# Chapter 6 Biological Control of Silverleaf Whitefly in the United States

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## NON-TECHNICAL SUMMARY

*Bemisia tabaci* was described in 1889 as a tobacco pest in Greece and named *Aleyrodes tabaci*, the tobacco whitefly. Many name changes (Brown et al., 1995) have occurred since its first description. Perring (2001) and later DeBarro et al. (2011) and Boykin and De Barro (2014) determined that the different biotypes were a species complex, each with different biological attributes, cross-mating success, and differences in virus transmission. In the 1990s, improved transportation technology and increased frequency of international transport of plant material contributed to the extension of the geographical range of the *B. tabaci* complex. At present, it is globally distributed and occurs on all continents except Antarctica (Martin et al., 2000). Losses due to this species complex in agricultural worldwide have been extensive. Damage includes leaf silvering in cucurbit crops such as squash, transmission of viruses that reduce quality and yield of tomatoes, sticky fiber in cotton from honeydew production, and direct damage from feeding on horticultural/floricultural crops such as poinsettias (Gerling and Henneberry, 2001).

In the early 1990s, a biological control program was initiated by the U.S. Department of Agriculture (USDA) in response to widespread outbreaks of the particularly damaging biotype B, which at that time had been described as the silverleaf whitefly, *Bemisia argentifolii* (Bellows et al., 1994). This involved worldwide exploration for natural enemies in the tropics and subtropics where *B. tabaci* was known to be endemic. Many unique populations and species of parasitic wasps in the genera *Eretmocerus* and *Encarsia* (both Hymenoptera: Aphelinidae) were imported, reared, and released in the United States to reduce the impacts of this pest. For several years, the *Eretmocerus* species were the dominant parasitoids in the field, post-release (1999–2012) (Goolsby et al., 2004; Pickett et al., 2013). However, now (2012–2022) *Encarsia sophia* (formerly *E. transvena*) is most responsible for parasitism of *B. tabaci* in North America (Goolsby et al., 2009a; Xiao et al., 2011; Naranjo, 2018; Davis et al., 2020). *Encarsia sophia* has likely emerged as the dominant species because it can exist at lower silverleaf whitefly population levels. *Encarsia sophia* is an autoparasitoid, meaning it can parasitize its own female progeny (if necessary) to produce males. Along with resident species of predators, *E. sophia* has driven whitefly populations to even lower levels in the mid-2000s, compared to 1999 when the *Eretmocerus*

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spp. became the dominant parasitoids (Goolsby et al., 2009a,b; Naranjo et al., 2018). Overall, the imported parasitoids, in combination with the local whitefly predators, have dramatically lowered pest populations an estimated 90%, allowing for the development of integrated pest management programs that further reduce the damage from the pest and allow for sustainable production of field/greenhouse crops and ornamental plantings. In the early 2000s, the silverleaf whitefly biological control program was estimated to be saving $300 million annually (Robinson and Taylor, 1996). For a complete review of the program, see Gould et al. (2008).

## HISTORY OF INVASION AND NATURE OF PROBLEM

The first specimens of *Bemisia tabaci* (Hemiptera: Aleyrodidae) (**Fig. 1**) collected in the Western Hemisphere were found in 1894 in the United States on sweet potato. They were initially described as *Aleyrodes inconspicua* and given the name sweetpotato whitefly, but were later recognized as *B. tabaci* biotype A. Except for its role as a vector of cotton leaf crumple in the late 1950s and early 1960s, *B. tabaci* was not recognized as an economic pest in the United States. However, by the 1980s, *B. tabaci* became a serious problem of agricultural communities in the United States and northern Mexico. Outbreaks occurred in California and Arizona in 1981 and were initially presumed to be the long-present *B. tabaci* biotype A. Field crops such as cotton and melons in the Imperial Valley of California and Lower Rio Grande Valley of Texas were significantly affected (Birdsall et al., 1995; Riley and Ciomperlik, 1997). These outbreaks were followed by heavy infestations on poinsettia crops and by the appearance of silverleaf symptoms on squash (Price et al., 1986; Maynard and Cantliffe, 1989). The source of these problems was soon recognized as a new biotype of *B. tabaci*, first formally recognized from Florida. Based on several attributes—high reproductive capacity, resistance to pesticides, alternative host plant utilization, and other differences—the new pest was designated as *B. tabaci* biotype 'B' (Costa and Brown, 1990) and subsequently as a new species, the silverleaf whitefly, *Bemisia argentifolii* (Bellows et al., 1994). Subsequent studies placed *B. argentifolii* as a member of the Middle East-Asia Minor clade (De Barro et al., 2011), and recently it has been grouped within the North Africa-Mediterranean-Middle East species complex (de Moya et al., 2019).

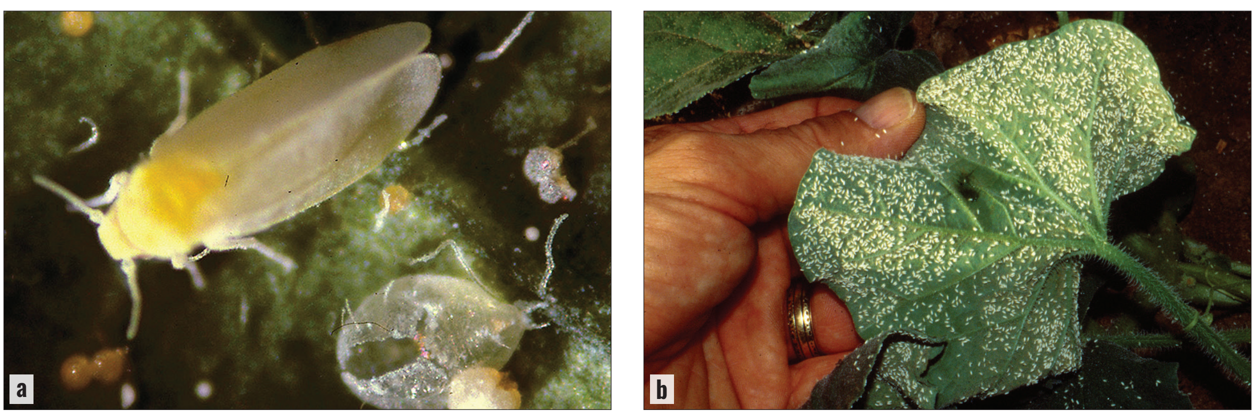


**Figure 1.** *Bemisia tabaci* on underside of a melon leaf. (a: J. Goolsby, USDA-ARS; b: K. Hoelmer, USDA-ARS)

## WHY CONTROL THIS INVASIVE SPECIES?

In Arizona, California, Texas, and Florida, losses in 1991 and 1992 were estimated to range from $200 to $500 million (Perring, 1996). In the Imperial Valley of California between 1991 and 1995, over $100 million were lost annually (Birdsall et al., 1995). In Arizona, California, and Texas, cotton growers spent $154 million from 1994 through 1998 to control silverleaf whitefly and prevent cotton lint stickiness (Ellsworth et al., 1999). Gonzalez et al. (1992) estimated that for every $1 million of primary silverleaf whitefly-induced crop loss in a multi-commodity-growing agricultural community, there was an estimated $1.2 million loss of farm income. Infestations in U.S. greenhouse and ornamental production also caused losses estimated in the millions (Barr and Drees, 1992). Losses to the tomato industry in Florida in 1991 were reported to exceed $125 million (Schuster, 1992). Similar crop and financial losses occurred in adjacent agricultural areas in northern Mexico (Silva-Sanchez, 1997).

These unacceptable whitefly-caused financial, social, and environmental losses highlighted the need for a nationally coordinated effort to provide long- and short-term solutions to the problem. The reasons for the outbreaks were unknown but clearly suggested biological and host plant preference differences between the outbreak populations of whitefly and the previously known *B. tabaci* populations. Actions to address the issues arising from these unprecedented outbreaks of the silverleaf whitefly led to the development of a classical biological control program against this new form of *B. tabaci*.

## THE ECOLOGY OF THE PROBLEM

The impact of released classical biological control agents on invasive whitefly pests has been well documented (e.g., Quezada, 1974; DeBach and Rose, 1976; Bellows et al., 1992). Designing methods to evaluate the impact of parasitoids released against silverleaf whitefly, however, was not straightforward. Evaluating the success of classical biological control programs for silverleaf whitefly was complicated due to its broad host plant range, coupled with the influence of farming practices, variations in cropping patterns across states, and differences in climate among locations. To further complicate matters, these factors operated at different spatial and temporal scales and were likely interrelated. In addition, landscape pests with broad host ranges like *B. tabaci* are also widespread in unmanaged non-crop habitats, and it is in these landscape populations that natural enemies are often most valuable. To address this complexity, data on parasitoid releases in the Imperial Valley of California were collected and analyzed using multivariate statistics to determine the impact of introduced whitefly parasitoids.

Silverleaf whitefly became a significant agricultural pest in states from North Carolina to California in the early and mid-1990s. The whitefly attacked a wide range of plants, many of them important agricultural crops (Davis et al., 2020). It was able to complete up to 20+ generations per year by moving from spring cucurbit crops like cantaloupe and watermelons into cotton in the summer months. Whiteflies overwintered on cole crops and winter weed species, as well as on ornamental plants around houses. Whiteflies reached their peak in cotton, often creating massive migrations from that host crop when it was defoliated. In peak years, clouds of whiteflies leaving cotton fields were so thick that fall melons became impossible to grow because of the overwhelming numbers of the whitefly and the plant viruses that they carried.

In the Imperial Valley of California, as well as other growing areas of the southern United States, a succession of host crops are available to silverleaf whitefly throughout the year. Under favorable weather conditions, gravid females can cause a population explosion if suppressive measures are not in place. Alfalfa (*Medicago sativa*) is the major crop in the Imperial Valley, with alfalfa planting varying from 71,000 to 91,000 ha (175,000–225,000 acres) over a 20-year period. Although present year-round, *B. tabaci* populations are generally low in alfalfa compared to cantaloupe (*Cucumis melo reticulus*) or cotton (*Gossypium hirsustum*). Alfalfa therefore provided a more stable habitat for *B. tabaci* parasitoids. Landscaping plants at residences or businesses scattered throughout the Imperial Valley also provided perennially stable habitats and refuges for both whiteflies and parasitoids. Seasonal crops are exceptionally good hosts for *B. tabaci*, but generally for short periods of time, making it difficult for parasitoids to discover, build up, and suppress whitefly populations on such short-cycle crops before the crops are harvested and plowed under.

If overwintering whitefly populations found on fall and winter cole crops (*Brassica* spp.) are not controlled, they may quickly colonize spring crops. Shortly after the cole-crop season ends and the fields are plowed under, spring cantaloupes and cotton emerge, providing highly favorable *B. tabaci* hosts. Cantaloupe fields planted for spring harvest are present into June, and cotton fields are hosts through September or October. A monitoring program using traps, conducted jointly by the Imperial County Agricultural Commissioner's office and USDA-APHIS (Animal and Plant Health Inspection Service), showed that peak *B. tabaci* populations historically occurred in August or September. Under crop production patterns used during the 1990s, cotton was the dominant host crop during these months, supporting the highest populations of *B. tabaci*. During the height of the of silverleaf whitefly outbreaks in the late 1980s and early 1990s, cantaloupe fields planted for fall harvest were available as whitefly habitat from July through November, but growers were forced to significantly reduce fall cantaloupe acreage because of pressure from *B. tabaci* populations and associated control costs (Legaspi et al., 1997; Gould et al., 2008).

Many control strategies were developed and implemented in the United States to control *B. tabaci* in the 1990s (Gould et al., 2008). New chemical tools became available that proved especially useful in controlling silverleaf whitefly in cantaloupe and cole crops, reducing extremely high populations observed in these crops during the peak outbreak years. Imidacloprid, applied to the soil, was widely used in cole crops and cantaloupe (in California 1990–2003); tank mixes of acephate and fenpropathrin were used on cotton (in California 1990–2003). Other factors that influenced *B. tabaci* populations were undergoing changes as well. Control costs for pink bollworm (*Pectinophora gossypiella*), boll weevil (*Anthonomus grandis*), and silverleaf whitefly, combined with increasing competition in world markets, led to reductions in cotton acreage from over 40,000 ha (99,000 acres) in the 1970s to less than 8,000 ha (20,000 acres) annually from 1989 through 2002. Acreage of cantaloupe peaked in the 1980s then plummeted in 1992, largely due to *B. tabaci* damage, and many fields were left unharvested. Between 1990 and 1991, fall cantaloupe acreage dropped by approximately 30%, and the gross value of the crop decreased by over $15 million. This reduction in cotton and cantaloupe (especially fall cantaloupe) acreage available to *B. tabaci* probably reduced regional whitefly populations. Alfalfa has remained the most stable whitefly host plant and parasitoid refuge, with the 2010–2020 area ranging from 65,000 to 89,000 harvestable ha (161,000–220,000 acres) annually. This increase in alfalfa acreage and reduction of more *B. tabaci*-susceptible crops most likely contributed to the overall reduction in silverleaf whitefly population levels and damage in the Imperial Valley. Similar changes occurred in the Lower Rio Grande Valley of Texas with reduced agreage of melons and cotton and subsequent increases in grain sorghum production. Shifts in cropping patterns can greatly affect the ecology of silverleaf whitefly.

## PROJECT HISTORY THROUGH AGENT ESTABLISHMENT

The classical biological control program directed against silverleaf whitefly in the 1990s was one the largest and most comprehensive programs in the history of biological control in the United States (Legaspi et al., 1996; Kirk et al., 2000, Gould et al., 2008). A team of scientists from USDA-APHIS, USDA-ARS (Agricultural Research Service), CDFA (California Department of Food and Agriculture) and several universities contributed to the discovery, importation, evaluation, release, and colonization of a suite of natural enemies. Field entomologists with USDA-APHIS were stationed in Arizona, California, and Texas to carry out the research where the infestations were the most damaging. To support the foreign exploration for natural enemies for *B. tabaci* and other biological control projects, a new APHIS quarantine facility was built at Moore Airbase near Edinburg, Texas, which eventually coordinated with mass-rearing facilities at the field locations to maximize the release efforts for the biological control program. The substantial level of commitment by USDA matched the level of damage caused to a wide range of crops by this 'super pest.' The national program leadership of ARS and APHIS produced a remarkable achievement in redirecting research programs, obtaining additional research and implementation funding from Congress, and developing a

5-Year National Research and Action Plan for Development of Management and Control Technology for the Silverleaf Whitefly (1992–1996), which was followed by the Silverleaf Whitefly 5-Year National Research, Action, and Technology Transfer Plan (1997–2001) to help organize research and track progress.

The foreign exploration program for natural enemies of *B. tabaci* resulted in more than 130 shipments of natural enemies from 30 countries being sent to quarantine facilities in the United States between 1991 and 1998 (**Table 1**). Climate matching software (CLIMEX) was used to match the affected areas in the United States with locations within the native distribution of *B. tabaci* and to rank areas for possible foreign exploration (Goolsby et al., 2004). The USDA-ARS European Biological Control Laboratory in Montpellier, France, contributed to the biological control program by having its staff engage in nearly year-round exploration, which led to the discovery of many parasitoids, predators, and pathogens for evaluation by U.S. researchers.

At the USDA-APHIS Mission, Texas, Biological Control Quarantine Laboratory, 50 populations of natural enemies (parasitoid wasps and predatory insects) were held in culture, including 16 new species of *Eretmocerus* and *Encarsia* parasitoids (Legaspi et al., 1996; Legaspi et al., 1997; Goolsby et al., 1998; Kirk et al., 2000; Gould et al., 2008). Only parasitoids that had been reared from *B. tabaci* (any biotype, as the biotypes could not be determined at the time of collection) and were either primary or autoparasitic species were considered for release. Predictive, pre-release studies were conducted in quarantine and in field cages to determine which species showed the most potential to control the whitefly populations (Goolsby et al., 1996, 1998). This information was used to rank species for large-scale releases based on mass rearing. Low-performing parasitoid species were also released at selected locations in substantial numbers to validate the predictions.

The silverleaf whitefly program was the first large-scale biological control program to use molecular genetic methods to characterize the imported natural enemies (Vacek et al., 2008). RAPD-PCR was used on the natural enemies reared in quarantine to identify potential cryptic species and maximize the release of the genetic diversity available from the exploration efforts. This was critical because many of the most valuable *Eretmocerus* species were extremely similar morphologically but had unique biological traits such as specific host-plant preferences and climatic adaptations. Molecular methods were also used to assure colony purity and to identify potentially exotic specimens recovered from the field. Taxonomic keys were developed to identify and describe the imported *Eretmocerus* parasitoids of *B. tabaci* in North America (Zolnerowich and Rose, 1998).

Mass-rearing facilities were established in Tucson, Arizona; the cities of Imperial and Sacramento, California; and Mission, Texas. At these locations, hundreds of millions of *Eretmocerus* and *Encarsia* species were mass reared (**Fig. 2**) over several years for release and evaluation in the areas affected by silverleaf whitefly (Roltsch et al., 2008a; Gould et al., 2008, Goolsby et al., 2009b), which included the subtropical agricultural areas of the United States and Mexico. Mass-rearing techniques improved dramatically over the course of the program, beginning with laboratory rearing in environmental chambers on whitefly-infested hibiscus plants, to heated outdoor field cages with large pots of kale and eggplant, to highly managed greenhouses that used large-leaf eggplants and mechanical removal of parasitoid pupae (Simmons et al., 2008a; Goolsby et al., 2009b). The large number of parasitoids available for release enabled a large-scale field evaluation of biological control as an integrated component of management programs.

Field evaluation programs were conducted in Phoenix, Arizona; Brawley and Sacramento, California; and Mission, Texas. Candidate natural enemies were tested in field cages on multiple crops, including alfalfa, broccoli, cotton, and melons (Hoelmer, 2007; Hoelmer and Roltsch, 2008). The results showed strong tri-trophic interactions and verified the importance of adequate climatic adaptation. The four species of Palearctic *Eretmocerus* that established in the western United States were morphologically similar, representing a group of closely related taxa that appear to be specialist parasitoids of the *B. tabaci* complex of biotypes. Their ability to readily attack whiteflies in the *B. tabaci* complex may have given them an advantage in the field versus the native North American *Eretmocerus tejanus* (**Fig. 3a**) and *Eretmocerus eremicus*, which have broader host ranges that include *Trialeurodes* species.

**Table 1.** Parasitic Hymenoptera imported into the United States and evaluated for biological control of *Bemisia tabaci* (biotype "B"), 1992 to 1998. (All specimens were collected from *Bemisia tabaci* complex unless otherwise noted.)

| Species | MBCL Asseccion Code | MBCL DNA Pattern | Collection Locality | Collector [1] | Date | Identifier | Host Plant | Biology |
|---|---|---|---|---|---|---|---|---|
| ***Encarsia* species** | | | | | | | | |
| *Enc. bimaculata* | M92018 | EN-1 | India, Parbhani | G. Butler | Jan-92 | Woolley & Schauff | | |
| *Enc. bimaculata* [2] | M93010 | EN-1 | India, Parbhani | G. Butler | Jan-92 | Woolley & Schauff | | Autoparasitoid |
| *Enc. formosa* [3] | M92017 | EN-2 | Greece, Angelohori | J. Kashefi | Jan-92 | Woolley & Schauff | Bean | Uniparental |
| *Enc. formosa* | M92030 | EN-2 | Egypt, Nile Delta | Kirk & Lacey | Jan-92 | Schauff | Lantana | Uniparental |
| *Enc. lutea* | M93064 | EN-10 | Cyprus, Mazotos | Kirk & Lacey | Jan-93 | Woolley & Johnson | Lantana | |
| *Enc.* nr. *hispida* | M94056 | EN-16 | Brazil, Sete Lagoas | Rose | Feb-94 | Rose & Woolley | Poinsettia | Uniparental |
| *Enc. lutea* | M94107 | EN-10 | Israel, Givat Haim | Kirk & Lacey | Oct-94 | Woolley & Johnson | Cotton | Autoparasitoid |
| *Enc. lutea* | M94115 | EN-10 | Israel, Ein Gedi | Kirk & Lacey | Oct-94 | Woolley & Johnson | Lantana | Autoparasitoid |
| *Enc. lutea* | M94129 | EN-10 | Spain, Mazarron Casas Nuevas | Kirk & Lacey | Nov-94 | Woolley & Johnson | *Ipomea* sp. | Autoparasitoid |
| *Enc. lutea* | M96044 | EN-10 | Sicily, Ragusa | Kirk & Campobasso | Sep-96 | Johnson | Solanaceous weed | Autoparasitoid |
| *Enc. pergandiella* | M94055 | EN-15 | Brazil, Sete Lagoas | Rose | Feb-94 | Rose & Woolley | Poinsettia, Soybean | Uniparental |
| *Enc. sophia* | M93003 | EN-7 | Spain, Murcia | Kirk & Lacey | Jan-93 | Woolley & Schauff | Lantana | Autoparasitoid |
| *Enc. sophia* | M94017 | EN-3 | Taiwan, Shan-Hua | Legaspi, Carruthers, Poprawski | Mar-94 | Woolley & Johnson | Soybean, Tomato | Autoparasitoid |
| *Enc. sophia* | M94019 | EN-4 | Taiwan, Shan-Hua | Legaspi, Carruthers, Poprawski | Mar-94 | Woolley & Johnson | Soybean, Tomato | Autoparasitoid |
| *Enc. sophia* | M94041 | EN-5 | Thailand, Chiang Mai | Kirk & Lacey | Mar-94 | Woolley & Johnson | Poinsettia | Autoparasitoid |
| *Enc. sophia* | M94047 | EN-5 | Malaysia, Kuala Lumpur | Kirk & Lacey | Mar-94 | Woolley & Johnson | *Mussaenda* sp. | Autoparasitoid |
| *Enc. sophia* | M95107 | EN-5 | Pakistan, Multan | Kirk & Lacey | Nov-95 | Goolsby | Cotton | Autoparasitoid |
| *Enc. sophia* | M96065 | EN-5 | Pakistan, Jalari | Kirk | Oct-96 | Goolsby | Cotton | Autoparasitoid |
| *Enc. sophia* [3] | M94014 | EN-11 | Philippines, Benguet | Legaspi, Carruthers, Poprawski | Mar-94 | Woolley & Johnson | White potato | Autoparasitoid |
| *Enc. sophia* | M94016 | EN-11 | Taiwan, Shan-Hua | Legaspi, Carruthers, Poprawski | Mar-94 | Woolley &Johnson | Poinsettia | Autoparasitoid |
| *Encarsia* sp. [2] | M95023 | EN-5 | Thailand, Doi Suthep | Carruthers & Legaspi | May-95 | | unknown woody plant | Autoparasitoid |
| *Encarsia* sp. | M94024 | EN-6 | Thailand, Kampang Saen | Kirk & Lacey | Mar-94 | Woolley & Johnson | Snakeweed | Autoparasitoid |
| *Enc.* sp. (*parvella* group) | M95001 | EN-18 | Dominican Republic, Azua | Ciomperlik | Jan-95 | Schauff | Tomato | Autoparasitoid |

**Table 1.** (continued)

| Species | MBCL Asseccion Code | MBCL DNA Pattern | Collection Locality | Collector[1] | Date | Identifier | Host Plant | Biology |
|---|---|---|---|---|---|---|---|---|
| ***Eretmocerus* species** | | | | | | | | |
| *Eret. emiratus* | M95104 | ERET-12 | United Arab Emirates | Porter, Romadon | Nov-95 | Rose & Zolnerowich | Okra | Biparental |
| *Eret.* sp. nr. *furuhashii*[2] | M95026 | ERET-11 | Taiwan, Chiuju | Kirk | May-94 | Goolsby | Cabbage | Biparental |
| *Eret.* sp. nr. *furuhashii* | M95098 | ERET-11 | Taiwan, Tainan | Talekar & Jones | Oct-95 | Rose & Zolnerowich | Tomato | Biparental |
| *Eret. hayati* | M93005 | ERET-2 | India, Thirumala | Kirk & Lacey | Jan-93 | Rose & Zolnerowich | | Biparental |
| *Eret. hayati* | M95012 | ERET-10 | Pakistan, Multan | Kirk, Lacey & Akey | Apr-95 | Rose & Zolnerowich | Mulberry | Biparental |
| *Eret. hayati* | M95105 | ERET-10 | Pakistan, Multan | Kirk & Lacey | Sep-95 | Rose & Zolnerowich | Eggplant | |
| *Eret. hayati*[2] | M96064 | ERET-10 | Pakistan, Jalari | Kirk | Oct-96 | Goolsby | Cotton | Biparental |
| *Eret. melanoscutus* | M94036 | ERET-3 | Thailand, Chiang Mai | Kirk & Lacey | Mar-94 | Rose & Zolnerowich | *Chromolaena* | Biparental |
| *Eret. melanoscutus* | M94040 | ERET-3 | Thailand, Kampang Saen | Kirk & Lacey | Mar-94 | Rose & Zolnerowich | Cotton | Biparental |
| *Eret. melanoscutus*[2] | M94023 | ERET-8 | Thailand, Sai Noi | Kirk & Lacey | Mar-94 | Rose & Zolnerowich | Eggplant, Melon | Biparental |
| *Eret. melanoscutus* | M95097 | ERET-3 | Taiwan, Tainan | Talekar & Jones | Oct-95 | Rose & Zolnerowich | Tomato | Biparental |
| *Eret. mundus* | M92014 | ERET-1 | Spain, Murcia | Kirk, Chen, Sobhian | Jan-92 | Schauff | Cotton | Biparental |
| *Eret. mundus* | M92019 | ERET-1 | India, Padappai | Kirk & Lacey | Jan-92 | Rose & Zolnerowich | Eggplant | Biparental |
| *Eret. mundus* | M92027 | ERET-1 | Egypt, Cairo | Kirk & Lacey | Jan-92 | Rose & Zolnerowich | Lantana | Biparental |
| *Eret. mundus*[2] | M93004 | ERET-1 | Spain, Murcia | Kirk & Lacey | Jan-93 | Woolley & Schauff | *Sonchus* | Biparental |
| *Eret. mundus* | M93058 | ERET-1 | Taiwan, Tainan | Moomaw | Dec-93 | Rose & Zolnerowich | Tomato | Biparental |
| *Eret. mundus*[2] | M94085 | ERET-1 | Italy, Frascati | Kirk & Campobasso | Sep-94 | Rose & Zolnerowich | Hibiscus | Biparental |
| *Eret. mundus* | M94092 | ERET-1 | Italy, Castel Gondolfo | Kirk & Campobasso | Sep-94 | Rose & Zolnerowich | *Ipomea* sp. | Biparental |
| *Eret. mundus* | M94097 | ERET-1 | Italy, Testa Di Lespe | Kirk & Campobasso | Sep-94 | Rose & Zolnerowich | Eggplant | Biparental |
| *Eret. mundus* | M94103 | ERET-1 | Israel, Gat | Kirk & Lacey | Oct-94 | Rose & Zolnerowich | Kohlrabi | Biparental |
| *Eret. mundus* | M94105 | ERET-1 | Israel, Gat | Kirk & Lacey | Oct-94 | Rose & Zolnerowich | *Sonchus* sp. | Biparental |
| *Eret. mundus* | M94120 | ERET-1 | Israel, Golan Ma'Aleh Gamla | Kirk & Lacey | Oct-94 | Rose & Zolnerowich | Melons | |
| *Eret. mundus* | M94124 | ERET-1 | Israel, Negev Desert | Kirk & Lacey | Oct-94 | Rose & Zolnerowich | Cucumber | Biparental |
| *Eret. mundus* | M94125 | ERET-1 | Israel, Golan Kibutz | Kirk & Lacey | Oct-94 | Rose & Zolnerowich | *Euphorbia* | Biparental |
| *Eret. mundus* | M96028 | ERET-1 | Sicily, Santa Groce | Kirk & Campobasso | Sep-96 | Goolsby | Eggplant | Biparental |
| *Eret. mundus* | M97046 | ERET-1 | Cyprus, Nicosia | Kirk | Jul-97 | Goolsby | Lantana | Biparental |
| *Eretmocerus* sp. | M96076 | ERET-13 | Ethiopia, Melka Werer | Gerling, Terefe | Nov-96 | Goolsby | Cotton | Biparental |

[1] Affiliations of collectors: A. Kirk, L. Lacey, R. Sobhian (USDA-ARS- EBCL, Montpellier, France), D. Akey and G. Butler (USDA-ARS Phoenix, Arizona),G. Campobosso (USDA-ARS, Rome, Italy), W. Jones (USDA-ARS, Weslaco, Texas), J. Kashefi (USDA-ARS, Thessaloniki, Greece), J. & B. Legaspi (USDA-ARS, Weslaco, Texas), M. Rose & C. Moomaw (Texas A&M Univ.), T. Poprawski, R. Carruthers (USDA-ARS, Weslaco, Texas), N. Talekar (AVRDC, Shanhua, Taiwan), D. Gerling (Israel), E. Porter & L. Romadon (USDA-APHIS-FAS, United Arab Emirates), A. Terefe (Melka Werer, Ethiopia)
[2] Not evaluated; all other species evaluated at MBCL quarantine and/or in field
[3] Host *Trialeurodes vaporarorum* or *Trialeurodes* sp.


**Figure 2.** Field cage production system (a–i) and greenhouse production system (j–o) for mass rearing *Bemisia* parasitoids (explanation of images given on following page).

**Figure 2 Explanation.** (a) *Eretmocerus hayati* male anntenating emerging female in advance of mating; (b) *Eretmocerus mundus* pupae inside exuviae of whitefly, note empty areas on either side of pupae which allows the parasitized whiteflies to float as compared to unparasitized whiteflies that sink. This feature is used for separation of parasitoid pupae; (c) *Encarsia sophia* pupae inside exuviae, note presence of dark meconia that are characteristic of this parasitoid genus; (d) vacuum collection of whitefly adults from the mother colony to use for infesting field cages; (e) release of parasitoid adults onto infested plants in field cage; (f) field cage full of infested eggplants that have been inoculated with parasitoids. Plants are mature and ready for harvest of leaves with parasitized whitefly; (g) harvested leaves drying on racks for one day; (h) harvested leaves inside Plexiglass emergence cages that are used to collect adult parasitoids; (i) emergence cage with black shroud to force adult parasitoids towards light and into petri dishes used for collection; (j) large eggplants infested with *B. tabaci* shrouded to contain adult parasitoids that have just been released; (k) eggplants held in greenhouse for maturation of parasitoid pupae; (l) funnel showing bulk unparasitized *B. tabaci* and parasitoid pupae floating in water, which have just been removed from the eggplant leaves using a high-pressure flat fan sprayer; (m) funnel showing separation of unparasitized whitefly that sink to bottom and top layer of floating parasitoid pupae; (n) parasitoid pupae drying on nylon mesh cloth; (o) parasitoid pupae being weighed to determine approximate numbers. (a,b: Mike Rose, TAMU; c: Walter T. Nagamine, d–q: J. Goolsby, USDA-ARS)

The climate in the native range of each of the four imported *Eretmocerus* species closely matched the climate in the areas of the United States where they established: (1) *E. mundus* (from Mediterranean Europe and the Mediterranean climate of the San Joaquin Valley of California), (2) *Eret. emiratus* (from the dry, hot desert of the Arabian Peninsula and the Imperial Valley of California), (3) *Eret.* nr. *emiratus* (from the subtropical desert of Ethiopia and the areas around Yuma and Phoenix, Arizona), and (4) *Eret. hayati* (from the subtropical desert of the Indus River Valley and the Rio Grande Valley of Texas) (Goolsby et al., 2004; Pickett et al., 2013). The exotic autoparasitoid (i.e., a parasitoid that produces male progeny by parasitizing its own developing female progeny) *Enc. sophia* (**Fig. 3b**) also established at the same sites in California, Arizona, Florida, South Carolina, and Texas. As noted earlier, *Enc. sophia* did not become a dominant parasitoid until 2010 (to present), many years after its release in the 1990s.

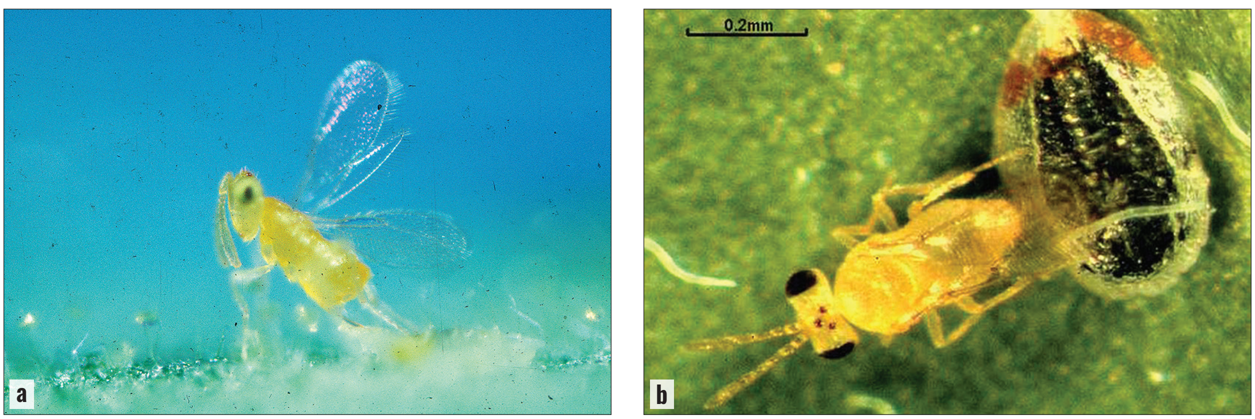


**Figure 3.** (a) *Eretmocerus tejanus* ovipositing into 2nd-instar silverleaf whitefly nymph; (b) *Encarsia sophia* autoparasitizing its own female pupa. (a: Mike Rose, TAMU; b: Walter T. Nagamine)

Several release methods were developed to enhance the likelihood of establishment of the released parasitoids in annual cropping systems. It was important that whiteflies and their habitat be available for parasitoids so that they could persist in the environment after the annual crops were plowed under. Refuge strips, home gardens, and commercial landscape nurseries were used as release sites because they had stable year-round populations of *B. tabaci* and were free of the use of broad-spectrum pesticides (Roltsch et al., 2008b). In addition to inoculative release methods, a more efficient method for augmentation of parasitoids was developed for use in cucurbit crops by using seedling transplants (bearing parasitized whiteflies) known as 'banker plants' (**Fig. 4**) (Goolsby and Ciomperlik, 1999; Pickett et al., 2004.). More recently, banker plants were modified for use in vegetable crops in Florida (Yinfang et al., 2011). Papaya plants infested with the less damaging greenhouse whitefly (*Trialeurodes vaporariorum*) that were parasitized by *Enc. sophia* were used for early-season releases of parasitoids into vegetable and greenhouse crops. This technique avoided the use or release of *B. tabaci* into the cropping system.

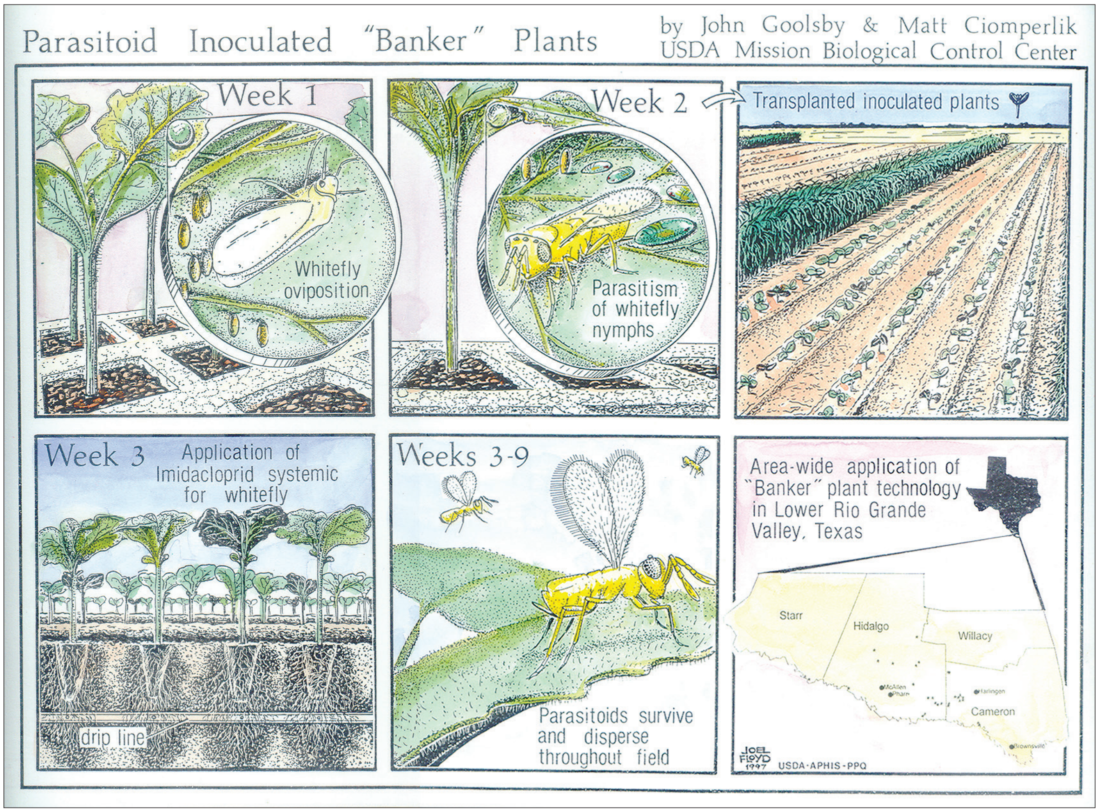


**Figure 4.** Parasitoid-inoculated 'Banker Plant' graphic used to show growers the technology. (J. Floyd, USDA-APHIS)

Field efforts to control *B. tabaci* were aided by the development of several narrow-spectrum insecticides that were effective against *B. tabaci* while still allowing substantial parasitoid activity. Biological control intensive-Integrated Pest Management (IPM) strategies were developed to take advantage of the new selective insecticides. Banker plants were transplanted into imidacloprid-treated fields, which reduced the cost of release and demonstrated how biological control could be incorporated in the IPM and local farming practices used during the release programs of the 1990s (Goolsby and Ciomperlik, 1999). A field-scale demonstration of mass-reared augmentation releases of *Eret. emiratus* in crops in the Imperial Valley in California showed that it was possible to increase parasitism in field crops through augmentative releases of parasitoids (Simmons et al., 2008b).

While more studies are needed to get a full assessment of the efficacy of the whole biological control program, some detailed quantitative studies have been conducted that indicate impacts of the introduced parasitoids were substantial in the years immediately following establishment in areas such as the Lower Rio Grande Valley. During these studies, regional differences in efficacy were apparent: life table studies conducted for survivorship of *B. tabaci* on cotton in Maricopa, Arizona documented the regional dominance in parasitism of *E. sophia*. The same studies also showed that in cotton, the most effective natural enemies were predatory insects (Naranjo, 2018). This contrasted with cotton in Turkey where life tables showed that parasitism by *Eret. mundus* was a significant mortality factor (Karut and Naranjo, 2009). Similar research is needed for other regions and habitats where the exotic parasitoids have become established. Only after evaluations of many crops, associated weeds, and other landscape hosts over time will we truly be able to accurately measure the impact and significance of benefits derived from the interagency silverleaf whitefly biological control program.

## HOW WELL DID IT WORK?

### What Impacts Really Matter?

Establishment of silverleaf whitefly parasitoids reduced the reservoir populations of whiteflies and helped to stabilize agricultural production in the affected farming areas in Arizona, California, Florida, Puerto Rico, South Carolina, and Texas within a few years, and populations of silverleaf whitefly continued to drop over time (**Table 2**). Production of crops affected by *B. tabaci*, such as squash, melons, and cucumbers again became economical, especially with the integration of new insecticides that were not as toxic to the silverleaf whitefly parasitoids and predators. Integrated pest management programs for crops such as cotton and alfalfa were able to lower and even eliminate insecticide use once the late-spring migration of silverleaf whitefly from melons into cotton was reduced. Insecticide use for whiteflies on ornamentals in urban landscapes was largely eliminated once the biological control agents became well established. In commercial greenhouse crops, methods for early-season release of commercially produced whitefly parasitoids stabilized production of crops such as tomatoes, cucumbers, peppers, and poinsettias.

**Table 2.** Timeline of the silverleaf whitefly, *Bemisia tabaci*, biological control program.

| | |
|---|---|
| **1990** | Invasion of silverleaf whitefly in USA |
| **1991** | Initiation of multi-agency biological control program |
| **1992** | Foreign exploration for biocontrol agents |
| **1995** | Establishment of *Eretmocerus* and *Encarsia* species |
| **1996** | Biocontrol agents shared with Australia and Mexico |
| **1997** | Biocontrol program shows early benefits, *Eretmocerus* species dominant |
| **2001** | Silverleaf whitefly outbreaks eliminated |
| **2001** | IPM programs reduce direct and virus-related damage |
| **2010** | *Encarisa sophia* becomes dominant |
| **2011** | Biocontrol agents shared with China, Uganda |
| **2022** | Silverleaf whitefly field populations remain low |

## BENEFITS OF BIOLOGICAL CONTROL OF SILVERLEAF WHITEFLY

Reduction in pesticide use against outbreak populations of silverleaf whitefly produced significant but uncalculated monetary benefits for the agricultural sector. Benefits to the environment and safety of agricultural workers were also significant, but not measured. The silverleaf whitefly biological control program clearly demonstrated the potential benefits of classical biological control in annual row-crop agriculture. The program also confirmed the utility of predictive evaluations, which showed that a multiple-species release strategy was needed due to the varied climates involved and the many different crops that were damaged by *B. tabaci*. This strategy should be considered for future biological control programs directed at multi-crop, multi-host plant invasive pests that become widely distributed in the United States.

Parasitoids imported for this project have also been shared globally with Mexico, the Dominican Republic, China, Australia, Tanzania, and Uganda. This international cooperation has allowed for greater benefit sharing of biological control agents, especially from the countries that received these silverleaf whitefly agents from the United States.

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