# Classical Biological Control of *Bemisia tabaci* in the United States - A Review of Interagency Research and Implementation

# Progress in Biological Control

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# Classical Biological Control of *Bemisia tabaci* in the United States - A Review of Interagency Research and Implementation

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Cover illustrations: A female *Eretmocerus* (an undescribed species native to Florida) feeds on fluids exuding from a *Bemisia tabaci* nymph that has been pierced by the wasp's ovipositor (top picture) and oviposits underneath a *B. tabaci* nymph (bottom picture).
Photograph credits: Mike Rose

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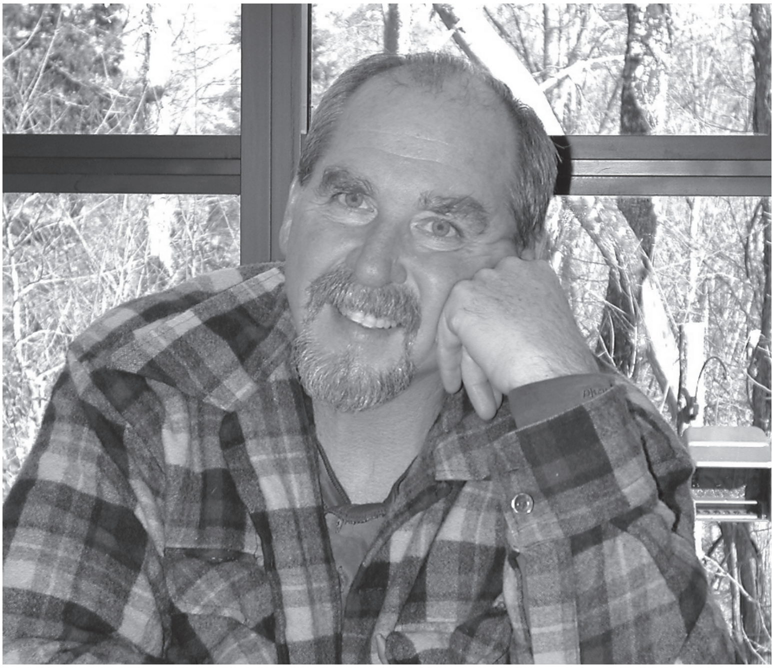
# Dedication



This book is dedicated to Mike Rose (1945–2004), an author of Chapter 5, preeminent biological control specialist and inspirational mentor to many of the book's authors. Mike Rose began his career at the University of California, Riverside, in the early 1960s working with Paul DeBach on biological control of whitefly, scale and mealybug pests of citrus. His career continued at Texas A&M University, and even in nominal retirement in Montana he remained very active as a biological control consultant. Mike's expertise in biological control of whitefly and in the aphelinid genus *Eretmocerus* made him a natural leader and proponent of the biological control program for *Bemisia tabaci* in the USA. Mike's influence can be seen in many aspects of the research reported in this book, especially in the taxonomy, quarantine evaluation, and postrelease evaluation of the natural enemies.

# Progress in Biological Control

## Series Preface

Biological control of pests, weeds, and plant and animal diseases utilising their natural antagonists is a well-established and rapidly evolving field of science. Despite its stunning successes world-wide and a steadily growing number of applications, biological control has remained grossly underexploited. Its untapped potential, however, represents the best hope to providing lasting, environmentally sound, and socially acceptable pest management. Such techniques are urgently needed for the control of an increasing number of problem pests affecting agriculture and forestry, and to suppress invasive organisms which threaten natural habitats and global biodiversity.

Based on the positive features of biological control, such as its target specificity and the lack of negative impacts on humans, it is the prime candidate in the search for reducing dependency on chemical pesticides. Replacement of chemical control by biological control – even partially as in many IPM programs – has important positive but so far neglected socio-economic, humanitarian, environmental and ethical implications. Change from chemical to biological control substantially contributes to the conservation of natural resources, and results in a considerable reduction of environmental pollution. It eliminates human exposure to toxic pesticides, improves sustainability of production systems, and enhances biodiversity. Public demand for finding solutions based on biological control is the main driving force in the increasing utilisation of natural enemies for controlling noxious organisms.

This book series is intended to accelerate these developments through exploring the progress made within the various aspects of biological control, and via documenting these advances to the benefit of fellow scientists, students, public officials, policymakers, and the public at large. Each of the books in this series is expected to provide a comprehensive, authoritative synthesis of the topic, likely to stand the test of time.

Heikki M.T. Hokkanen, Series Editor

# Editors Preface

This book reviews interagency research and development of classical (importation) biological control of *Bemisia tabaci* (biotype B) conducted in the USA from 1992-2002. The successful discovery, evaluation, release, and establishment of at least five exotic *B. tabaci* natural enemies in rapid response to the devastating infestations in the USA represents a landmark in interagency cooperation and coordination of multiple disciplines. The review covers all key aspects of the classical biocontrol program, beginning with foreign exploration and quarantine culture, through development of mass rearing methodology, laboratory and field evaluation for efficacy, to field releases, integration with other management approaches, and monitoring for establishment and potential non-target impacts. The importance of morphological and molecular taxonomy to the success of the program is also emphasized. The book's contributors include 28 USDA, state department of agriculture, and university scientists who participated in various aspects of the project.

*Bemisia tabaci* continues to be a pest of major concern in many parts of the world, especially since the recent spread of the Q biotype, so the publication of a review of the biological control program for the B biotype is especially timely. We anticipate that our review of the natural enemies that were evaluated and which have established in the USA will benefit researchers and IPM practitioners in other nations affected by *B. tabaci.* This book will also serve as a useful reference for scientists in the USA conducting research on the Q biotype of *B. tabaci*. It will complement other recent works on *Bemisia* that deal more broadly with a wide range of subject areas and consequently must treat importation biological control in much less detail. Although the book's theme is *B. tabaci*, the organization and conduct of the project serves as a useful model for programs directed at biological control of other whitefly species, as well as biocontrol programs for other pests. This book should also support and encourage classical biological control inputs into other integrated pest management systems.

We would like to acknowledge Deborah Winograd (USDA-APHIS-PPQ, Center for Plant Health Science and Technology) for her assistance in reviewing the book chapters for grammar, consistency, and reference citations.

Juli Gould
Kim Hoelmer
John Goolsby

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# Chapter 1
# Introduction

**Thomas J. Henneberry[1] and Robert M. Faust[2]**

*Bemisia tabaci* (Gennadius) biotype B (= *B. argentifolii* Bellows and Perring) was described in 1889 as a tobacco pest in Greece and named *Aleyrodes tabaci*, the tobacco whitefly (Gennadius 1889). Numerous synonymies (Russell 1957, 1975) and nomenclatural issues (Brown et al. 1995) have occurred since its first description. Perring (2001) indicates that the existence of a species complex is reaching acceptance by the scientific community. The complex has many biotypes and two described extant, cryptic species. Improved transportation technology and increased frequency of international transport of plant material has 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 1999; Martin et al. 2000). Losses from the species complex in worldwide agricultural systems have been extensive. Table 1.1, modified and updated from Oliveira et al. (2001), Cock (1986, 1993), and Ioannou (1997) shows the international scope of *B. tabaci* as an economic pest. Its emergence as a major threat in agricultural production systems has been characterized by outbreaks in many parts of the world (Gerling and Henneberry 2001). In the 1980s and early 1990s, infestations in the USA were particularly damaging.

## 1.1 Brief History of *B. tabaci* and its Economic Impact in the USA

The first *B. tabaci* collected in the New World was found in 1894 in the USA on sweet potato and described as *Aleyrodes inconspicua* Quaintance and given the name sweetpotato whitefly (Quaintance 1900). Except for its role as a vector of cotton leaf crumple in the late 1950s and early 1960s (van Schaik et al. 1962), *B. tabaci* was not recognized as an economic pest in the USA. However, the serious

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**Table 1.1** Some reports of *Bemisia tabaci* economic pest status: Crops involved, monetary losses, or percentages of crop-loss estimates.

| Commodity | Time frame | Geographical areas | Losses: US$ (millions) | Losses: % of crop | Sources |
|---|---|---|---|---|---|
| Aubergine | 1970 | Egypt | "Extensive" crop loss | – | Herakly and El-Ezz (1970) |
| Cassava | 1970s | Africa, India | – | 30–80 | Sauti (1982); Phillips (1973); Lopez-Avila and Cock (1986) |
| | 1988 | Ivory Coast | – | 40 | Fargette et al. (1988) |
| | 1990 | Africa | 2,000 | 50 | Fauquet and Fargette (1990) |
| Cotton | 1920s–1930s | Northern India (now Pakistan) | "Extensive" crop loss | – | Misra and Lamba (1929) |
| | 1920s–1984 | India, Sudan, Iran, El Salvador, Mexico, Brazil, Turkey, Israel, Thailand, Ethiopia | – | 41–81 | Basu (1995) |
| | 1960s | USA, California, Imperial Valley (leaf crumple) | – | 50 | van Schaik et al. (1962) |
| | 1965 | Sudan Gezira | – | 20–30 | Mound (1965) |
| | 1980s | Worldwide (sticky cotton) | 30–35 | – | Strolz (1992) |
| | 1981 | USA (Arizona, California) | >50[a] | – | Duffus and Flock (1992) |
| | 1982 | Sudan (sticky cotton) | 15 | – | Khalifa (1980); Khalifa and Gameel (1982); Khalifa (1983); Lopez-Avila and Cock (1986) |
| | 1981–1983 | India | – | 1–31 | Sukhija et al. (1986) |
| | 1992 | USA, Arizona (sticky cotton) | 10.3[b] | – | Wade and Tronstad (1993) |
| | 1995 | Australia | ? | | DeBarro (1995) |
| Lettuce | 1981 | USA, California, Arizona | – | 50–75 | Duffus et al. (1986) |
| Sugar beets | 1981 | USA, California, Arizona | – | 20–30 | Duffus et al. (1986) |
| Mung bean | 1970s | India | – | Up to 74 | Cock (1986) |

| | | | | | |
|---|---|---|---|---|---|
| Tomato | 1973 | India | – | 20–95 | Sastry and Singh (1973) |
| | 1991 | USA, Florida | 125 | – | Schuster (1992) |
| Sunflower | 1985 | India | – | 9.2 | Balasubramanian and Chelliah (1985) |
| Okra | 1989 | India | – | 54 | Chaudhary and Dadheech (1989) |
| Cotton, melons squash, watermelons, sesame, lettuce, vegetables | 1991 | Rio Grande Valley, Texas | 100 | | Kirk et al. (2001); Riley and Sparks (1993) |
| | 1992 | Imperial Valley, California | >100 | | |
| | 1991, 1992 | Mexico, Mexicali Valley | 33[a] | – | Medina-Esparza and Leon-Paul (1994) |
| | 1991, 1992 | USA (Arizona, California, Texas, Florida) | 200–500 | – | Perring et al. (1993) |
| | 1991–1995 | USA, California, Imperial Valley | >100/year[b] | – | Birdsall et al. (1995) |
| | 1995 | Mexico, Sonora | [c] | – | Silva-Sanchez (1997) |
| Cotton | 1994–1998 | USA (Arizona, California, Texas) (stickiness) | 154 | – | Ellsworth et al. (1999) |
| Cowpea | 1980s–present | Nigeria | – | Up to 90 | Cock (1986) |
| Black bean, mung bean, soybean | 1991 | India | 300 | – | Varma et al. (1991) |
| Soybeans | 1992–1994 | Mexico, Sonora | 41[d] | – | American Soybean Association (2000) |
| Tomato, okra, cotton tobacco, melon | 1990s | Central American area, Cuba, Barbados, Costa Rica, Dominican Republic, El Salvador, Haiti, Honduras, Guatemala, Jamaica, Montserrat, Nicaragua, Santa Lucia | "Extensive" crop loss | – | Hilje (1996); Vazquez (1999) |

(continued)

**Table 1.1** (continued)

| Commodity | Time frame | Geographical areas | Losses US$ (millions) | Losses % of crop | Sources |
|---|---|---|---|---|---|
| Melon, tomato pepper | 1998–1999 | Guatemala | – | 30–50 | Dávila (1999) |
| Beans, tomatoes, cotton, melons, watermelons, okra, cabbage and other crops | 1995–present | South America, Brazil, many areas losses reported from Argentina, Columbia, Paraguay, Bolivia | >5,000 | – | Lima et al. (2000); Viscarret et al. (2000); Quintero et al. (1998); Morales and Anderson (2001) |
| Poinsettias, tomatoes | 1990s–present | Mediterranean Basin, Italy, Southern France | "Extensive" crop loss | – | Traboulsi (1994); Ioannou (1997) |
| Citrus | 1990s–present | Azerbaijan, Georgia | "Extensive" crop loss | – | Dantsing and Shenderovska (1988); Traboulsi (1994) |
| Vegetables, ornamentals, citrus, cotton, olives, pears, melons, watermelons | 1990s–present | Near East, Algeria, Bahrain, Cyprus, Egypt, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Malta, Morocco, Saudi Arabia, Somalia, Sudan, Tunisia, Turkey, United Arab Emirates | – | 10–90 5–80 in field culture; 0–60 in protected culture | Traboulsi (1994), Bedford et al. (1994); Ioannou (1997); Lopez-Avila and Cock (1986) |
| Cotton | 1990s–present | Pakistan | 1,100 | 37<br>2–25 | Robinson and Taylor (1996);<br>ICAC (1994); Traboulsi (1994) |
| Multiple crops | 1990s–present | China, Taiwan, Yunnan, found in 10 additional provinces by 1995 | "Extensive" crop loss | ? | Rumei (1996) |
| Greenhouse production | 1991–present | New Zealand, Spain, worldwide | "Extensive" crop loss | | Oetting and Buntin (1996); Price et al. (1986); Martin (1989) |
| | 1992 | USA | 23 | | Barr and Drees (1992) |

[a] Cotton 39,415 ha to 653 ha.
[b] 7.4 cents discount/454 g = 10.3 million loss in 1992 in Arizona.
[c] Cotton acreage reduced 65%.
[d] Soybeans 89,000–124,000 ha to 25,000 ha.

nature of the *B. tabaci* problem and the potential for serious impact on agricultural communities in the USA and northern Mexico became dramatically evident in the 1980s and early 1990s. Outbreaks in California and Arizona in 1981, presumably *B. tabaci* biotype A, were followed by heavy infestations on poinsettias and appearance of silverleaf symptoms on squash (Price et al. 1986; Maynard and Cantliffe 1989) by a new biotype in Florida in 1986. Reproductive, host plant, allozyme and other differences resulted in designation of the new pest as *Bemisia tabaci* biotype B (Costa and Brown 1990) and subsequently a new species *B. argentifolii* Bellows and Perring was described (Perring et al. 1993). As mentioned earlier in this paper, the taxonomic definition of the *B. tabaci* complex remains open for discussion and *B. tabaci* biotype B (= *B. argentifolii*) will be referred to in this book as *B. tabaci*.

In Arizona, California, Texas, and Florida, economic losses from *B. tabaci* in 1991 and 1992 were estimated to range from $200 to $500 million (US dollars) (Perring 1996). In Imperial Valley, 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 (Ellsworth et al. 1999) during 1994–1998 to control sweetpotato whitefly and prevent cotton lint stickiness. Gonzalez et al. (1992) estimated that for every million dollars of primary *B. tabaci*-induced crop loss in a multi-commodity-growing agricultural community, there was an estimated $1.2 million loss of personal income as well as the elimination of 42 jobs. *Bemisia tabaci* infestations in the US greenhouse and ornamental production also caused estimated losses in millions of dollars (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 (Medina-Esparza and Leon-Paul 1994; Silva-Sanchez 1997; American Soybean Association 2000).

These unacceptable *B. tabaci*-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 *B. tabaci* outbreaks were unexplained but clearly suggested biological and host plant preference differences compared to previously encountered *B. tabaci* populations. Immediate and aggressive attention was required to address the issues arising from the unprecedented outbreaks of the new type of *B. tabaci*.

## 1.2 National Research and Action Plan for Development of Management and Control Methodology for the Sweetpotato Whitefly

In October, 1991, a sweetpotato whitefly Ad Hoc Working Group meeting was held in Atlanta, Georgia, to initiate planning for a coordinated research effort on *B. tabaci* (USDA 1992a). Twenty-six participants, representing USDA-ARS, USDA-APHIS and USDA-CSREES, state experiment stations, several universities and various commodity groups were in attendance. The need for high-priority research was agreed upon, and plans were made to organize a comprehensive working conference. Subject area coordinators from various agencies and institutions were identified to aid in the development of the conference. With support from the Secretary of Agriculture's Office, a group of 40 individuals representing several state universities, USDA-ARS, USDA-APHIS, USDA-CSREES, and commodity groups, met in Reno, NV in December 1991 (USDA 1992b) to further coordinate these activities. A draft of a coordinated, cooperative research and action plan was reviewed, and priority areas were highlighted for immediate action and assembly into a formal written document. The plan was finalized and accepted at a meeting of more than 200 participants in Houston, Texas in February 1992 (USDA 1992c).

At the national level, the USDA Sweetpotato Whitefly Research, Education and Implementation Coordinating Group (two members from ARS, two members from APHIS, two members from CSREES, and one member from a state agricultural experiment station) was formed in 1992 to coordinate the interagency activities related to the plan. The coordinating group and partner state agricultural experiment stations ensured a unified effort for the program, and provided an annual review to exchange research information, plan cooperative work, and evaluate research progress.

The high-priority research areas set forth for the 1992–1997 national plan were: (1) ecology, population dynamics, and dispersal; (2) fundamental research on behavior, biochemistry, biotypes, morphology, physiology, systematics, virus diseases, and virus vector interactions; (3) chemical control, biorationals, and pesticide application technology; (4) biological control; (5) crop management systems and host plant resistance; and (6) integrated techniques, approaches, and philosophies. Mandated annual reviews were held to review programs, priorities, consider new research thrusts and exchange information.

The need for research continuity, continuing high levels of communication, technology transfer, and coordination resulted in development of a second 5-year plan. The Silverleaf Whitefly (*Bemisia argentifolii* Bellows and Perring) Research, Action, and Technology Transfer Plan was finalized at the annual review meeting at San Diego, California in January 1997 (Henneberry et al. 1997). The high-priority research areas were: (A) biology, ecology, and population dynamics; (B) viruses, epidemiology, and virus-vector interactions; (C) chemical control, biopesticides, resistance management, and application methods; (D) natural enemy ecology and biological control; (E) host plant resistance, physiological disorders, and host-plant interactions; and (F) integrated and area-wide pest management approaches, and crop management systems. The last meeting for the second 5-year plan occurred in February 2002 at San Diego, California.

## 1.3 The Role of Biological Control

Biological control was identified as a high-priority research area in the US national research and action plans. Developing long-term integrated *B. tabaci* population management, with a strong natural enemy component, in lieu of individual farmers focusing on local infestations, was a mandate developed in the formative phase of the research and action plan. The positive role of natural enemy interactions in *B. tabaci* populations and their potential as control agents have been recognized by numerous authors (Mound and Halsey 1978; Greathead and Bennett 1981; Cock 1986, 1993; Gerling 1990, 1996; Gerling and Heneberry 2001). The complexity of nomenclature issues for *B. tabaci* and its natural enemies, agroecosystem and geographic variability and the lack of essential biological and ecological information have made evaluations of the impact of natural enemies on *B. tabaci* populations a formidable challenge to biological control workers worldwide.

Although high *B. tabaci* nymph parasitism (70–80%) often occurs in southern California cotton, adequate control of *B. tabaci* has not been obtained with native parasitoids (Gerling 1967; Natwick and Zalom 1984; Bellows and Arakawa 1988; Hoelmer 1996; Gerling and Naranjo 1998). Similar results have been reported from Israel (Gerling et al. 1980; Gerling 1986). In the USA (Nuessly 1990) and Israel (Gerling 1996) the results of introductions of new parasitoid species in 1985–1987 were disappointing. In contrast, reports from the Sudan (Abdelrahman and Munir 1989), Syria (Stam and Elmosa 1990), and Egypt (Hafez et al. 1979) indicate effective parasitoid regulation of *B. tabaci* populations in diverse cropping ecosystems when no insecticides were used (Hafez et al. 1979; Abdel-Fattah et al. 1986; Abdel-Gawaad et al. 1990). There are many possible explanations for the differences in biological control efficacy: *B. tabaci* host range; multiple cropping systems, providing year-round host biomass; lack of information on natural enemy-*B. tabaci*-host interactions; geographical variability; and different crop production inputs. Insecticides have also frequently been identified as the cause of suppression of natural enemies, resulting in *B. tabaci* outbreaks (Eveleens 1983). Resistance of *B. tabaci* to insecticides, in combination with hormoligosis (increased reproduction of resistant strains), has been suggested as contributing to outbreaks (Dittrich et al. 1990). Under laboratory and greenhouse conditions, highly toxic effects of insecticides on several parasitoid species have been reported, but species responses vary and generalizations appear to be risky (see Hoelmer 1996 for review). In the field, Hoelmer (1996) suggested that insecticide impact on some parasitoids may not be as severe as under controlled laboratory conditions. Alternate approaches such as manipulating timing and placement of insecticides and the use of selective and new chemicals offer potential for integrating chemical and biological control. This possibility was strengthened considerably for *B. tabaci* with the development of the insect growth regulators (IGRs), such as buprofezin and pyriproxyfen, for control on cotton and imidacloprid for control on melons. Natural enemy conservation was found to be much improved with IGR use in cotton (Naranjo 2001). Ellsworth and Martinez-Carillo (2001) found that the combination of natural enemy conservation and IGR use increased *B. tabaci* mortality by more than 50% compared to conventional chemistry because of direct mortality by the IGRs plus increased predation. Soil applications of imidacloprid on melons were also found to be environmentally compatible and broke the host continuity by reducing dispersal from melons to cotton in the spring and cotton to melons in the fall (Palumbo et al. 2001).

The precise combinations of biotic and abiotic factors that trigger *B. tabaci* outbreaks remain unknown, but the large number of natural enemies species recorded attacking *B. tabaci* and the high level of observed activity, leading to effective *B. tabaci* control in some areas, strongly supported the need to exploit their usefulness (Greathead and Bennett 1981; Onillon 1990; Hoelmer 1996; Gerling and Kravchenko 1996). *Bemisia tabaci* natural enemy records have been cataloged by several authors (Greathead and Bennett 1981; Lopez-Avilla 1986; Lopez-Avilla and Cock 1986; Gerling 1990). A summary of the most recent *Encarsia* spp. status was included in a 1993 natural enemy update (Cock 1993). Additional reviews of *B. tabaci* fungal entomopathogens (Lacey et al. 1996), *Eretmocerus* spp. (Rose et al. 1996), and *B. tabaci* predators (Nordlund and Legaspi 1996) further informed the effort to locate new *B. tabaci* biological control agents. New introductions from this broad base of biological material to complement existing natural enemies, development of mass-rearing and release augmentation, and conservation approaches were considered important components for long-term *B. tabaci* management systems (Cock 1986; Gerling 1990; Onillon 1990; Cock 1993). Cock (1986, 1993) suggested that workers in *B. tabaci* infested areas lacking specific natural enemies noted as beneficial in other areas should consider introduction of these effective natural enemies into their areas. This strategy was considered a particularly promising way to strengthen *B. tabaci* biological control by providing new natural enemies to supplement indigenous species. The approach was further supported by the overall *B. tabaci* research management effort to develop ecologically oriented technology to conserve natural enemy resources and provide a receptive environment for augmentation and new introductions.

Thus, foreign explorations for natural enemies were initiated within the framework of the national plans in the early 1990s by the USDA-ARS European Biological Control Laboratory, Montpellier, France (Kirk et al. 1996). Areas selected for initial natural enemy exploration were in Greece, Spain and the Indian subcontinent. These areas were chosen because their climate and crop-productions systems were similar to those areas in the USA with problem *B. tabaci* populations. It was expected that if new natural enemies were identified they could easily adapt after introduction into similar US ecosystems (Kirk et al. 2001). Explorations were focused on the Indian subcontinent because the area has been suggested as the point of origin for *B. tabaci* (Brown et al. 1995). From the worldwide explorations in 28 countries, 55 parasitoid cultures were established. Numerous isolates of the fungal pathogen, *Paecilomyces fumosoroseus* (Wize), were collected from five countries. Of these, a large number of strains were isolated that have been reported as having good *B. tabaci* insecticidal activity. Field studies have been promising (Kirk et al. 2001), but additional research will be required to develop these materials to effectively control *B. tabaci* populations.

After field collection, all exotic parasitoids were shipped to the USDA-APHIS Quarantine Facility in Mission, Texas for further study (Goolsby et al. 1996, 1998). Several native parasitoids were also evaluated in comparison with exotic species, and *Eret. eremicus* has been widely used for augmentative release, especially in greenhouse crops. Parasitoid species that showed high fecundity on major commercially cultivated field crops in quarantine studies were further evaluated in field cages in the Imperial Valley, California and the Rio Grande Valley, Texas. The parasitoids that performed best under field conditions were then mass reared for release programs (Goolsby et al. 1998, 1999).

Large-scale exotic parasitoid augmentation controlled *B. tabaci* in melons, and releases were found compatible with a commonly used systemic insecticide (imidacloprid) (Goolsby and Ciomperlik 1999; Simmons et al. 1998). Area-wide parasitoid release programs to reduce *B. tabaci* overwintering populations in central California (Pickett et al. 1999) also proved particularly promising. Three of the imported and released parasitoid species, *Eretmocerus emiratus* Zolnerowich and Rose, *Eretmocerus* sp. nr *emiratus*, and *Encarsia sophia* (Girault and Dodd), have been established in agricultural ecosystems in California and Arizona (Hoelmer and Kirk 1999; Gould et al. 1998; Goolsby et al. 2005, chapters 12–14) and two additional species (*Eret. mundus* Mercet and *Eret. hayati* Zolnerowich and Rose) in Texas (Goolsby et al. 1998, chapter 11). Continuing long-term monitoring will be essential to determine the spread of these species into *B. tabaci* habitats and to quantify their impact on *B. tabaci* population dynamics.

The successful exploration, screening, evaluation, importation and establishment of at least five exotic *B. tabaci* natural enemies in rapid response to the devastating infestations occurring in the USA in the late 1980s and early 1990s is a landmark in interagency, multiple discipline coordination and cooperation. The integration of exotic biological control components into highly effective *B. tabaci* management programs has been achieved. Key contributing factors to this achievement were the efforts of many scientists who developed multifaceted *B. tabaci* management strategy using (1) non-*B. tabaci* preferred cultivars, (2) spatial and temporal considerations in sequential crop systems, (3) intensive sampling and monitoring of *B. tabaci* populations, (4) chemical control focused on natural enemy conservation, action thresholds, alternating chemistry, new chemistry, and resistance monitoring, (5) optimum crop yield goals, allowing for early harvests and destruction of crop residues, and (6) active education and extension outreach to provide timely communication of new developments and guidelines for implementation of new technology (Henneberry et al. 1998). In this volume, the various authors will present the detailed documentations of natural enemy exploration, introduction, and evaluation efforts that will serve as a guide to support and encourage classical biological control inputs into other integrated pest management systems.

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# Chapter 2
# Foreign Exploration for Insect Natural Enemies of *Bemisia* for Use in Biological Control in the USA: A Successful Program

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**Abstract** European Biological Control Laboratory scientists (USDA-ARS) and collaborators sent 130 shipments of *Bemisia* species and natural enemies from 28 countries to the Mission Biological Control Laboratory (MBCL) in Mission Texas. More than 235 collections resulted in 13 species of parasitoids and several predators for evaluation in the USA. Climate modeling software was used to focus on collecting areas with climates similar to Arizona, California and Texas. Field crops, glasshouse crops and weeds were searched and many host plant species yielded parasitized *Bemisia*. Field parasitism by *Bemisia* parasitoids was shown to be 39–44% in Spain and 0–67% in Thailand. Taxonomists identified *Bemisia* biotypes, parasitoids and predators; geneticists characterized *Bemisia* and natural enemy species. This information was used for evaluation, release, and experimentation.

## 2.1 Introduction

*Bemisia tabaci* (Gennadius) has been recorded as collected from over 900 plant species in 74 families (Cock 1986, 1993; Mound and Halsey 1978). Taxonomically *B. tabaci* is now regarded as a species complex, and in 1994 a new species, *B. argentifolii* (Bellows and Perring), known as silverleaf whitefly, was described for the form known as "biotype B" (Bellows et al. 1994). The name *B. tabaci* will be used here to avoid confusion and because natural enemies were obtained from various biotypes of *B. tabaci*. Outbreaks of *B. tabaci* biotype B in Arizona, California, Florida, and Texas caused estimated crop losses in excess of $500

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million in 1992 (Faust and Coppedge 1995). First recorded in the USA in Florida in 1894 and in Texas and Georgia in the late 1940s, *B. tabaci* was not known as a serious pest until 1986–1988 in Florida (Schuster et al. 1990), and late 1989 in Texas and California (Brown et al. 1991). Before the late 1980s *Bemisia* was unknown on cole crops that are grown as a winter crop in the southern USA. After its accidental introduction, presumably from the Middle East, *B. tabaci* biotype B was found attacking cole crops in the agricultural region of southern California and was recognized as a new problem when several visible disorders of cruciferous crops appeared at the same time (Perring et al. 1991). In southern Texas severe damage to cabbage was also noted (Elsey and Farnham 1994). In addition to sustaining considerable direct damage, cole crops acted as reservoir plants for overwintering whitefly populations that moved onto melons in spring when the crucifers were harvested.

Recent genetic evidence points to an expansion in range of *B. tabaci* from an ancestral Mediterranean home throughout the world (Brown et al. 2000). Without a doubt, increased transportation of ornamental plants as seedlings and full-grown plants has led to this global spread. As a rule, natural enemies do not travel with their host and in the case of *Bemisia* extraordinary attempts at obtaining clean plants by applying pesticides for export would have eliminated the natural enemies at the source. *Bemisia tabaci*, however, because of its comprehensive resistance to pesticides would have traveled with its host plant.

A series of planning meetings to develop coordinated research and management plans for *B. tabaci* led to a 5-year national research and action plan for development of management and control methodology for *Bemisia* (Faust 1992, Chapter 1). The plan identified six areas of priority research, including biocontrol. The diverse landscapes and agricultural systems present worldwide suggested a potential for foreign exploration of many suitable habitats for whiteflies and natural enemies. The USDA-ARS European Biological Control Laboratory (EBCL) in Montpellier, France conducted exploration for *Bemisia* and its natural enemies throughout the world from 1991 to 1998 for importation and evaluation in the USA (Kirk et al. 1993; Lacey et al. 1993; Kirk and Lacey 1996). In addition to the main effort by EBCL some collections were made by collaborators and exported to the USA (Legaspi et al. 1996; Goolsby et al. 1998).

The potential of aphelinid (Hymenoptera: Aphelinidae) insect parasitoids as biocontrol agents of *Bemisia* was considered to be very high. They are widespread and their ability to find and attack whitefly nymphs is well documented (Cock 1986, 1993). The hymenopterous parasitoids obtained through foreign exploration were identified by morphological taxonomy, or by a characteristic identifying pattern using the RAPD-PCR molecular technique (Chapter 6), an important tool in maintaining the quality of parasitoid species colonies in quarantine. Colonies of these parasitoids were established, evaluation experiments were performed, and selected natural enemies were then released into the field. Whiteflies from source collections were also identified using morphological characters, and molecular characterization was accomplished using a DNA fragment of the mitochondrial cytochrome oxidase I (mtCOI) gene (Kirk et al. 2000).