Epilogue

Controlling pests with natural enemies reduces pesticide use, stabilizes food supplies and ultimately benefits the public worldwide. The *Bemisia* program shared these objectives. Classical biological control practitioners often distribute natural enemies to researchers in other countries, subject to export and import regulations. Rather than reinventing the wheel, programs in one country can learn from the experiences of scientists in other countries, and biological control is often obtained with the same agents in various parts of the world. Foreign explorers from the USA were granted access to many countries throughout the world to collect natural enemies of *Bemisia*. In turn, natural enemies that performed well in the USA were shared with researchers in other nations affected by *Bemisia*.

Table 1 lists the dates, countries, cooperators, and natural enemies shipped. It is not yet known which species permanently established in most of the receiving countries, with the exception of Australia. Paul DeBarro (CSIRO Entomology), Indooroopilly, Queensland, Australia, conducted extensive research to determine if imported natural enemies were needed for control of *B. tabaci* biotype B that invaded Australia, causing problems starting in 1997. He concluded that *B. tabaci* did not have effective parasitoids despite the presence of parasitoids adapted to the indigenous *B. tabaci* 'Australasian' biotype. He then collaborated with US researchers to determine which single species should be the first to be imported and tested. The single release approach is required in Australia due to the extensive regulatory requirements for both insect and weed biological control agents. The decision was to import *Eretmocerus hayati*, originally from Pakistan, from field populations that had established in Texas. This was based on the fact that *Eret. hayati* had performed very well in the US program and was the most common exotic parasitoid in southern Texas, which is climatically similar to affected areas in Queensland, Australia. *Eretmocerus hayati* was imported in 2001. Host range testing of numerous related whitefly species that were indigenous to Australia showed that *Eret. hayati* posed little or no risk of unintended nontarget impacts. *Eretmocerus hayati* was released in Bundaberg, Queensland in late 2004 and has spread rapidly from the release sites. As of January 2005 it had been recovered far from release sites 300 km to the south in the Lockyear Valley near Brisbane. Cotton and vegetable growers reported that 2004–2005 were the first years since 1995 that *B. tabaci* was not a significant pest in eastern Queensland (P. Debarro, personal communication).

Table 1 Shipments of *B. tabaci* parasitoids and predators to cooperators overseas.

Year	Country	Receiving scientist and institution	Species	M#	Origin	#'s released
1995	Honduras	Ron Cave	*Eret. mundus*	M92014	Spain	1,000
		Zamarano College	*Eret. mundus*	M92019	India	10,000
1996	Dominican Republic	Colmar Serra	*Enc. sophia*	M93003	Spain	2,000
		DR Department of Agriculture				
	Italy	Genaro Viggiani	*Enc. sophia*	M93003	Spain	100
		Silvestri Institute				
	Puerto Rico	Leyinska Wiscovitch	*Enc. sophia*	M93003	Spain	18,650
		USDA-APHIS-PPQ	*Enc. formosa*	M92030	Egypt	23,480
			Eret. mundus	M92014	Spain	42,644
			Serangium parcestosum	M93008	India	100
1997	Israel	Dan Gerling	*Enc. sophia*	M95107	Pakistan	800
		Tel Aviv University				
	Mexico	Jesus Vargas Camplis	*Eret. hayati*	M95012	Pakistan	33,000
		National Institute of Forestry, Agricultural	*Eret. mundus*	M92014	Spain	33,000
		and Animal Research	*Eret. emiratus*	M95104	U.A.E.	33,000
	Puerto Rico	Leyinska Wiscovitch	*Eret. hayati*	M95012	Spain	128,508
		USDA-APHIS-PPQ	*Eret. mundus*	M92014	Spain	11,000
			Eret. emiratus	M95104	U.A.E.	10,000
			Enc. sophia	M93003	Spain	8,000
			Enc. formosa	M92030	Egypt	10,000
2001	Australia	Paul DeBarro	*Eret. hayati*	M95012	Pakistan	5,000
		CSIRO Entomology				

Plans are presently being made to export *Eret. hayati* to China and *Eret. melanoscutus* to Colima, Mexico. Both countries have been affected by outbreaks of *B. tabaci* biotype B.

The recent discovery of *B. tabaci* biotype Q in Arizona and California has prompted calls for additional screenings of exotic *B. tabaci* parasitoids on this biotype. However, this may not be necessary, since many of the *Eretmocerus* spp. imported and established in the US program were obtained from collections of *B. tabaci* biotypes other than B. At least three native North American *Eretmocerus* species in Florida, Texas, Arizona and California readily adapted from *B. tabaci* biotype A to attack biotype B. It is likely that the already established native and introduced natural enemies will readily attack the Q biotype, as has been demonstrated for Spanish populations of *Eret. mundus* (Urbaneja and Stansly 2004).

Reference

Urbaneja, A. and P.A. Stansly. 2004. Host suitability of different instars of the whitefly *Bemisia tabaci* ‘biotype Q’ for *Eretmocerus mundus*. BioControl 49: 153–161.

Summary

The classical biological control program directed against *Bemisia tabaci* (Gennadius) biotype B (= *B. argentifolii* Bellows and Perring) in the 1990s was one the largest and most comprehensive programs in the history of biological control. A team of scientists from USDA-APHIS, USDA-ARS, CDFA, and several universities contributed to the discovery, importation, evaluation, release, and colonization of a suite of imported natural enemies. Field entomologists 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 in Mission, 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 Methodology for the Sweetpotato 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* was comprehensive, covering 28 countries, and more than 130 shipments of natural enemies were sent to quarantine facilities in the USA between 1991 and 1998. Climate matching was used to compare the affected areas in the USA with locations within the native distribution of *B. tabaci* and thereby prioritize foreign exploration. The ARS European Biological Control Laboratory in Montpellier, France was extremely valuable to the biological control program; its staff engaged in nearly year-round exploration, which led to the discovery of many parasitoids, predators and pathogens for evaluation by US researchers.

In the USDA APHIS Mission Biological Control Laboratory quarantine, 55 populations of natural enemies were established in culture, including 13 species of *Eretmocerus* and *Encarsia* parasitoids. Only parasitoids reared from *B. tabaci* (any biotype) and with a primary or autoparasitic biology were considered for release.

Predictive, prerelease studies were conducted in quarantine and in field cages to determine which species showed the most potential to impact whitefly populations. This information was used to prioritize species for mass rearing and field release. Low-performing parasitoid species were also released in substantial numbers at selected locations to validate the predictions.

The sweetpotato whitefly program was the first large-scale biological control program to use molecular genetic methods to characterize the imported natural enemies prior to their release. RAPD-PCR was used to screen the natural enemies reared in quarantine to identify cryptic species and maximize available genetic diversity 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 host-plant preferences and climatic adaptations. The molecular methods were also used to assure colony purity and to identify exotic specimens recovered in the field programs. Taxonomic keys were developed to identify and describe the native and imported *Eretmocerus* and *Encarsia* parasitoids of *B. tabaci* in North America.

Mass rearing facilities were established in Tucson, Arizona; Imperial and Sacramento, California; and Mission, Texas. Hundreds of millions of *Eretmocerus* and *Encarsia* species were mass reared for several years for release and evaluation in the areas affected by sweetpotato whitefly, which included the subtropical agricultural areas of the USA 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. The substantial 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. The results showed strong tri-trophic interactions and the significance of climatic adaptation. Four species of Palearctic *Eretmocerus* that established in the western USA were morphologically similar, representing a group of closely related taxa that appear to be specialist parasitoids of the *B. tabaci* complex that includes several known biotypes. Their ability to readily attack whiteflies in the *B. tabaci* complex may have given them an advantage in the field versus the native *Eret. tejanus* Rose and Zolnerowich and *Eret. eremicus* Rose and Zolnerowich, which have a broader host range that includes *Trialeurodes* species. To date no nontarget impacts have been detected from the exotic parasitoids, which is likely due to their narrow host range.

The climate in the native range of each of the four imported *Eretmocerus* spp. closely matched the climate in the areas of the USA where they established: *Eret. mundus* Mercet from Mediterranean Europe to San Joaquin Valley, California; *Eret. emiratus* Zolnerowich and Rose from the hot desert of the Arabian Peninsula to Imperial Valley, California; *Eret.* sp. nr. *emiratus* from the tropical desert of Ethiopia in equatorial Africa to Yuma and Phoenix, Arizona; and *Eret. hayati*

Zolnerowich and Rose from the subtropical desert of the Indus River Valley in Pakistan to the Rio Grande Valley, Texas. The exotic autoparasitoid *Enc. sophia* (Girault and Dodd) also established in the Imperial Valley of California, although several endemic autoparasitioids were previously present in this agroecosystem.

Several release methods were developed to enhance the likelihood of establishment of the parasitoids in the annual cropping systems. Refuge strips, home gardens, and commercial nurseries were used as release sites because they had stable year-round populations of *B. tabaci* and were free of broad spectrum pesticide use. In addition to inoculative release methods, a more efficient method for augmentation of parasitoids using seedling transplants as 'banker plants' was developed for cucurbit crops.

Field efforts to control *B. tabaci* were aided by the development of several narrow spectrum insecticides that were effective against *B. tabaci* while allowing substantial parasitoid activity. Biological control-intensive 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 the BC-IPM could be integrated with current farming practices.

Trials with the entomopathogens *Beauveria bassiana* and *Paecilomyces fumosoroseus* showed they caused significant mortality to *B. tabaci* nymphs under high humidity conditions. Specialized spray equipment was developed and tested to apply the pathogens under commercial field conditions. Field trials showed that the biopesticides were effective during the early season and compatible with natural enemies. Two different formulations of *B. bassiana* (Mycotrol) and a formulation of *Paecilomyces fumosoroseus* were later commercialized.

The sweetpotato whitefly biological control program clearly demonstrated the potential benefits of classical biological control in annual row-crop agriculture. The program also demonstrated the utility of predictive evaluations, which showed that a multiple species release strategy was needed due the varied climates and crops that were impacted by *B. tabaci*. This strategy should be considered for future biological control programs directed at polyphagous invasive pests that become widely distributed in the USA.

Following their establishment, detailed quantitative studies are now needed to document the impact of the introduced species, which appeared to be substantial in the years immediately following establishment in areas such as the Lower Rio Grande Valley. Life table studies similar to those conducted for survivorship of *B. tabaci* on cotton in Maricopa, Arizona (Naranjo and Ellsworth 2005) are needed for all areas where the exotic parasitoids have become established. Only with such evaluations will we truly be able to accurately measure the impact and significance of benefits derived from the interagency sweetpotato whitefly biological control program.

Reference

Naranjo, S.E. and P.C. Ellsworth. 2005. Mortality dynamics and population regulation in *Bemisia tabaci*. Entomologia Experimentalis et Applicata 116: 93–108.

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