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Effectiveness of Parasitoids of Bemisia tabaci (Hemiptera: Aleyrodidae) on Cotton Cultivars Differing in Leaf Morphology

Authors: Cetintas, Ramazan, and McAuslane, Heather

EFFECTIVENESS OF PARASITOIDS OF *BEMISIA TABACI* (HEMIPTERA: ALEYRODIDAE) ON COTTON CULTIVARS DIFFERING IN LEAF MORPHOLOGY

Ramazan Cetintas and Heather McAuslane

University of Florida, Department of Entomology and Nematology, Gainesville, FL 32611

ABSTRACT

Field and laboratory experiments were conducted to determine resistance of cotton *Gossypium hirsutum* L. cultivars differing in leaf morphology (shape and pubescence) to the B biotype of sweetpotato whitefly *Bemisia tabaci* (Gennadius) and impacts on its parasitoids. Five cotton cultivars were evaluated in a field-plot experiment at Hastings, Florida. The pubescent cultivars, DP DES 119 and Stoneville 453, were significantly hairier than moderately hairy okra-leaf cultivar, Gumbo 500, and smooth-leaved cultivars NU COTN 33B and DP 51. There were significant differences among cultivars in eggs laid on the second and fifth node leaves. DP DES 119 and Stoneville 453 had greater numbers of whitefly eggs than did the glabrous cultivars. The okra-leaf cultivar, Gumbo 500, had greater numbers of eggs than the 2 glabrous varieties. There were significant differences among cultivars in numbers of first and second instars (young instars), third instars, unparasitized fourth instars and red-eyed nymphs on fifth node leaves, with higher populations occurring on pubescent cultivars and lower populations on glabrous cultivars. The abundant parasitoids were *Encarsia pergandiella* Howard, *Encarsia nigricephala* Dozier and *Eretmocerus* spp., however parasitism did not differ among the cultivars. The responses of *Eretmocerus rui* Zolnerowich & Rose and *Encarsia formosa* Gahan (Nile Delta strain) (Hymenoptera: Aphelinidae) as a function of density of the host were investigated in laboratory experiments on 3 cotton cultivars differing in leaf pubescence and shape (DP 51, DP DES 119, and Gumbo 500). *Eretmocerus rui* showed a type II functional response to second instars of the host with the mean number of parasitized hosts increasing as host density increased on all 3 cultivars. *Encarsia formosa* showed a type II functional response to fourth instars, where the number of hosts parasitized increased up to a density of 16 but remained constant for 32 and 64 hosts. Significantly more whiteflies were parasitized by both *E. formosa* and *E. rui* on DP 51, the smooth-leaved cotton cultivar, than on the hairy cotton cultivars. We conclude that glabrous cotton cultivars are likely to support lower whitefly populations than pubescent cultivars because of reduced whitefly oviposition and increased parasitoid foraging efficiency.

Key Words: *Bemisia tabaci*, biological control, functional response, parasitoid, whitefly, *Eretmocerus, Encarsia*

RESUMEN

Se realizaron experimentos en el campo y en el laboratorio para determinar la resistencia de variedades de algodón, *Gossypium hirsutum* L., con diferencias en la morfología de la hoja (forma y pubescencia) hacia el biotipo B de la mosca blanca de camote, *Bemisia tabaci* (Gennadius) y el impacto sobre sus parasitoides. Se evaluaron cinco variedades de algodón en un experimento de parcelas de campo en Hastings, Florida. Las variedades con hojas pubescentes, DP DES 119 y Stoneville 453, fueron significativamente mas peludas que las variedades de hojas de okra moderadamente peludas, Gumbo 500 y variedades con hojas lisas NU COTN 33B y DP 51. Hubo diferencias significativas entre las variedades en cuanto a los huevos puestos sobre las hojas del segundo y quinto nódulo. La DP DES 119 y Stoneville 453 tuvieron un mayor número de huevos de mosca blanca que las variedades con hojas glabrosas. La variedad de hoja de okra, Gumbo 500, tuvo un mayor número de huevos que las 2 variedades glabrosas. Hubo diferencias significativas entre las variedades en cuanto al número de los estadios de primero y segundo estadio (estadios jóvenes), tercer estadio, cuarto estadio no parasitados y de las ninfas de ojos rojos sobre hojas del quinto nódulo, con poblaciones más altas sobre las variedades pubescentes y poblaciones menores sobre las variedades glabrosas. Los parasitoides mas abundantes fueron *Encarsia pergandiella* Howard, *Encarsia nigricephala* Dozier y *Eretmocerus* spp., sin embargo el nivel del parasitismo no fue diferente entre las variedades. Se investigo la respuesta de *Eretmocerus rui* Zolnerowich & Rose y *Encarsia formosa* Gahan (cepa Nile Delta) (Hymenoptera: Aphelinidae) como una función de la densidad de hospedero en experimentos del laboratorio sobre 3 variedades de algodón con diferencias en la forma y la pubescencia de la hoja (DP 51, DP DES 119 y Gumbo 500). *Eretmocerus rui* mostró una respuesta funcional de tipo II hacia el segundo estadio del hospedero con un promedio del número de hospederos parasitados incrementándose con el aumento en la densidad del hospedero en todas las 3 variedades. *Encarsia formosa* mostró una

respuesta funcional de tipo II hacia el cuatro estadio, donde el número de hospederos parasitados aumento hasta una densidad de 16 pero se mantuvo constante para los 32 y 64 hospederos. Significativamente un mayor numero de moscas blancas fueron parasitadas por ambos *E. formosa* y *E. rui* en DP 51, la variedad de algodón con hojas lisas, que en las variedades de algodón con hojas peludas. Concluimos que las variedades glabrosas de algodón son más propensas de apoyar poblaciones menores de la mosca blanca que las variedades pubescentes por la oviposición reducida de la mosca blanca y el aumento en la eficiencia del parasitoide para forrajear.

The B biotype of the sweetpotato whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), also known as the silverleaf whitefly, *Bemisia argentifolii* Bellows & Perring, is a worldwide tropical and subtropical pest of many crops, including agronomic field crops such as cotton. The A biotype of the sweetpotato whitefly had been present in the United States since 1894 (Quaintance 1900) and was seen on cotton as early as 1929 (Mound & Halsey 1978). After introduction into Florida in the late 1980s, and subsequent spread throughout the United States, outbreaks of the B biotype of *B. tabaci* in cotton and other crops caused widespread economic losses (Choen et al. 1992; Perring et al. 1993). Huge infestations of whiteflies on cotton reduce the vigor of young plants, leading to reduced yields, and produce copious quantities of sticky honeydew. Cotton fibers contaminated with honeydew and stained with sooty mold are unacceptable to buyers because this "sticky cotton" is difficult to process (Hendrix et al. 1995). Whiteflies have been reported to vector many important viral diseases, including crumple cotton and cotton leaf curl (Costa 1976; Butler & Henneberry 1994). All of these problems can cause plant stunting, premature leaf drop, defoliation, boll shed, and reduced yields in cotton.

The use of resistant cultivars may be an effective tactic in the management of *B. tabaci*. Cotton cultivars which have smooth leaves have been shown to support smaller whitefly populations than highly pubescent cultivars (Butler & Henneberry 1984; Butler at al. 1986). Plants with an okra-leaf shape and an open canopy have been shown to exhibit resistance to *B. tabaci* (Ozgur & Sekeroglu 1986; Chu at al. 2002). Recent observations have shown that cotton cultivars with lower numbers of stellate trichomes on the abaxial leaf surface supported lower numbers of *B. tabaci* eggs, nymphs, and adults (Chu at al. 2001).

In addition to the potential reduction in whitefly populations due to use of less susceptible cultivars, considerable mortality can be imposed by natural enemies, such as parasitoids, predators, and pathogens (Carruthers et al. 1993). Of these agents, most research on biological control has focused on parasitoids, particularly parasitic wasps in the *Encarsia* and *Eretmocerus* genera (Carruthers et al. 1993). Apparent parasitism levels ranging from 70 to 80% have been reported in cotton (Horowitz 1993) and kenaf (Legaspi et al. 1997). A study by Chu et al. (1998) indicated that whitefly colonization could be reduced significantly by planting cotton cultivars that are attractive to parasitoids.

However the success of parasitoids is highly variable, depending on the host plant, climate, presence of competing natural enemies, use of nonselective insecticides, and a number of environmental factors (Butler & Henneberry 1994; Hoelmer 1995). In addition, the parasitism ability of whitefly parasitoids may be directly affected by plant resistance traits (McAuslane et al. 1995; van Roermund & van Lenteren 1995; van Lenteren et al. 1995; McAuslane et al. 2000). Leaf pubescence has received the most study for its potential effect on whitefly parasitoids. An early study showed the negative effect of leaf hairs on cucumber varieties on walking speed and walking pattern of *Encarsia formosa* Gahan (Hulspas-Jordaan & van Lenteren 1978). Consequently, the rate of parasitism of the greenhouse whitefly, *Trialeurodes vaporariorum* Westwood, by *E. formosa* decreased linearly with increasing hair density on cucumber hybrids (van Lenteren et al. 1995). A greenhouse study by Gruenhagen & Perring (2001) showed that among 5 host plants studied, including cotton, the plants with higher trichomes levels resulted in lower parasitism of silverleaf whitefly by *Eretmocerus eremicus* Rose & Zolnerowich. This was, in part, attributed to exudate from glandular trichomes, which entrapped parasitoids.

The objective of the experiments reported here was to determine the susceptibility to *B. tabaci* of cotton cultivars suitable for production in Florida and the southeastern United States and the effectiveness of parasitoids of *B. tabaci* on these cultivars. We chose 5 cultivars that differed in leaf morphology (okra-leaf or normal-leaf) and pubescence. Whitefly populations and parasitism were assessed in a replicated field trial of all cultivars. In a second experiment, we evaluated the functional responses of 2 whitefly parasitoids, *E. formosa* (MCB 92030, Nile Delta strain) and *Eretmocerus rui* Zolnerowich & Rose on 3 of the cultivars. We chose 1 species of each genus because of differences in the oviposition behavior of the genera. *Encarsia formosa* oviposits directly into the body of third, fourth, and prepupal stages of the whitefly (Nell et al. 1976). *Eretmocerus* species

lay eggs under earlier stages of the host, preferably the second nymphal stage (McAuslane & Nguyen 1996). Ease of inserting the ovipositor underneath the whitefly host may be affected by how well the host can seal itself to the leaf with wax. Leaf hairs may reduce the ability of the whiteflies to seal themselves to the leaf.

MATERIALS AND METHODS

Field Experiment and Design

The field experiment was conducted in 1997 in Hastings, Florida. Five commercial cotton cultivars (*Gossypium hirsutum L.*) with different leaf pubescence and shape were evaluated for their susceptibility to *B. tabaci* and the effectiveness of parasitoids of *B. tabaci* on these cultivars. The experiment was designed as a randomized block design with 5 replications. Plots were 12.2 m long by 6 rows wide and plots were separated by a break of 1.2 m. Delta Pine 51 (DP 51) and NU COTN 33B (genetically modified to express to Bt toxin Cry1Ac) were both smooth (i.e., glabrous) normal-leaf cultivars. Delta Pine DES 119 (DP DES 119) and Stoneville 453 were hairy (i.e., pubescent) normal-leaf cultivars and Gumbo 500 was a moderately hairy okra-leaf cultivar. Cotton cultivars were planted on 23 May 1997; however, due to poor germination, Gumbo 500 was replanted 2, 9, 16, and 23 Jun. Sampling began approximately 9 weeks after first planting.

Sampling

Sampling was carried out for 7 weeks, from 27 Jul to 12 Sep. Each week 40 plants were sampled randomly in each replicate. On the first day of the week, a leaf from the second node (counting down from the top) of 20 plants, and on the third day of the week a leaf from the fifth node of another 20 plants were sampled. In the laboratory, the area of each leaf was measured with a LiCor 3000 leaf area meter (LiCor, Lincoln, NE). Leaf hairs were counted within an area of the abaxial leaf surface contained within a No. 3 cork borer impression (area = 0.384 cm^2). Numbers of whitefly eggs, young nymphs (first and second instars combined), third instars, unparasitized fourth instars, red eyed nymphs, exuvia (as parasitized and unparasitized separately), and parasitized fourth instars (as *Encarsia* parasitized, *Eretmocerus* parasitized or as unidentifiable) were counted within an area (located between the central main vein and the medial vein (Ellsworth et al., 1996) on the abaxial leaf surface contained within a No.13 cork borer impression (area = 3.14 cm^2). All counts were made with a dissecting microscope at 20× magnification.

Beginning with the fourth week of sampling, the leaf disks sampled from the fifth node were kept in 450-mL cardboard cartons so that all parasitoids emerging from parasitized nymphs could be counted and identified to species 5 weeks later.

Cotton cultivars were monitored for insect pests other than whiteflies by standard cotton scouting procedures. When pests reached economic threshold levels, insecticides were used in order to prevent economic loss. Whenever feasible, the plots were treated with selective insecticides that would have the least effect on whiteflies and beneficial insects. Dimilin 2L (diflubenzuron, (N-(4-chlorophenyl) amino) carbonyl)-2, 6-difluorobenzamide (224 giA) (Chemtura, Middlebury, CT), and Dipel 2X ((6.4% w/w), *Bacillus thuringiensis var. kurstaki* (450 giA)) (Valent BioSciences, Libertyville, IL) were applied twice, on Aug 8 and 12. Other agronomic practices used were standard for the area.

The experiment was designed as a randomized complete block design with 5 replications, however data for replications 1 and 2 were dismissed because of hurricane damage to plant stand; consequently data for the remaining 3 replications were evaluated. Data were pooled across sampling dates (over a 7-week period) and analyzed for whitefly numbers, trichome densities, and proportional parasitism on the 5 cotton cultivars with Proc GLM (SAS Institute, 2001) at a significance level of $P \leq 0.05$. Proportional parasitism on the fifth leaf node was calculated with the following equation:

$$FPER+FPEN+FPAR/FPER+FPEN+FPAR+FNPA,$$

where FPER = Fourth instar parasitized by *Eretmocerus sp.*, FPEN = Fourth instar parasitized by *Encarsia sp.*, FPAR = Fourth instar parasitized (parasitoid unknown), FNPA = Fourth instar nonparasitized. Means were separated by Waller-Duncan's multiple-range test.

Laboratory Experiment and Insects Used

Whiteflies used in the laboratory study came from a colony reared on DP 50 cotton and collards, *Brassica oleraceae* L., in an indoor rearing room maintained at the Department of Entomology and Nematology, University of Florida, Gainesville, Florida. The photoperiod was 14:10 (L: D) h, temperature averaged 27 ± 1°C during the day and 24 ± 1°C at night, and relative humidity ranged from 40 to 60 percent. *Encarsia formosa* (Nile Delta strain, MCB 92030) was acquired from USDA-APHIS-PPQ, Mission Plant Protection Center (Mission, Texas). This species was reared on *B. tabaci* in Mission and is considered a *Bemisia*-adapted, rather than a *Trialeurodes*-adapted, strain. A subcolony of this parasitoid was maintained in an indoor rearing room at the University of Florida on *B. tabaci* on hibiscus, *Hibiscus rosa-sinensis* L., (red single flower) under

the same conditions used to rear the whitefly host. *Eretmocerus rui* originated from a separate indoor colony rearing room with the same conditions as *E. formosa. Eretmocerus rui* is a thelytokous species and was imported into the United States from Hong Kong in Jul 1992 (McAuslane & Nguyen 1996). Parasitoids used in this experiment were obtained from the colony and were standardized as 2 ± 1 d old.

Functional Responses of Parasitoids

The purpose of this study was to determine the functional responses of 2 whitefly parasitoids, *E. rui* and *E. formosa,* on 3 different cotton cultivars differing in leaf shape and trichome density. The experiment was designed as a randomized complete block with a factorial design. The factors were 3 cotton cultivars [DP DES 119 (normal-leaf, hairy), Gumbo 500 (okra-leaf), DP 51 (normal-leaf, smooth)], four different whitefly nymph densities (8, 16, 32 and 64 per plant), and 2 parasitoid species (*E. rui* and *E. formosa*). The experiment was conducted in small cylindrical cages, in the laboratory, 3 times for *E. rui* (5 individual females at a time for a total of 15 replicates) and 4 times for *E. formosa* (5 individual females at a time for a total of 20 replicates), under a 14:10 light/dark cycle and 25°C temperature conditions. The cages measured 18.5 cm in diameter and 61.5 cm in height and were formed of 0.02-mm-thickness Vivak plastic. The measured average numbers of hairs for DP DES 119, Gumbo 500 and DP 51 were 182.5, 68.1 and 7.0, respectively, within an area of 0.384 cm^2.

The 3 cotton cultivars were grown in a greenhouse in 15-cm-diameter pots containing Metro-Mix 220 (Grace Sierra, Milpitas, CA). Plants were watered as necessary and fertilized twice a month with liquid fertilizer (20:20:20, N: P: K, Peters, W. R. Grace, Fogelsville, PA). Plants were grown in the greenhouse until the Gumbo 500 plants had developed 2 fully extended okra-shaped leaves. All other leaves were removed from the 3 cultivars in order to standardize the number of leaves on the plants. Following this, male-female pairs of adult whiteflies (5, 10, 20, and 40) were released onto each plant to obtain an appropriate infestation. After 24 h, the adult whiteflies were removed. Extra nymphs were removed after 5 d with a minuten pin to obtain the desired 4 different densities of immature whitefly instars of 8, 16, 32, and 64 per plant.

A single female parasitoid was introduced onto each plant when the correct whitefly stage was available for parasitism. This appropriate stage was determined as fourth instar for *E. formosa*, and second instar for *E. rui*. The parasitoid was removed after 24 h. Parasitism of the host was recorded as pupae of the parasitoids became evident within the host after 15 d for *E. formosa* and after 11 to 12 d for *E. rui*. The number of whiteflies parasitized was analyzed using Proc GLM (SAS Institute, 1989) at a significance level of $P \leq 0.05$. Means were separated by Waller-Duncan's multiple-range test. Functional response types for the 2 parasitoids were determined visually.

RESULTS

Field Experiment

Pubescence on the second (F = 1297.2; df = 4, 24; P < 0.0001) and fifth node leaves (F = 1303.7; df = 4, 24; P < 0.0001) differed significantly among the cultivars (Table 1). The mean number of hairs was greatest in Stoneville 453 (second leaf) and DP DES 119 (fifth leaf) and was lowest in DP 51 and NU COTN 33B (for second and fifth leaves). Pubescence was intermediate on the okra-leaf variety, Gumbo 500.

There were significant differences among cultivars for number of eggs on both the second node leaf (F = 489.2; df = 4, 24; P < 0.0001) and on the fifth node leaf (F = 29.2; df = 4, 24; P < 0.0001) (Table 2). DP DES 119 and Stoneville 453 had the greatest number of eggs on the second node leaf and fifth node leaf, respectively, whereas NU COTN 33B and DP 51 had the least number of whitefly eggs.

There were significant differences among cultivars for young instars (F = 107.8; df = 4, 24; P < 0.0001) and third instars (F = 15.8; df = 4, 24; P < 0.0001) on the second node leaf (Table 2). DP DES 119 sustained the greatest numbers of these instars among cultivars. The mean numbers of other whitefly stages varied among plant cultivars on the second node leaf. There were significant differences among cultivars for young instars (F = 88.87; df = 4, 24; P < 0.0001), for third instars (F = 89.75; df = 4, 24; P < 0.0001), for fourth unparasitized instars (F = 98.72; df = 4, 24; P < 0.0001), and for red-eyed nymphs (last instar) (F = 81.92; df = 4, 24; P < 0.0001) for fifth node

TABLE 1. MEAN (± SD) NUMBER OF HAIRS PER 0.384 CM^2 ON THE ABAXIAL SURFACES OF THE SECOND AND FIFTH NODE LEAVES OF 5 COTTON CULTIVARS DIFFERING IN LEAF MORPHOLOGY AND PUBESCENCE GROWN IN HASTINGS, FLORIDA.

Cultivar	Second node leaf	Fifth node leaf
DP DES 119	182.8 ± 67.3 b	104.2 ± 37.3 a
Stoneville 453	194.7 ± 68.1 a	98.3 ± 33.6 b
Gumbo 500	68.1 ± 36.4 c	37.0 ± 24.2 c
NU COTN 33B	9.0 ± 11.2 d	4.3 ± 7.2 d
DP 51	7.0 ± 8.3 d	3.0 ± 4.7 d

Data were pooled across sampling dates. Means within a column with the same letter did not differ significantly (Waller-Duncan's multiple-range test; α = 0.05). (*n* = 320).

TABLE 2. MEAN (± SD) NUMBER OF WHITEFLY LIFE STAGES PER 3.14 CM^2 ON THE ABAXIAL SURFACES OF SECOND AND FIFTH LEAVES OF 5 COTTON CULTIVARS DIFFERING IN LEAF MORPHOLOGY AND PUBESCENCE GROWN IN HASTINGS, FLORIDA.

	Mean ± SD per 3.14 cm^2				
Whitefly life stages	DP DES 119	Stoneville 453	Gumbo 500	NU COTN 33B	DP 51
			Second node leaf		
Eggs	224.2 ± 23.5 a	97.7 ± 135.0 a	280.8 ± 131.0 b	101.4 ± 59.0 c	44.6 ± 36.0 d
Young instars[a]	54.5 ± 34.5 a	8.7 ± 11.5 b	6.7 ± 8.6 b	4.4 ± 6.2 c	4.2 ± 5.7 c
Third instars	1.5 ± 2.8 a	0.7 ± 1.7 b	0.3 ± 0.7 b	0.4 ± 0.85 b	0.3 ± 0.82 b
Fourth (unparasitized)	0.5 ± 0.2 a	0.4 ± 0.2 a	0.1 ± 0.8 b	0.2 ± 0.8 b	0.1 ± 0.1 b
Red-eyed nymphs	0.1 ± 0.2a	0.1 ± 04 a	0 b	0.1 ± 0.1 a	0 b
			Fifth node leaf		
Eggs	14.0 ± 16.7 b	17.8 ± 22.4 a	9.2 ± 12.4 c	3.6 ± 7.1 d	5.0 ± 7.9 d
Young instars	31.5 ± 32.5 a	35.1 ± 30.8 a	13.0 ± 14.9 b	6.7 ± 7.6 c	6.3 ± 7.8 c
Third instars	7.7 ± 7.9 a	7.3 ± 6.5 a	3.1 ± 3.3 b	1.3 ± 1.9 c	1.6 ± 1.8 c
Fourth (unparasitized)	6.7 ± 7.9 a	6.8 ± 6.5 a	2.7 ± 3.3 b	1.3 ± 1.9 c	1.3 ± 1.8 c
Red-eyed nymphs	6.6 ± 8.7 a	5.2 ± 5.8 b	1.5 ± 2.3 c	0.9 ± 1.3 c	0.9 ± 1.5c

[a]Sum of first and second instars.
Data were pooled across sampling dates. Means within a row within a leaf node followed by the same letter did not differ significantly (Waller-Duncan's multiple-range test; $\alpha = 0.05$) ($n = 320$).

leaves. The mean numbers of all whitefly stages were always greater on the pubescent cultivars, DP DES 119 and Stoneville 453, than on the glabrous cultivars, DP 51 and NU COTN 33B.

There were no significant differences in proportional parasitism among cultivars (Fig. 1). Although one pubescent cultivar, DP DES 119, had higher peak parasitism than the others, there was only a slight trend toward higher parasitism. DP 51, a glabrous cultivar, and Gumbo 500, the intermediate hairy cultivar, apparently had the lowest peak parasitism. Proportional parasitism increased as the season progressed to a peak in August, after which parasitism steadily declined (Fig. 1). This is probably because parasitism follows the availability of hosts to parasitize and there was a new generation of susceptible whiteflies available at that time (Fig. 2).

The parasitoids emerging from parasitized whiteflies were identified as *Encarsia pergandiella* Howard, *Encarsia nigricephala* Dozier and *Eretmocerus californicus* Howard. *Encarsia pergandiella* comprised 93.3% (68.5% ♀ and 25.0% ♂) of all the parasitoids that emerged from sampled leaves. DP DES 119 had the highest number of parasitoids emerging from collected leaves (149, comprising 47.75% of all parasitoids) (Table 3). NU COTN 33B had the lowest number of parasitoids emerging (17, 5.44%).

Laboratory Experiment (Functional Responses of Parasitoids)

There was an increase in mean number of second instars parasitized by *E. rui* as host density increased from 8 to 64 hosts on all 3 cotton cultivars (Fig. 3). A maximum mean of 27.7 hosts parasitized in 24 h was reached when the parasitoid was offered 64 whitefly second instars. Curves obtained from *E. rui* on all 3 cultivars visually approximated a type II functional response (Fig. 3).
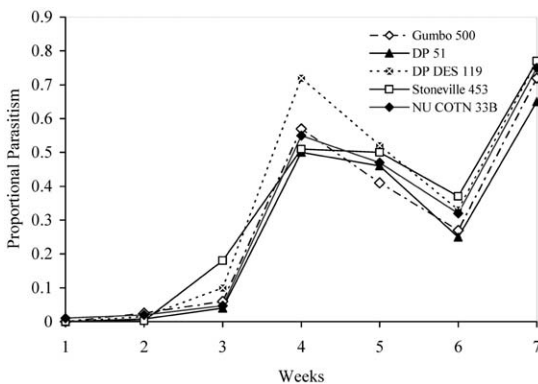

Fig. 1. Proportional parasitism of *B. tabaci* over the season (7-week period) for the fifth leaf of 5 cotton cultivars differing in leaf morphology and pubescence.
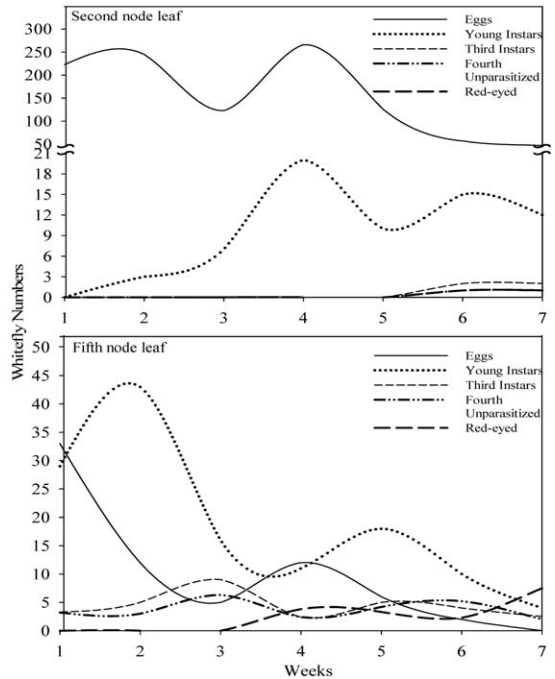

Fig. 2. Seasonal trend in overall mean number of different life stages of *B. tabaci* over the season (7-week period) for the second and fifth node leaves of 5 cotton cultivars differing in leaf morphology and pubescence in field trials.

Cultivar ($F = 23.61$; $df = 2, 154$; $P < 0.0001$) and host density ($F = 449.47$; $df = 3, 154$; $P < 0.0001$) significantly affected parasitism of second instars by *E. rui*. The interaction of cultivar and host density also significantly influenced the number of second instars parasitized by *E. rui* ($F = 5.01$; $df = 6, 154$; $P < 0.0001$). On all 3 cultivars, the number of hosts parasitized increased with increasing host densities. However, the increase in parasitism on the smooth-leaved DP 51 was greater than the increase on the hairy cultivars, DP DES 119 and Gumbo 500 (Fig. 3), thus accounting for the significant density by cultivar interaction.

Parasitism of fourth instar whitefly nymphs by *E. formosa* also visually approximated a type II functional response (Fig. 3). However, the maximum mean number of whiteflies parasitized by *E. formosa,* 11.7 in 24 h, was only half that of *E. rui*. Cultivar was a significant source of variation ($F = 5.78$; $df = 2, 209$; $P = 0.0036$) with more whiteflies parasitized on DP 51 than on DP DES 119 and Gumbo 500. Density of whitefly hosts significantly influenced parasitism ($F = 95.3$; $df = 3, 209$; $P < 0.0001$); only half as many whiteflies were parasitized at the 8-nymph density as at the other densities, but the number parasitized did not differ at the 16, 32, or 64 nymph densities. The interaction of culti-

TABLE 3. PARASITOID EMERGENCE FROM LEAF DISKS OF 5 COTTON CULTIVARS DIFFERING IN LEAF MORPHOLOGY AND PUBESCENCE GROWN IN HASTINGS, FLORIDA.

	Parasitoids						
	Encarsia nigricephala		*Encarsia pergandiella*		*Eretmocerus californicus*		Total	
Cotton cultivars (leaf morphology)	No.	%[a]	No.	%	No.	%	No.	%
Gumbo 500 (okra)	4	1.3	35	11.2	7	2.2	46	14.7
DP 51 (smooth)	3	1.0	16	5.1	2	0.6	21	6.7
NU COTN 33B (smooth)	2	0.6	15	4.8	0	0	17	5.4
DP DES 119 (hairy)	1	0.3	147	47.1	1	0.3	149	47.8
Stoneville 453 (hairy)	1	0.3	78	25.0	0	0	79	25.8
Sum Total	11	3.5	291	93.3	10	3.2	312	100

[a] Percentage of total parasitoids emerged from leaves collected during 7 weeks.
Data were pooled across sampling dates (*n*=320).

var and host density did not significantly influence the number of fourth instars parasitized by *E. formosa*.

DISCUSSION

Our field study results indicated a preference for oviposition of female *B. tabaci* on pubescent cotton cultivars over glabrous cultivars. Correspondingly, the density of *B. tabaci* nymphs was higher on cultivars with higher leaf hair density. Several other studies have indicated increased whitefly populations on pubescent cotton cultivars relative to glabrous cultivars (Butler & Henneberry 1984; Butler et al. 1986; Wilson et al. 1993; Chu et al. 2000, 2001). The intermediately hairy, okra-leaf cultivar, Gumbo 500, had an intermediate number of whitefly instars. Because Gumbo 500 has an okra-leaf shape and has reduced number of hairs compared to the pubescent cultivars, it is unclear which factor may have contributed to reduced whitefly oviposition. However, supporting our results, several previous studies have shown that okra-leaf cotton cultivars were colonized with fewer whitefly adults, eggs and nymphs compared to normal-leaf cultivars, indicating the potential of okra-leaf genetic traits for reducing the population of this pest (Ozgur & Sekeroglu 1986; Chu et al. 1999, 2002; Raghuraman et al. 2004). On the other hand, NU COTN 33B, a cultivar genetically modified to express the Bt toxin Cry1A(c), had the lowest number of whitefly numbers and lowest parasitoids emerging (17, comprising 5.44% of all parasitoids). Higher susceptibility of parasitized hosts to intoxication by NU COTN 33B could contribute to the observed differences between parasitoid and its host (Baur & Boetel 2002). The parasitoid species that emerged from whitefly nymphs on cotton were the common species that have been collected in Florida on wild and cultivated hosts (Bennett et al. 1990) and on the agronomic crops, peanut and
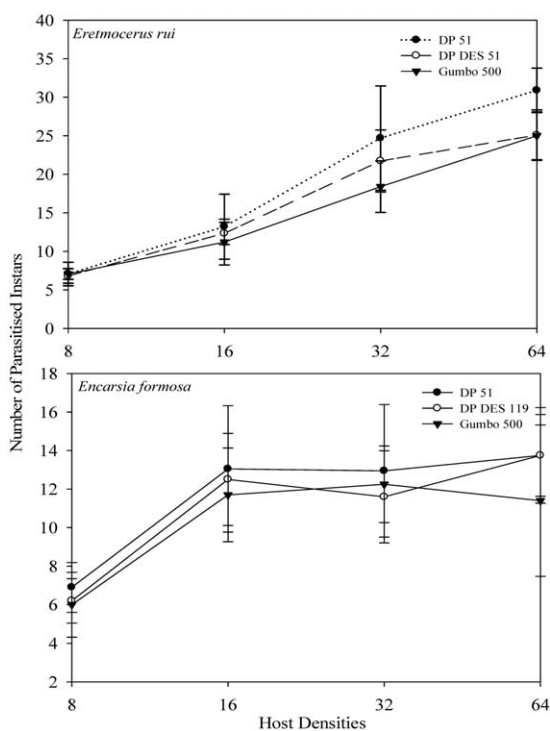

Fig. 3. Mean (± SD) number of second instars of *B. tabaci* parasitized by *E. rui* and mean (± SD) number of fourth instars of *B. tabaci* parasitized by *E. formosa* on 3 cotton cultivars differing in pubescence and leaf morphology: DP 51 (smooth normal-leaf), DP DES 119 (pubescent normal-leaf), and Gumbo 500 (intermediate okra-leaf) in laboratory trials.

soybean (McAuslane et al. 1995). Parasitism was similar among all 5 cotton cultivars tested in this study. However, in soybean fields in Florida, whiteflies on a glabrous isoline suffered more parasitism than whiteflies on a pubescent isoline (McAuslane et al. 1995).

Our laboratory studies indicated a higher daily fecundity for *E. rui* than for *E. formosa* on whitefly nymphs. The average maximal daily fecundity of 31 nymphs for *E. rui* corresponds well with that indicated previously by McAuslane & Nguyen (1996) of approximately 30 eggs in 24 h. There have been a number of studies on the fecundity of *Encarsia* species and *E. formosa*, in particular, parasitizing whitefly species on various plant cultivars (Vet & van Lenteren 1981; Bethke et al. 1991; Heinz & Parrella 1994; Qiu et al. 2004). Vet & van Lenteren (1981) recorded a maximal daily fecundity rate of 12 for *Encarsia* species in general attacking *Trialeurodes vaporariorum* Westwood. Qiu et al. (2004) estimated a maximum daily fecundity of 14.5 for *E. formosa* strain D at 25°C attacking *B. argentifolii* on poinsettia, although the mean daily parasitism was quite low, being 11.2 and 9.88 for temperatures of 20°C and 25°C, respectively. The maximum daily fecundity for *E. formosa* at 25°C obtained in our study was 15.8, which was slightly greater than that obtained by Qiu et al. (2004). Our study indicated that the number of hosts parasitized by *E. formosa* remained stable at around the maximum daily fecundity even when plenty of hosts were available. This study showed that *E. rui* parasitized almost twice as many instars as *E. formosa*. It is unclear which factor(s) resulted in the low maximal daily fecundity of *E. formosa* compared to *E*. rui. It is likely that the *E. formosa* strain we used in this study has an innately low maximum daily fecundity or is not very well adapted to *B. tabaci*. We can conclude that *E. rui* might be more effective than *E. formosa* in biological control of *B. tabaci* on cotton.

In this study, *E. rui* showed lower parasitism on pubescent cotton cultivars than on smooth and okra-leaf shape cotton cultivars. However, parasitism by *E. formosa* did not show any cultivar effect. The reason for this might be that *E. formosa* and *E. rui* have different oviposition behavior or preference on different plants. Results from these evaluations suggest that the probability of achieving successful biological control will likely be greater on cotton cultivars with fewer trichomes. Previously, a number of studies were conducted to understand the potential effect of plant trichomes on whitefly parasitoids (Hulspas-Jordaan & van Lenteren 1978; Heinz & Parrella 1994; van Lenteren et al. 1995; Hoddle et al. 1998; Gruenhagen & Perring 2001). An early study by Hulspas-Jordaan & van Lenteren (1978) showed the negative effect of leaf hairs on cucumber varieties on walking speed and walking pattern of *E. formosa*. Similarly, the rate of parasitism of the greenhouse whitefly, *T. vaporariorum*, by *E. formosa* decreased linearly with increasing hair density on cucumber hybrids (van Lenteren et al. 1995). A greenhouse study of parasitism of silverleaf whitefly by *E. eremicus* on 5 host plants, including cotton, indicated that fewer whiteflies were parasitized on plants with higher trichome densities (Gruenhagen & Perring 2001). These 3 studies corroborate our results where we found a significantly greater mean number of nymphs were parasitized on glabrous-leaf DP 51 than on hairy DP DES 119 and Gumbo 500 by both *E. formosa* and *E. rui*.

Contrary to the laboratory studies, parasitism rates in the field were similar, regardless of the pubescence of the cotton cultivars. There are several potential reasons for this. The higher populations of whiteflies on the pubescent varieties could have represented higher quality host patches than the lower population density patches on the glabrous cultivar so that the parasitoids stayed and searched for hosts on the pubescent plants, despite the trichome abundance. This could cause a numerical response not observed in the lab when individual parasitoids were confined on each plant. There could be parasitoid species-specific responses to trichomes; for example, *E. pergandiella*, the most abundant parasitoid in the field, was not tested in the laboratory study. In addition, parasitism in the field could have been affected by other plant-related factors and/or abiotic factors (Butler and Henneberry 1994; Hoelmer 1995) that were not present in the laboratory study.

These results indicate that there may be a disadvantage to planting pubescent cultivars of cotton in Florida if whiteflies are expected to be abundant; whitefly females prefer to oviposit on pubescent cultivars. Consequently, there will be more eggs laid and more adults emerging on pubescent cultivars than on glabrous cultivars. By planting a glabrous cotton cultivar, a grower may be able to avoid severe infestation of whitefly due to reduced whitefly oviposition and also due to increased performance by parasitoids resulting in an increase in parasitism and decrease in whitefly numbers. Additional studies to aid in the understanding of the effectiveness of parasitoids of *B. tabaci* and their dynamics, and to determine the mechanisms behind differences in both whitefly and parasitoid oviposition on cotton cultivars differing in leaf morphology are warranted.

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