parasitism of *E. sophia* on *T. variabilis* reared on papaya plants and on *B. tabaci* infesting on tomato plants under greenhouse conditions.

2. Materials and methods

2.1. Insects and plant cultures

Colonies of two whitefly species (*B. tabaci* and *T. variabilis)* and a parasitoid (*E. sophia*) originally established from multiple locations were maintained in air-conditioned greenhouses and rearing rooms [27 ± 2 °C, 60 ± 10% RH, and a photoperiod of 16:8 (L:D) h] at the University of Florida's Mid-Florida REC, Apopka, FL, USA. *B. tabaci* (B biotype) (pest) were reared on the fully expanded leaves of tomato ('Patio', Ball Horticulture Co., USA) and green bean seedlings (~30 d) ('Dusky bean', Syngenta Seeds, Inc., CA). These plants were grown in 8-cm diameter plastic pots filled with Fafard 2-Mix growing medium (Conrad Fafard, Inc., Agawam, MA, USA) and enclosed in screen net cages. *T. variabilis* (alternative insect hosts) were reared on papaya plants ('Caribean Red', from a local shopping center). Seeds of papaya were sown in plug trays, and seedlings were transplanted singly into 15-cm pots filled with the same Fafard 2-Mix. *E. sophia* (parasitoid) were reared and maintained on papaya plants infested with *T. variabilis* in different greenhouses. The insects and plants were monitored daily, and plants were watered and fertilized as needed. Only uniform, pesticide-free plants of all species were used for the following experiments.

2.2. Host specificity of T. variabilis and B. tabaci

2.2.1. Multiple choice experiments

Three separate choice experiments were conducted to evaluate the host specificity (or preference) of *T. variabilis* and *B. tabaci* adults to papaya (60 d after planting), tomato (30 and 60 d), green bean (20 d), and cabbage (40 d), respectively. Experiment 1 was a multiple-choice test, and performed in cages (80 × 80 × 80 cm) made from nylon screen net in the greenhouses. Each replicate cage held five plant treatments (papaya, green bean, cabbage, and two ages of tomato) arranged with one plant at one of the four corners and the fifth plant in the center of one cage, the position of each plant treatment (species or age) in the cage was arranged randomly and rotated during each replication. The experiment was replicated five times. For each cage, ~150 adults of *T. variabilis* (80% females and 20% males) were introduced into the center of the cage. The number of individual adults on each plant (all leaves) was counted at 2, 12, 24, 48, and 96 h after the insects were released into the cage.

Based on the results of the multiple choice experiment, the host plant specificity of *T. variabilis* was further investigated in experiment 2 (two-choice test) by using only two hosts (papaya and tomato plants at 30 d). Each replicate cage consisted of two papaya and two tomato plants, with each plant randomly placed in one of the four corners of the cage. About 150 *T. variabilis* adults were introduced into the center of the cage. The experiment was replicated six times. The number of *T. variabilis* adults on each plant was counted at 2, 12, 24, 48, 72, and 96 h. The numbers of eggs and nymphs were counted by sampling three leaves of the same size from each plant at 10 d for eggs and 20 d for nymphs after *T. variabilis* adults were released into the cage. Leaves were examined using a hand lens (10×).

Experiment 3 (two-choice test) was also conducted to evaluate the host specificity of the target pest, *B. tabaci* to papaya and tomato plants. The experiment was designed the same as the experiment 2 except that *B. tabaci* was released instead of *T. variabilis*.

2.2.2. No-choice experiments

Similarly, three separate no-choice experiments were conducted to evaluate the specificity of either *T. variabilis* or *B. tabaci* adults to papaya, tomato, green bean, and cabbage plants. Experiments 1, 2, and 3 were conducted in the same way as the corresponding multiple choice experiments except that each cage held the same species or ages of plants instead of different plant species.

2.3. Evaluation of dispersal of E. sophia

Three greenhouse experiments were performed to investigate the dispersal capability of *E. sophia* from papaya banker plants to papaya control plants or crop hosts infested with either *T. variabilis* or *B. tabaci*. In experiment 1, 12 potted (8-cm diameter) young parasitoid free papaya plants (45 d, ~50 cm tall) were used as sentinel plants (S-plants). Plants were infested with *T. variabilis* (second–third instar) and randomly placed at each of the four corners of three replicate greenhouses (10.0 × 7.0 m). A larger potted (15-cm diameter) papaya plant (90 d, ~100 cm) was used as a banker plant (B-plant). The banker plant was infested with both healthy and *E. sophia* parasitized *T. variabilis* and placed in the center of each greenhouse. The distance from the B-plant to each S-plant was ~5.0 m. After recording the total numbers of *E. sophia* adults on the B-plants (all leaves), the total numbers of *E. sophia* on the S-plants were recorded at 12 h, 1, 3, and 5 d of the B-plant release in each replicate greenhouse.

Experiment 2 was designed to measure the dispersal capacity of *E. sophia* from the papaya banker plant (B-plant) to green bean plants (S-plants) infested with *B. tabaci*. The experimental design was the same as dispersal experiment 1, except that green beans (20 d) were used as sentinel plants (S-plants) instead of papaya, and the distance from the papaya plant (B-plant) to each bean plant (S-plants) was increased from 5.0 to 6.5 m. *E. sophia* adults were counted on B-plants prior to S-plants. Three replicate greenhouses were used and data were collected as previously described for the first dispersal experiment.

Experiment 3 was designed to evaluate if *E. sophia* could disperse an extended distance between B-plants and S-plants in larger greenhouses (15 × 10 m). Tomato (30 d) and green bean (20 d) plant seedlings infested by *B. tabaci* nymphs (second–third instar), and younger papaya plants (45 d) infested by *T. variabilis* (second–third instar) were placed in one side (as S-plant) of the greenhouses in a completely randomized arrangement. The B-plant was located in the opposite side. The distance between the two sides was 14.5 m. Three replicate greenhouses were used and data were collected as previously described for dispersal experiments.

2.4. Percent parasitism by E. sophia

Three experiments were conducted to determine the percent parasitism by *E. sophia* on *B. tabaci* (pest) infested tomato plants and on *T. variabilis* (alternative host) reared on papaya plants. The first experiment (open, without cage) was designed to evaluate the percent parasitism by *E. sophia* in same growing condition greenhouses. Ten potted papaya plants ($n = 10$) exposed to *T. variabilis* and 10 tomato plants ($n = 10$) exposed to *B. tabaci* were respectively placed into two different inoculation cages in greenhouse 1 for laying eggs. After 48 h, the plants were placed into two holding cages in greenhouse 2 until 3rd instar nymphs were observed. These infested plants were then moved to greenhouse 3 for exposure to *E. sophia* on papaya banker plants for 48 h, and finally moved into greenhouse 4 until pupal stage. The spatial arrangement consisted of 10 papaya banker plants placed on one side of greenhouse 4 and 20 sentinel plants (10 papaya plants and 10 tomato plants) randomly placed on the opposite side. Three infested leaves per plant, 30 leaves ($n = 30$) per plant species (or treatment) were randomly collected. Total number of parasitized 3rd instar, parasitized pre-pupae (4th instar), and pupae of *E. sophia* (including adults if available) on each leaf was recorded under a stereomicroscope. The percent parasitism was calculated with the following formula: (the number of parasitized 3rd instar, pre-pupae, pupae, and adults parasitoids)/(total number of whiteflies = parasitized whiteflies + healthy whiteflies, excluding eggs and 1–2nd instar).

The second parasitism experiment was conducted in cages (80 × 80 × 80 cm). Papaya plants ($n = 4$) were exposed to *T. variabilis* in a inoculation cage, and tomato ($n = 4$) and green bean plants ($n = 4$) were respectively exposed to *B. tabaci* for 48 h for laying eggs in two inoculation cages in an air-conditioned greenhouse. These plants were removed to holding cages until 3rd instar nymphs were observed. Twelve *E. sophia* adults were released into each holding cage (2 females + 1 male adult per plant) for feeding and parasitism for 48 h. These plants were later moved into another set of evaluation cages until pupal stage. The experiment was replicated three times using a total of 12 plants per species. The detection and recording of *E. sophia* were the same as described in parasitism experiment 1.

The third parasitism experiment was a survey conducted in greenhouses. Thirty papaya plants (60 d) were infested with *T. variabilis* in greenhouse 1, and 30 tomato plants (40 d) were infested with *B. tabaci* in greenhouse 2. *E. sophia* were reared on papaya infested with *T. variabilis* in greenhouse 3. When both *T. variabilis* in greenhouse 1 and *B. tabaci* in greenhouse 2 were at the 3rd instar stage, their host plants were moved into greenhouse 3. The spatial arrangement was the same as parasitism experiment 1. Three infested leaves per plant, 30 leaves ($n = 30$) per plant species (or treatment) were randomly collected, respectively at 2, 5 and 8 weeks (early June, late June and July) after the plants were placed into greenhouse 3. Over time, a total of 90 leaves were collected from each plant species. The detection and recording of *E. sophia* were the same as described in the first parasitism experiment.

2.5. Data analysis

All data obtained from the experiments were first normalized by using the square-root transformation ($\sqrt{x} + 0.5$) or arcsin square-root transformation if they were in percentage. Significant differences in the number of individuals recorded on each treatment were established using either one-way analysis of variance (ANOVA), student's t test, or nonparametric Kruskale–Wallis test when the assumption of normality or equality of variance was not met, followed by Tukey–Kramer honestly significant difference (HSD) comparison test ($P < 0.05$, JMP Version 8.01, SAS Institute, 2009).

3. Results

3.1. Host specificity of T. variabilis

In the multi-choice experiments, a significantly greater number of adults of *T. variabilis* were found on papaya plants at each time interval than on tomato, green bean, or cabbage when they were simultaneously presented in the same cage. Mean numbers of adult *T. variabilis* ranged from 31.4 to 75 per plant from 2 h to 96 h after its release compared to 0.2–17.6 on green bean, 0.2–8.0, and 0.2–2.8 on 30 d and 60 d tomato plants, and 0–0.2 on cabbage plants, respectively (Table 1). In the no-choice test, the numbers of *T. variabilis* adults on papaya plants were even higher than those of the choice test, varying from 35 to 98.5 per plant. *T. variabilis* on tomato, green bean, and cabbage plants were significantly lower than papaya at each time interval and varied from 0 to 5.0 per plant.

Results from the two-choice experiment further revealed that significantly more adults were found on papaya than on tomato

Table 1
The number of *T. variabilis* adults (alternative host) recorded on different host plants in multi-choice and no-choice experiments.

Tests	Host plants	Mean (±SE) no. of *T. variabilis* adults/plant				
		2 h	12 h	24 h	48 h	96 h
Multi-choice	Papaya	75.0 ± 15 a	69.0 ± 19a	33.5 ± 14a	71.0 ± 18a	31.4 ± 7.4a
	Green bean	17.6 ± 7.8b	8.0 ± 3.5b	6.6 ± 2.4b	1.2 ± 0.4b	0.2 ± 0.1b
	Tomato (30 d)	8.0 ± 5.7b	3.6 ± 1.9b	3.3 ± 1.5b	0.2 ± 0.4b	0.2 ± 0.1b
	Tomato (60 d)	2.8 ± 1.3b	0.8 ± 0.4b	0.8 ± 0.4b	0.4 ± 0.4b	0.2 ± 0.1b
	Cabbage	0 ± 0c	0 ± 0b	0 ± 0b	0 ± 0b	0 ± 0b
	ANOVA	$F = 15.4$	$F = 11.03$	$F = 21.2$	$F = 15.7$	$F = 17.9$
	df = 4, 20	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
No-choice	Papaya	96.2 ± 10a	98 ± 8.7a	93.4 ± 8.0a	98.5 ± 6.8a	35 ± 7.4a
	Green bean	5.2 ± 1.9b	0.8 ± 0.3b	0.8 ± 0.4b	0.6 ± 1.3b	0 ± 0b
	Tomato (30 d)	5.0 ± 1.8b	3.0 ± 1.1b	0.6 ± 0.4b	1.0 ± 0.3b	0 ± 0b
	Tomato (60 d)	5.0 ± 0.9b	2.3 ± 0.9b	0.4 ± 0.2b	0.6 ± 0.4b	0 ± 0b
	Cabbage	0.2 ± 0.2b	0 ± 0b	0 ± 0b	0 ± 0b	0 ± 0b
	ANOVA	$F = 77.3$	$F = 120.7$	$F = 137.5$	$F = 217.5$	$F = 8.13$
	df = 4, 20	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.0001$

Mean (±SE) number within the same column in the same experiment followed by different letter is significantly different ($P < 0.05$, Tukey–Kramer HSD test). About 150 adults were released per cage, each experiment had five replicates.

plants after *T. variabilis* were released into the cages at 2 h ($t = 6.55$; df = 10; $P = 0.0002$), 12 h ($t = 4.75$; df = 10; $P = 0.0048$), 24 h ($t = 6.6$; df = 10; $P = 0.0009$), 48 h ($t = 5.4$; df = 10; $P = 0.0087$), 72 h ($t = 7.66$; df = 10; $P = 0.0003$), and 96 h ($t = 7.1$; df = 10; $P = 0.0008$) (Fig. 1A). The no-choice test confirmed the results obtained in the two-choice test at 48 h ($t = 2.5$; df = 6; $P = 0.055$), 72 h ($t = 3.83$; df = 6; $P = 0.031$), 96 h ($t = 3.8$; df = 6; $P = 0.03$); and 144 h ($t = 12.22$; df = 6; $P = 0.001$). However, at initial 24 h, no more significant adults were found on papaya than on tomato plants [at 2 h ($t = 1.55$; df = 6; $P = 0.2102$), 12 h ($t = 1.1$; df = 6; $P = 0.3455$), 24 h ($t = 1.5$; df = 6; $P = 0.2114$)] (Fig. 1B).

As a consequence of more adults on papaya plants, significantly greater numbers of eggs and nymphs were also recorded on papaya plants. The mean number of *T. variabilis* on papaya were 667.3 eggs per three leaves at 10 days and 395.2 nymphs at 20 days, respectively after *T. variabilis* release compared to 16.0 eggs and 10.1 nymphs per three leaves on tomato plants in the two-choice test (Table 2). In the no-choice test, the mean number of *T. variabilis* on papaya was 727–790.2 eggs per three leaves at 6–10 days and 616.3 nymphs at 20 days after *T. variabilis* release compared to 8.7–11.5 eggs and 23.2 nymphs on tomato plants. These results clearly demonstrated that *T. variabilis* is highly specific to papaya over tomato plants (Fig. 1A). On the contrary, fewer *T. variabilis* adults were attracted to tomato plants, and significantly fewer eggs and nymphs were found on tomato plants than on papaya plants (Table 2, Fig.1A and B).

3.2. Host specificity of B. tabaci

Results from both choice and no-choice tests indicated that there was little attraction of *B. tabaci* to papaya plants; while tomato plants were specifically preferred by *B. tabaci* in adult feeding and oviposition. The mean numbers of *B. tabaci* adults found on tomato plants were significantly greater than the numbers recorded on papaya plants in the two-choice test after the release at 2 h ($t = 5.5$; df = 10; $P = 0.0008$), 12 h ($t = 6.3$; df = 10; $P = 0.0008$), 24 h ($t = 6.8$; df = 10; $P = 0.0008$), 48 h ($t = 6.2$; df = 10; $P = 0.0005$), 72 h ($t = 7.6$; df = 10; $P = 0.0003$), and 96 h ($F = 9.8$; df = 10; $P < 0.0001$) (Fig. 2A) as well as in the no-choice test at 2 h ($t = 2.9$; df = 6; $P = 0.027$), 12 h ($t = 3.34$; df = 6; $P = 0.021$), 24 h ($t = 4.65$; df = 6; $P = 0.0052$), 48 h ($t = 4.4$; df = 6; $P = 0.0045$), 72 h ($t = 10.5$; df = 6; $P = 0.0001$), 96 h ($t = 7.6$; df = 6; $P < 0.0004$), and 144 h ($t = 16.6$; df = 6; $P < 0.0002$) (Fig. 2B). Consequently, whitefly immatures were also higher on tomato compared to papaya plants. The mean numbers of eggs were 322 per three tomato leaves compared to 5.3 per three papaya leaves at 10 d and nymphs were 352 per three tomato leaves compared to 3.6 per three papaya leaves at 20 d after *B. tabaci* release in the two-choice test (Table 3). In the no-choice test, eggs ranged from 104 to 492 and nymphs were 647 per three tomato leaves compared to 12–24 eggs and 14 nymphs per three papaya leaves (Table 3).

3.3. Dispersal ability of E. sophia

This study showed that adults of *E. sophia* were able to migrate from banker plants to sentinel plants (papaya, tomato, and bean) in search of new hosts and/or prey. In the first experiment, about 58% of *E. sophia* traveled 5.0 m in 48–72 h to papaya plants infested with *T. variabilis*, and ~49% of the parasitoid migrated 6.5 m to green beans infested with *B. tabaci* in 48 h in the second experiment (Table 4). Further tests indicated *E. sophia* adults migrated at least 14.5 m in 48–96 h, searching for papaya plants infested with *T. variabilis*, and for tomato plants and green beans both infested with *B. tabaci* after papaya banker plants were released in larger greenhouses ($15 \times 10 = 150$ m^2). Their movement was random with regard to hosts and plant location or direction. Prevailing light did not influence the dispersal of parasitoids. However, the results appeared to indicate that more *E. sophia* (34%) migrated to papaya plants infested with *T. variabilis* compared to their migration to the target pest, *B. tabaci* on tomato or bean plants (21–24%) ($F = 7.05$; df = 2, 6; $P = 0.026$), when the parasitoids were provided with multiple choices (Table 4).

3.4. Parasitism by E. sophia on target pest

The parasitism studies indicated that *E. sophia* equally parasitized on *T. variabils* and on *B. tabaci* in the open and caged experiments (Table 5). Open experiments indicated that the percent parasitism on *T. variabils* reared on papaya plants was 36.4% compared to 29.0% on *B. tabaci* on tomato plants ($t = 1.94$; df = 58; $P = 0.057$). Cage experiments also showed that the percent parasitism by *E. sophia* on *T. variabils* on papaya plants was 36.2%, which was not significantly different from 30.2% on *B. tabaci* on tomato plants and 27.7% on green bean ($F = 1.007$; df = 2, 33; $P = 0.3778$). A similar trend was also observed in the survey experiments where no significant differences in the percent parasitism either on *T. variabils* hosted by papaya plants (~41.0–47.4%) or on *B. tabaci* hosted by tomato plants (~31.9–45.9%) at 5 ($t_2 = 0.726$; df = 58; $P = 0.13$) and 8 weeks ($t_3 = -1.78$; df = 58; $P = 0.08$) (or late June and July) after these host plants were exposed to parasitoids on

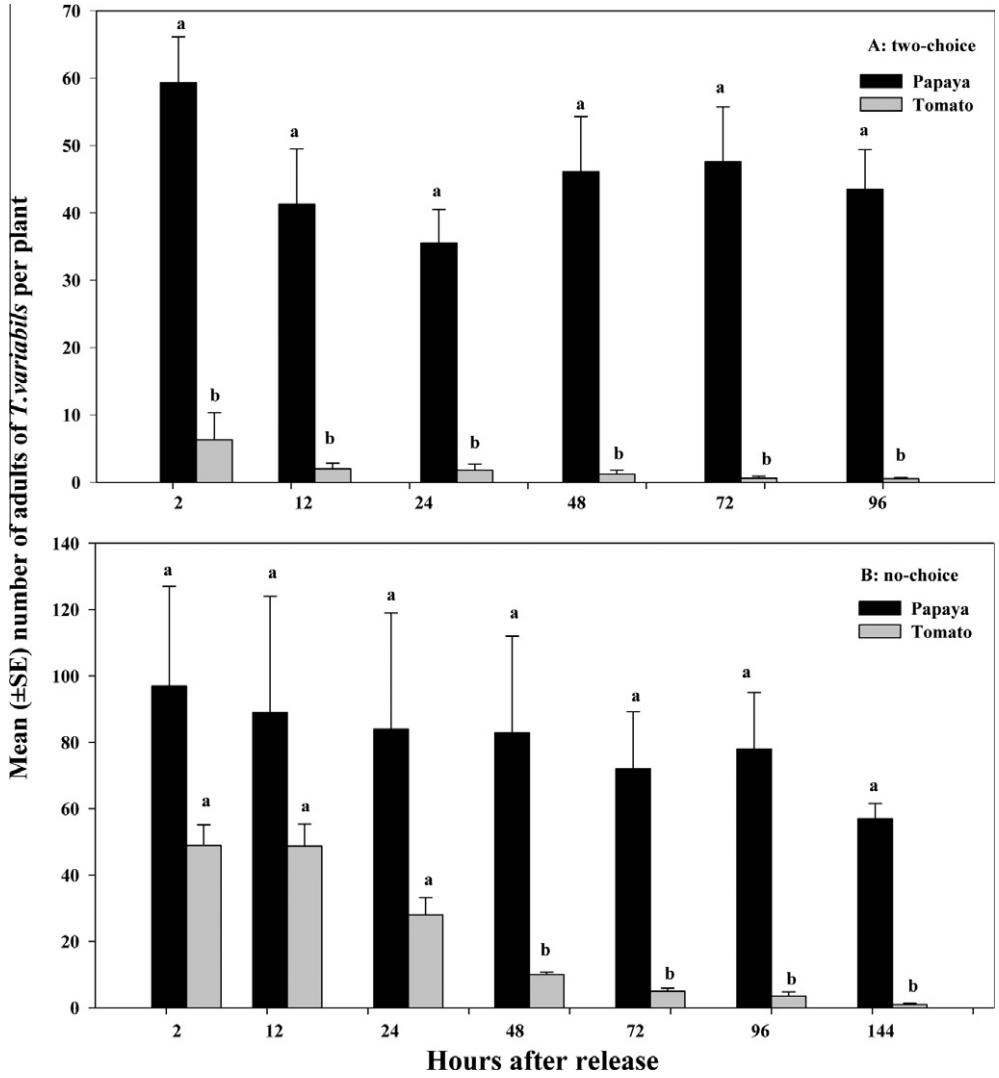

Fig. 1. The number of alternative host, *T. variabilis* adults recorded on papaya and tomato plants after they were released via two-choice test (A) and no-choice test (B) in greenhouses.

Table 2
The number of eggs and nymphs of *T. variabilis* (alternative host) recorded on papaya and tomato plants in two-choice and no-choice tests in greenhouses.

Tests	Host plants	Mean no (±SE). of *T. variabilis* immatures/3 leaves		
		Eggs 6 d	Eggs 10 d	Nymphs 20 d
Two-choice	Papaya	–	667.3 ± 81a	395.2 ± 39.0a
	Tomato	–	16.0 ± 3.1b	10.1 ± 3.8b
	t-test		*t* = 4.2	*t* = 3.37
	df = 10		*P* = 0.006	*P* = 0.008
No-choice	Papaya	727.0 ± 163.0a	790.2 ± 135.2a	616.3 ± 184.0a
	Tomato	8.7 ± 0.9b	11.5 ± 0.6b	23.2 ± 1.2b
	t -test	*t* = 4.3	*t* = 5.75	*t* = 4.3
	df = 6	*P* = 0.005	*P* = 0.001	*P* = 0.005

Mean (±SE) number within the same column in the same experiment followed by different letter is significantly different ($P < 0.05$, Tukey–Kramer HSD test).

papaya banker plants, However, the percent parasitism on *B. tabaci* was significantly lower than on *T. variabils* at 2 weeks (early June) after release ($t_1 = 2.57$, df = 58, $P = 0.013$).

4. Discussion

This study established a papaya-based banker plant system (Fig. 3) for potentially effective control of *B. tabaci*. As outlined by Osborne et al. (2005) and Frank (2010), a banker plant system generally consists of three basic components: host plant, alternative host or prey, and natural enemies. In this established system, papaya is a non-crop host plant for *T. variabilis* that serves as an non-pest alternative host of *E. sophia*, which is a natural enemy of *B. tabaci*, a notorious pest of tomato and other crops.

Banker plant systems are a relatively new concept; it uniquely combines the advantages of both augmentative and conservation

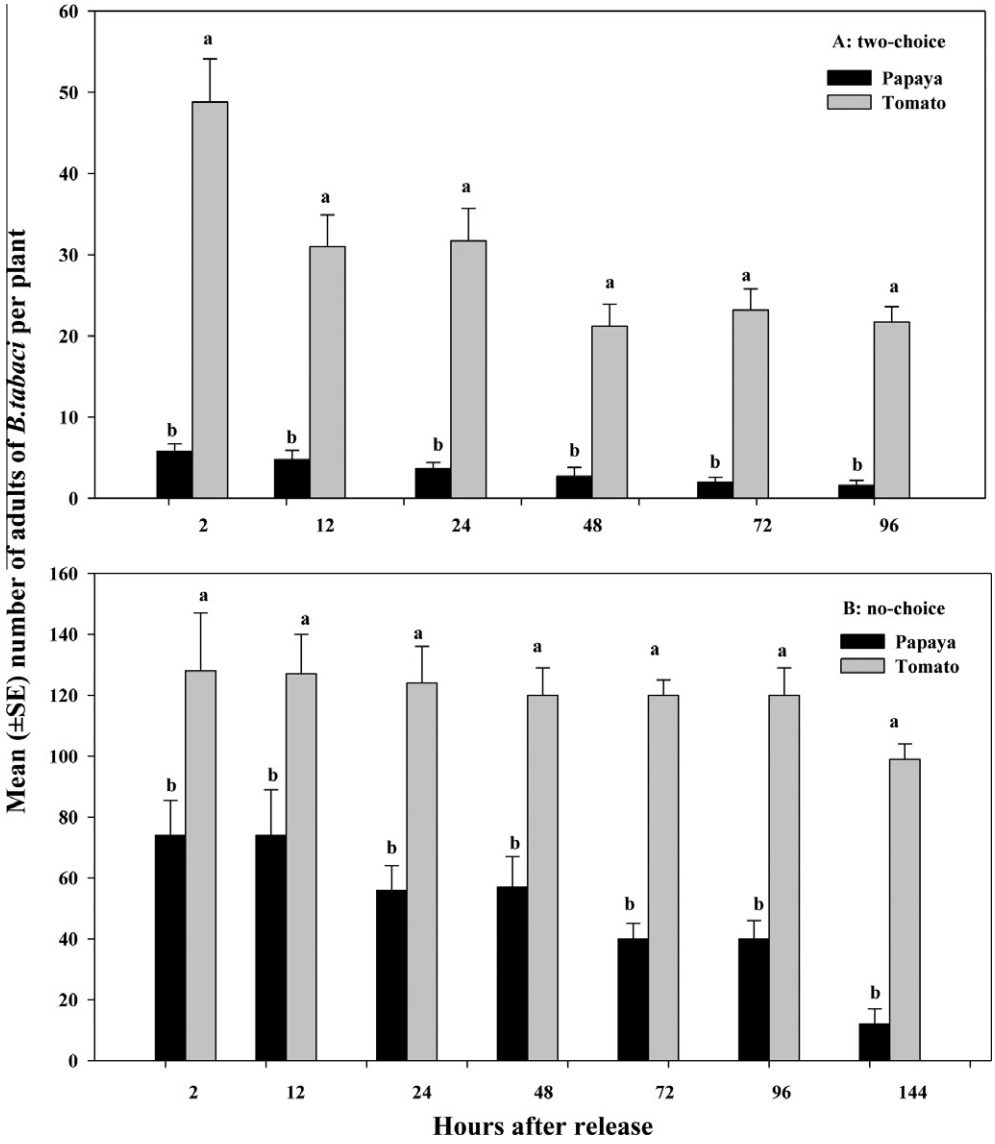

Fig. 2. The number of silverleaf whitefly, *B. tabaci* adults recorded on papaya and tomato plants after they were released via two-choice test (A) and no-choice test (B) in greenhouses.

Table 3
The number of eggs and nymphs of *B. tabaci* recorded on papaya and tomato plants in two-choice and no-choice experiments after adults released at the various days in greenhouses.

Tests	Host plants	Mean no (±SE). of *B. tabaci* immatures/3 leaves		
		Eggs 6 d	Eggs 10 d	Nymphs 20 d
Two-choice	Papaya	–	5.3 ± 3.5b	3.6 ± 1.1b
	Tomatoes	–	322.0 ± 85a	352.0 ± 44a
	t-test		*t* = 3.6	*t* = 7.8
	df = 10		*P* = 0.0014	*P* = 0.005
No-choice	Papaya	12.0 ± 2.9b	24.2 ± 7.4b	14.0 ± 0.7b
	Tomatoes	104.2 ± 13.2a	492.0 ± 71a	647.0 ± 49.8a
	t-test	*t* = 6.86	*t* = 6.56	*t* = 12.7
	df = 6	*P* = 0.0048	*P* = 0.006	*P* < 0.0001

Mean (±SE) number within the same column in the same experiment followed by different letter is significantly different ($P < 0.05$, Tukey–Kramer HSD test).

biological controls for sustainable suppression of targeted pests. As a form of conservation biological control, a banker plant system provides an alternative host or prey for a natural enemy, so that it can survive and reproduce for extended periods even in the absence of pests. As in augmentative biological control, the natural enemy is established on the banker plants to target a specific pest by increasing survival and reproduction of natural enemies within the cropping system (Frank, 2010). Although there is little

Table 4
Dispersal of *E. sophia* from papaya banker plant (B-plant) infested with *T. variabilis* to different crops (S-plant) infested with *B. tabaci* in greenhouses.

Exp.	Banker plants	Crop (S-plant)	Whitefly species	Dispersal distance (m)	Time for the distance (h)	Mean (±SE) number	
						E. sophia. (no)	*E. sophia* (%)
1st	Papaya→	Papaya	*T. variabilis*	5.0	48–72	17.3 ± 1.7	57.7 ± 1.1
2nd	Papaya→	Green bean	*B. tabaci*	6.5	24–48	18.6 ± 1.2	49.0 ± 3.0
3rd	Papaya→	Papaya	*T. variabilis*	14.5	72–96	15.3 ± 2.0	34.0 ± 3.4a
	→	Tomato	*B. tabaci*	14.5	48–72	9.0 ± 1.1	21.0 ± 2.4b
	→	Green bean	*B. tabaci*	14.5	72–96	10.3 ± 1.5	24.0 ± 2.2b

The numbers of *E. sophia* released from papaya plants were 30, 39 and 44 adults in experiments 1, 2 and 3, respectively. For experiment 3: mean (±SE) number within the same column followed by different letter is significantly different ($P < 0.05$, Tukey–Kramer HSD test).

Table 5
Relative parasitism of *E. sophia* on both *T. variabilis* and *B. tabaci* hosted by two different plants after release of parasitoids of papaya banker plants.

Tests	Weeks	Banker plants		Crop hosts	Whitefly species	Mean (±SE) number per leaf		
						Total number	Parasitized number	Parasitism (%)
Open		Papaya	→	Papaya	*T. variabilis*	230.0 ± 18.7	85.1 ± 9.7	36.4 ± 2.7a
			→	Tomato	*B. tabaci*	87.0 ± 9.9	21.9 ± 2.7	29.0 ± 3.4a
Cages		Papaya	→	Papaya	*T. variabilis*	224.5 ± 23.7	78.5 ± 10.7	36.2 ± 4.9a
			→	Tomato	*B. tabaci*	105.0 ± 16.4	26.8 ± 4.6	30.2 ± 5.9a
			→	Beans	*B. tabaci*	94.3 ± 16.1	22.0 ± 2.7	27.7 ± 4.5a
Survey	2nd	Papaya	→	Papaya	*T. variabilis*	309.0 ± 36.7	127.6 ± 16.7	41.7 ± 2.8a
			→	Tomato	*B. tabaci*	29.2 ± 1.8	9.1 ± 0.8	31.9 ± 2.5b
	5th	Papaya	→	Papaya	*T. variabilis*	322.3 ± 39.7	140.8 ± 21.2	40.2 ± 2.0a
			→	Tomato	*B. tabaci*	29.5 ± 1.7	12.2 ± 1.2	45.9 ± 7.5a
	8th	Papaya	→	Papaya	*T. variabilis*	321.0 ± 33.6	155.5 ± 18.7	47.4 ± 3.0a
			→	Tomato	*B. tabaci*	25.9 ± 2.1	9.5 ± 0.8	39.5 ± 3.2a

Mean (± SE) number within the same column in the same experiment followed by different letter is significantly different ($P < 0.05$; Tukey–Kramer HSD test).

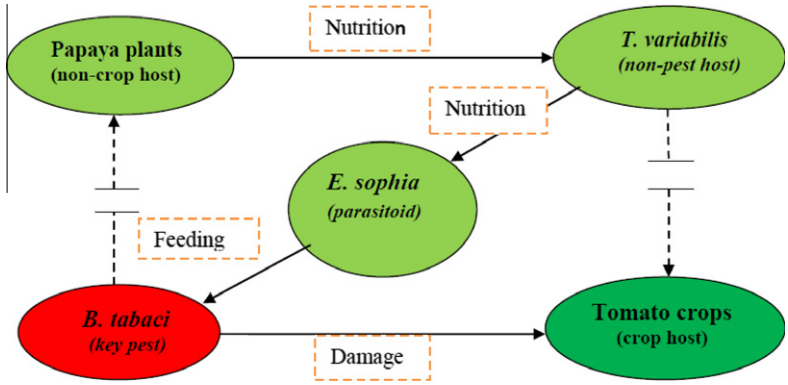

Fig. 3. A established papaya banker plant system consisted of: (1) papaya is the banker plant hosting *T. variabilis*; (2) *T. variabilis* is an alternative host of *E. sophia*, fed on papaya plants, but not a pest of tomato; (3) *E. sophia* is natural enemy, which exhibits strong dispersal ability and great parasitism to both *B. tabaci* and *T. variabilis*; (4) *B. tabaci* is a key pest of tomato which is major fresh vegetable crop.

consensus on an optimal banker plant system, we believe that in a valuable banker plant system, the alternative host should have great specificity to banker plants and the natural enemy should be able to disperse and parasitize the alternative host as well as the targeted pest without detrimental effects on economical crops.

4.1. Host specificity of *T. variabilis* and *B. tabaci*

Results from our study showed that papaya plants were specifically preferred by *T. variabilis* adults, since *T. variabilis* were almost exclusively attracted to papaya plants at 96 h after infestation in both choice and no-choice tests (Tables 1 and 2; Fig. 1); whereas *T. variabilis* were slightly attracted to tomato, green bean, or cabbage plants. This specificity of *T. variabilis* for papaya could be due to certain chemical signals released from papaya rather than morphological characteristics of plants, because papaya, green bean, and cabbage all have a smooth leaf surface with the exception for tomato which has long and dense trichomes. Chemicals released from plants play a key role in mediating host preference in herbivorous insect species, most of which use host secondary chemicals (semiochemicals) known as kairomones for host location (Brown, 1984; Pasteels et al., 1988; Bowers, 1990; Rank et al., 1998; Xiao and Fadamiro, 2009).

A non-pest herbivore is particularly favored for use in banker plant systems as it serves as an alternative host for a parasitoid or predator (Frank, 2010). Our results demonstrated that *T. variabilis* is a non-pest alternative herbivore for maintaining the parasitoid, *E. sophia* (Tables 1 and 2), and not a pest of tomato. *E. sophia* is a highly effective parasitoid of *B. tabaci* (Antony et al., 2003; Zang and Liu, 2007). With the support of papaya banker plants, *T. variabilis* could sustain *E. sophia* survival and reproduction even in the absence of *B. tabaci*. This study also showed that *B. tabaci* is not a pest of papaya and is a pest of tomato plants (Fig. 2) (Schuster and Stansly, 2009). In two-choice tests, the eggs and nymphs of *B. tabaci* were 60

and 90-fold more abundant on randomly selected tomato leaves than on papaya leaves. In the no-choice tests, the eggs and nymphs were 20 and 46-fold more abundant on tomato leaves than on papaya leaves.

The documented specificity of *T. variabilis* for papaya plants and the parasitism of both *T. variabilis* and *B. tabaci* by *E. sophia* strongly support our claim that papaya can be used as a banker plant for indirect support of *E. sophia.* We envision that the introduction of a papaya plant banker system to greenhouses should provide better control of *B. tabaci*, compared to the earlier banker plants (Stacey, 1977), in which tomato plants were used as both crop and banker plants for *B. tabaci* or *T. vaporariorum* (Hemiptera: Aleyrodidae) where both were pests and alternative host for *Eretmocerus hayati* Zolnerowich and Rose (Hymenoptera: Aphelinidae) or *E. formosa* (Hymenoptera: Aphelinidae) (Goolsby and Ciomperlik, 1999; Pickett et al., 2004). Obviously, the use of either *B. tabaci* or *T. vaporariorum* as alternative hosts has significant risks to greenhouse crops.

4.2. Dispersal and parasitism of parasitoid, E. sophia

Our study also revealed that *E. sophia* has strong dispersal capability, flying at least ~14.5 m within 48–96 h after banker plants were placed in the greenhouse (~150 m^2). Approximately 20–60% of *E. sophia* on banker plants were dispersed and were able to establish a parasitoid relationship in 5 days (Table 4). The dispersal distance of *E. sophia* was equal to or longer than that of *E. formosa*, which migrated up to 5.0 m on tomato in 90 min (Van der Laan et al., 1982) and was also almost equal to the distance dispersed by another parasitoid, *Aphidius colemani* (Hymenoptera: Braconidae) (Langhof et al., 2005). Most natural enemies have strong dispersal capability through flight (Heinz, 1998; Osborne et al., 2004). Such long distance dispersal exhibited by *E. sophia* adults in greenhouses may indicate that they could be much more mobile in commercial crop production settings where crop density is much higher. Additionally, parasitism studies combined showed that the percent parasitism by *E. sophia* on *T. variabilis* reared on papaya plants (36.2–47.4%) was not significantly higher than that on *B. tabaci* feeding on tomato and green bean plants (27.7–45.9%) (Table 5). These percentages were comparable to reports of other investigators. For example, the parasitism percentage by *E. sophia* was 35–45% on cabbage (Antony et al., 2003; Simmons and Abd-Rabou, 2005; Zang and Liu, 2007); and no significant differences were observed among cabbage, cucumbers and eggplants (Pavis et al., 2003; Simmons and Abd-Rabou, 2005). Furthermore, *E. sophia* also was proved to be great host-feeding capacity compared to other parasitoids (Zang and Liu, 2007). Although *E. sophia* is a native, dominant parasitoid of *B. tabaci* in Florida, it has been found to be a dominant parasitoid of *B. tabaci* worldwide (Osborne et al., 1990). Its strong parasitism of both *T. variabilis* and *B. tabaci* and its great mobility suggest that this papaya banker plant system could be a valuable approach for *B. tabaci* control in commercial greenhouse tomato production.

4.3. Potential of papaya plant as banker plant in crop greenhouses

Compared to the other banker plant systems, we believe that this established papaya banker plant system has several advantages for control of *B. tabaci*. First, this banker plant system could provide a more effective and economical way of controlling *B. tabaci* than augmentative release of its natural enemies. Key issues with augmentative biological control agents are that a large number of natural enemies have to be purchased and released, which are expensive and time consuming (Goolsby and Ciomperlik, 1999; Pickett et al., 2004; Van Driesche and Heinz, 2004; Frank, 2010). In some cases, no commercialized natural enemies are available and some biological control agents may not be effective due to adverse environmental conditions.

Secondly, papaya plants are easy to grow in the greenhouse and can be heavily fed on by non-pest *T. variabilis*, which provides prolonged support to *E. sophia.* Additionally, papaya banker plants provide commercial growers with great flexibility for introducing *E. sophia,* prior to targeted pest occurrence without risks. Augmentative biological control agent releases have to occur at a critical time and use a designated method (Collier and Van Steenwyk, 2004; Crowder, 2007). We also noted that the non-pest host on the papaya banker plant may also provide food for other natural enemy species, such as a predatory mite, *Amblyseius swirskii* and spider predators (Xiao et al., unpublished data). It could be possible that papaya may support multiple natural enemies for controlling multiple pests.

Thirdly, this papaya banker plant system can be compatible with other pest control methods. This option may be attractive to growers as it increases the effectiveness of overall pest control in commercial greenhouse crop production. Ongoing studies of the banker plant system for its effectiveness are being performed in commercial greenhouses.

Acknowledgments

The authors would like to thank Irma Herrera, Fabieli Irizarry, and Younes Belmourd for their technical assistance in laboratory and in greenhouses. Funding for this study was provided by grants from the EPA, IFAS/UF Line Item grants program, and the USDA-ARS Floriculture and Nursery Research Initiative.

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