Introduction

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The Problem of Whiteflies and Whitefly-Transmitted Viruses in the Tropics

Although Mound and Halsey (1978) catalogued 1156 species of whiteflies (Homoptera: Aleyrodidae), only a limited number of whitefly species are considered pests of economic importance. Two whitefly species are key pests throughout the tropics: *Bemisia tabaci* (Gennadius) and *Trialeurodes vaporariorum* (Westwood). Five additional whitefly species are considered as important pests in specific regions: *Aleurotrachelus socialis* (Bondar), *Trialeurodes variabilis* (Quaintance), *Bemisia tuberculata* (Bondar), *Trialeurodes abutiloneus* (Haldman) and *Aleurocanthus woglumi* (Ashby).

Whiteflies are phloem (sap) feeders. They cause direct damage in some hosts by extracting large quantities of sap. The honeydew that they excrete, as a result of the copious sap intake, serves as substrate for sooty mould fungi, which can also damage hosts by blocking photosynthesis. Sooty mould can discolour harvestable fruits and fibre, affecting the quality of produce, and can cause plant death in crops such as potato (*Solanum tuberosum* L.), tomato (*Lycopersicon esculentum* Mill.) and common bean (*Phaseolus vulgaris* L.). In addition, *B. tabaci* is a vector of plant begomoviruses (Geminiviridae: Begomovirus). These whitefly-transmitted viruses (WTVs) are among the most destructive plant viruses; early virus infection often results in total crop loss.

Although the problems caused by *B. tabaci*, both as pest and vector, have been recognized for more than 100 years, serious damage had been limited to a handful of crops in particular geographic areas. This scenario has changed over the past 2 decades. The known WTVs have extended their geographic range and other WTVs are emerging in new crops and geographic zones, globally. Whitefly infestations now have become severe in both traditional and non-traditional food and industrial crops throughout the tropics.

In Africa, cassava mosaic disease (CMD) was first described in 1894 from Tanzania (Warburg, 1894). In East Africa, the disease was not reported to cause serious losses until the 1920s. In West Africa, it was first recorded in the coastal areas of Nigeria, Sierra Leone and Ghana in 1929 and had spread northward by 1945. By 1987, CMD had been reported from all countries in Africa producing cassava (*Manihot*

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esculenta Crantz) (Fauquet and Fargette, 1990). The disease had been caused by African cassava mosaic virus (ACMV) in South Africa and Africa west of the Rift Valley, and by East African cassava mosaic virus (EACMV) in Madagascar and Africa east of the Rift Valley (Hong et al., 1993; Swanson and Harrison, 1994). ACMV and EACMV are both *B. tabaci*-transmitted begomoviruses.

In 1988, an extremely severe form of CMD was reported from north-eastern Uganda. Infected cassava plants showed severe disease symptoms and produced little or no yield. The epidemic caused total crop failure in north-eastern Uganda (Otim-Nape et al., 1997). Each year since 1988, the epidemic moved progressively southwards along a broad front at a rate of approximately 20 km per year (Otim-Nape et al., 2000). By 1995, the epidemic had reached Kenya (Otim-Nape et al., 2000), with losses estimated at 140,000 tons of cassava per year, conservatively worth US$14 million (Legg, 1999). The severe outbreak in Uganda and neighbouring countries has been associated with a novel recombinant (EACMV+ACMV) begomovirus, currently recognized as EACMV-Ug (Pita et al., 2001).

Soon after, Latin America was struggling with *Bemisia*-transmitted bean and tomato viruses. *Bean golden mosaic virus* (BGMV) was first described in Brazil in the early 1960s as a minor disease (5%-10% incidence) of common bean in the state of São Paulo (Costa, 1965). Since then, BGMV has become a widespread problem in Brazil and now is known to cause epidemics in north-western Argentina and eastern Bolivia. Simultaneously, another begomovirus, *Bean golden yellow mosaic virus* (BGYMV), which causes similar symptoms, was ravaging common bean production in over 12 countries of Central America and the Caribbean (Morales, 1994). Yield loss from either BGMV or BGYMV is often 100% because of the high incidence of flower abortion and the malformation of pods in infected plants (Morales and Niessen, 1988). BGMV and BGYMV are considered to be the limiting biotic constraint to bean production in Latin America (Gálvez and Morales, 1989).

Then, in the late 1980s, tomato-producing areas in Latin America and across the tropics began to suffer from high incidences of whitefly-borne begomoviruses with devastating economic consequences. While no formal assessment studies of crop loss had been undertaken for the tomato diseases caused by begomoviruses, the empirical data were impressive. One of the more complete data sets came from the Dominican Republic (Polston and Anderson, 1997). In 1988, multiple begomoviruses began to affect tomato production in the Dominican Republic. Crop damage from 1988 to 1995 ranged from 5% to 95%. Economic losses in 1988 were estimated at US$10 million dollars, with losses from 1989 to 1995 totalling an estimated US$50 million dollars.

These scenarios were being repeated across the tropics, with significant consequences to food security and poverty alleviation efforts as well as human and ecosystem health.

Food security

In Africa, cassava is one of the most widely grown staple crops and second only to maize (*Zea mays* L.) in terms of calorie intake in sub-Saharan Africa. About 200 million people, or 40% of the sub-Saharan Africa population, rely on cassava for their well-being. In some countries, people derive approximately 1000 calories a day, or 50% of daily food intake, from cassava (IITA, 1988).

In addition to the yield losses caused by CMD, an estimated 150,000 ha of cassava-growing land was abandoned in Uganda during the height of the epidemic; that is, equivalent to over 2.2 million metric tons (US$440 million). This caused food shortages and famine in a number of districts, particularly in the eastern and northern regions where the crop was the principle staple food (Otim-Nape, 1997).

In Latin America, common bean is one of the main staple foods, particularly among the rural and urban poor. In Central America, beans are the most important source of protein, usually being consumed three times a day. Central America, despite its small area (498,368 km^2), devotes twice as much of its geographical area to the cultivation of beans (735,00 ha), when compared to major bean producers such as Brazil (>5,000,000 ha). Beans also are produced in some Caribbean islands, such as Cuba (26,000 t), the Dominican Republic (55,000 t) and Haiti (56,000 t) where they play an important nutritional role in the diet of the lower socio-economic classes. Smallholdings cultivated by farmers with limited resources are characteristic of bean production in Central America and the Caribbean. In El Salvador, for instance, 85% of the bean producers cultivate less than 14 ha, and 50% of these producers have holdings of less than 3.5 ha.

Despite the large area planted to beans in Central America, average productivity is low (495 kg/ha) compared to the average yield expected (over 1500 kg/ha) in most bean-producing regions of the USA and other temperate countries in the world. The main factor identified as responsible for the low bean productivity in Latin America has been the incidence of biotic constraints, particularly diseases. Morales (1992) estimated that by the early 1990s, approximately 2,500,000 ha were under attack by BGMV/BGYMV and that at least 1 million additional hectares could not be planted to beans each year because of the possibility of total yield losses, mainly during the dry seasons, when whitefly populations peak. Throughout Central America and the Caribbean Basin, figures for crop damage indicated that the BGYMV infection was devastating. And there was continuing consensus that BGYMV was the major biotic factor limiting bean production in Latin America (Morales, 1994).

Poverty alleviation

Many resource-poor producers in the tropics modified their traditional cropping systems in the 1980s, to incorporate non-traditional cash and export crops. The shift from subsistence to commercial agriculture is an opportunity to alleviate poverty in rural areas. Smallholder producers across the tropics have begun to cultivate cash crops such as tomato (*Lycopersicon esculentum*), pepper (*Capsicum* spp. L.), melon (*Cucumis melo* L.), watermelon (*Citrullus lanatus* [Thunb.] Matsum. & Nakai), squash (*Cucurbita moschata* Duchesne), grape (*Vitis vinifera* L.), okra (*Abelmoschus esculentus* [L.] Moench), cucumber (*Cucumis sativus* L. var. *sativus*), cabbage (*Brassica oleracea* L.), eggplant (*Solanum melongena* L.), broccoli (*Brassica oleracea* L. var. *italica* Plenck) and ornamentals. However, most of these horticultural crops are particularly susceptible to pests previously unknown to most small-scale farmers.

In the absence of adequate technical assistance for small-scale farmers in the tropics, the new pest problems were primarily dealt with by a myriad of pesticides applied indiscriminately. To further complicate this situation, a new biotype (B) of *B. tabaci* was introduced in the Americas in the early 1990s. This biotype proved to be far more polyphagous and fecund that the original A biotype and has been an important factor in most of the major outbreaks of whiteflies and whitefly-borne viruses. During the past decade, the outbreak of whitefly pests and the epidemics caused by whitefly-transmitted begomoviruses in cash crops has been often devastating. Pesticide abuse is the norm in all whitefly-stricken regions of the tropics, which increases production costs and disqualifies contaminated (pesticide residues) produce for export.

At present, many of the small-scale farmers that attempted to diversify their cropping systems have failed to do so because of whitefly-associated problems. Prime agricultural land remains unexploited in many developing countries during the dry seasons, when whitefly populations peak, despite the availability of water (irrigation districts) in these areas. The welfare of developing countries and their low-income citizens is tightly linked to the existence of cash-earning commodities, principally agricultural products.

The main force driving whitefly outbreaks and crop losses due to whitefly attack and WTVs is the lack of qualified technical assistance to small- and medium-scale farmers in the tropics. The Tropical Whitefly Integrated Pest Management (TWF-IPM) Project is currently entering a final phase when most of the information presented in this book and the lessons learned during the validation of IPM practices in Phase II will be translated into practical recommendations for resource-poor farmers throughout the tropics.

Human and ecosystem health

The reliance of farmers on agrochemicals to protect their cash crops against whitefly pests and whitefly-borne viruses has resulted in the systematic destruction of natural enemies that were once effective in providing natural control, whitefly populations with high levels of insecticide resistance and the creation of new secondary pest problems. The rejection of contaminated produce in international markets has led to the sale of highly contaminated food products in developing countries, with obvious detrimental health consequences for rural and urban consumers alike. Whiteflies provide a classic example of the pesticide treadmill. Insecticide abuse has become a serious threat to the environment as well as a health hazard to producers and consumers.

About 10% of the world's population lives in the main highlands and mountainous areas of the developing world (the Andes of South America, the Africa ranges and the Himalayas). The management of resources in those ecosystems affects an additional 40% of the world's population, which inhabits adjacent areas such as Inter-Andean valleys in the Andean Zone. Traditionally, people in the highlands have been marginalized from major development efforts, with significant repercussions on poverty, migration and social unrest as well as environmental deterioration *in situ* and downstream (IFPRI, 1995).

One major issue regarding the welfare of those living in highland areas of Latin America is environmental degradation caused by excessive pesticide use. It is well known that pesticide consumption in the developing world is increasing rapidly. It was thought initially that increases in pesticide use in Latin America were mainly due to the growth of plantation crops, an important source of export revenue (Bellotti et al., 1990). However, as pointed out by Whitaker (1993), the developing country share of the world agrochemical usage, currently valued at US$10.6 billion, was forecast to rise from 19% in 1988 to an estimated 35% by the year 2000. Much of this projected growth was attributed to a wider and more intensive use of chemical protection by smallholder farmers. Unfortunately, highly toxic insecticides represent up to 45% of pesticide use in the developing world.

In the early 1980s, the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood), became a very serious pest of several hillside-grown crops in the Andes. Major outbreaks occurred in 1987, 1991 and 1994 in selected areas of Colombia, northern Ecuador and the Constanza Valley in Dominican Republic. For example, insecticide use by small-scale bean farmers, which was negligible until 1975-77 (Schoonhoven and Cardona, 1980), has increased steadily and became excessive in Colombia and Ecuador. Surveys conducted in two regions of Colombia and the northern part of Ecuador (CIAT, 1994) revealed that 100% of 893 farmers surveyed sprayed their crops in an attempt to control the greenhouse whitefly. Highest insecticide use occurred in the Sumapaz region of Colombia where farmers make an average of 11.1 applications per season.

Most alarming was the fact that some growers sprayed their crops up to 24 times in a crop cycle of 90-100 days, that is, every 3 to 4 days. Insecticide abuse on beans in Colombia (5.6 kg active ingredient per ha per season) could be compared to insecticide consumption for cotton (*Gossypium hirsutum* L.) (6.2 kg active ingredient per hectare per season), a crop that has been known traditionally as the worst offender in terms of insecticide use. And, of the insecticides utilized for whiteflies, 78% were classified in toxicological category I (highly toxic) and most often applied in mixture with other insecticides, broad-spectrum fungicides and foliar fertilizers. Farmers usually did not take precautions when handling pesticides; up to 24% of those surveyed admit that they have been intoxicated at least once in the prior 10 years (CIAT, 1994).

In the east African highlands, a contributing factor to environmental degradation was the indiscriminate and/or excessive use of broad-spectrum insecticides as part of the intensive crop protection system in industrial crops, especially cotton, and to some extent on plantation crops such as coffee (*Coffea* spp. L.) and tea (*Camellia sinensis* [L.] Kuntze). The problems of pesticide resistance and pest resurgence although initially created on these target crops had extended to the other seasonal crops grown in rotation and/or combination with the plantation crops, as in the case of whiteflies.

The increasing importance of horticultural production also brought with it the attendant strategy of pesticide-based protection in an effort to harvest damage-free produce. Intensive use of pesticides in vegetable crops had become quite common in large areas of Sudan, Uganda, Kenya, Tanzania and Zimbabwe. In a survey of vegetable farmers in Kenya it was found that the majority perceived that they would lose up to 90% of their harvest if they did not use pesticides. By the early 1990s, these vegetable farmers were applying up to 19 sprays a season, with a significant proportion of farmers spraying 9-12 times per season (KARI-GTZ, 1994). It was critical to begin work in eastern Africa in hopes of intervening with alternative whitefly crop protection measures, before the whitefly pests and WTVs reach the severity witnessed in the Neotropics.

There was an urgent need to develop IPM systems that would reduce pesticide use and help re-establish the ecological equilibrium by means of non-chemical approaches to whitefly management. For whitefly pests this implies identifying the principal crop hosts, establishing economic injury levels (EILs) and developing new approaches to maintain whiteflies below the EIL. For whitefly vectors, however, the traditional IPM approach will not suffice. Vectors must be studied and managed within an epidemiological framework, that is, study and analysis of the WTV system with IPM intervention strategies resulting from the epidemiological analysis.

Origin and Organization of the CGIAR TWF-IPM Project

The Systemwide Programme on Integrated Pest Management (SP-IPM)

The Consultative Group for International Agricultural Research (CGIAR) consists of 15 International Agricultural Research Centres (IARCs) located around the world. Historically, each Centre has worked in a relatively independent and autonomous fashion. During the 1990s, the CGIAR Secretariat recognized that significant benefits could be derived by pooling human capital, infrastructure and economic resources to jointly tackle research problems that numerous centres were working on independently. New inter-centre initiatives included the creation of the SP-IPM. Whitefly and WTV research had been ongoing at several of the IARCs since the 1970s. Due to the growing importance of the whitefly and WTV problem, the TWF-IPM Project was the first inter-centre project approved within the new programme. The International Center for Tropical Agriculture (CIAT, the Spanish acronym) was designated as the convening centre to organize the Inter-Centre Whitefly IPM Task Force and to formulate the Inter-Centre proposal on Sustainable Integrated Management of Whiteflies as Pests and Vectors of Plant Viruses in the Tropics (the CGIAR TWF-IPM Project).

A Task Force Meeting was held at CIAT in Cali, Colombia, from 13-15 February 1996. The objectives of the meeting were to discuss: (a) the goal, purpose, outputs and activities that should be proposed for the project; and (b) a structure for the global Whitefly IPM project, as well as how to link and coordinate the institutions that would be involved in the project.

The Task Force Meeting included 24 participants representing IARCs, National Agricultural Research Systems (NARS) and Advanced Research Institutions (ARIs). After considerable discussion on the nature of the whitefly problem, the Task Force agreed that it was possible to define three whitefly problems that should be prioritized:

(1) Whiteflies as vectors in mixed cropping systems in low to mid altitudes of the tropics;
(2) Whiteflies as pests in mixed cropping systems in tropical highlands; and
(3) Whiteflies as vectors and pests of the semi-perennial cassava.

The first problem focused on whiteflies as vectors of plant viruses in annual crops, especially legumes and vegetables, in the tropical lowlands. The second problem focused on whiteflies as direct pests in annual crops in the highlands. And the third problem focused on whitefly pests and vectors in a semi-perennial crop, cassava.

Based on the initial Whitefly IPM Task Force Meeting, and within the CG framework for an eco-regional problem approach (Bouma et al., 1995), the project was structured into six sub-projects:

(1) *Bemisia tabaci* as a virus vector in cassava and sweet potato in sub-Saharan Africa – led by IITA;
(2) *Bemisia tabaci* as a virus vector in mixed cropping systems of the Caribbean, Mexico and Central America – led by CIAT;
(3) *Bemisia tabaci* as a virus vector in mixed cropping systems of Eastern and Southern Africa – led by the International Centre of Insect Physiology and Ecology (ICIPE);
(4) *Bemisia tabaci* as a virus vector in mixed cropping systems of S.E. Asia – led by the Asian Vegetable Research and Development Center (AVRDC);
(5) *Trialeurodes vaporariorum* as a direct pest in the tropical highlands of Latin America – led by CIAT; and
(6) Whiteflies as direct pests on cassava in South America – led by CIAT.

There was consensus by the Task Force on the project goal, project purpose and project outputs for the TWF-IPM project. The project goal is to improve living conditions of rural families through the effective management of whiteflies, resulting in increased crop production and a safer environment. The project purpose is to reduce crop losses due to whitefly feeding damage and WTVs. The Task Force agreed to organize the project around six outputs:

(1) Formation of an international network for research on whiteflies and WTVs in the tropics;
(2) Characterization of whitefly problems in order to prioritize critical target areas;
(3) Improvement of the understanding of whitefly pest and disease dynamics in critical target areas;
(4) Development and testing of IPM strategies and tactics;
(5) Strengthening of NARS research capacity, policy formulation and IPM implementation; and
(6) Assessment of project impact.

Phase 1 of the CGIAR TWF-IPM Project

The project was conceptualized in three phases, to be carried out over 10 years. Phase 1 of the project would focus primarily on Output 1 (network formation) and Output 2 (problem characterization) as the basis for Phase 2 work, with limited activities in Output 3 (pest and disease dynamics) and Output 4 (development and testing of IPM strategies and tactics). The Project was officially launched in 1997 and evolved into a pan-tropical partnership. Five IARCs were included:

CIAT	Centro Internacional de Agricultura Tropical
IITA	International Institute of Tropical Agriculture
AVRDC	Asian Vegetable Research and Development Center
ICIPE	International Centre of Insect Physiology and Ecology
CIP	Centro Internacional de la Papa

Twelve ARIs were also included:

NRI	Natural Resources Institute (UK)
JIC	John Innes Centre (UK)
BBA	Biologische Bundesanstalt für Land-und Fortwirtschaft (Germany)
CATIE	Centro Agronómico Tropical de Investigación y Enseñanza (Costa Rica)
UA	University of Arizona-Tucson (USA)
UFL	University of Florida-Gainesville (USA)
UW	University of Wisconsin-Madison (USA)
MSU	Montana State University (USA)
FSAC	Florida State Arthropod Collection
USDA-(ARS)	U.S. Department of Agriculture-Agricultural Research Service
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
C&F	New Zealand Crop and Food Research

And 31 National Agricultural Research and Extension Systems (NARES) in Latin America, the Caribbean, Africa and Asia were included from:

Mexico, Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panama, El Salvador, Cuba, Haiti, Dominican Republic, Colombia, Ecuador, Sudan, Benin, Ghana, Nigeria, Cameroon, Kenya, Uganda, Tanzania, Malawi, Madagascar, Nepal, Sri Lanka, Bangladesh, Thailand, Malaysia, Vietnam, Indonesia and the Philippines.

This collaborative partnership was possible due to the support of six donor partners:

DANIDA	Danish International Development Agency
ACIAR	Australian Centre for International Agricultural Research
USAID	United States Agency for International Development
MFAT	Ministry of Foreign Affairs and Trade (New Zealand, now New Zealand Aid)
USDA-(ARS)	U.S. Department of Agriculture-Agricultural Research Service
DFID	Department for International Development (UK)

The CGIAR TWF-IPM Project was launched in 1997 with the DANIDA-funded Phase 1 project on Sustainable Integrated Management of Whiteflies as Pests and Vectors of Plant Viruses in the tropics. This project covered activities in Output 1 (network formation) and Output 2 (characterization) activities in 23 African and Latin American partner countries in Sub-projects 1, 2, 3 and 5. ACIAR then approved funding for the project Sustainable Integrated Management of Whiteflies as Pests and Vectors of Plant Viruses in S.E. Asia, which covered Output 2 (characterization) activities in the eight Asian countries in Sub-project 4. The USAID-funded project on Biological Control of Whiteflies by Indigenous Natural Enemies for Major Food Crops in the Neotropics and the MFAT-funded project on Sustainable Integrated Management of Whiteflies through Host

Plant Resistance contributed to Output 2 (characterization) and Output 4 (IPM) activities in Sub-project 6. USDA-ARS signed a Scientific Cooperative Agreement to link the ARS national research on whitefly IPM research with the international effort. This agreement on Integrated Pest Management Strategies for Whitefly-transmitted Viruses supported Output 1 (network formation) and preliminary Output 3 (disease dynamics) research activities on epidemiology of whitefly-transmitted begomoviruses.

The CMD epidemic in eastern Africa was of particular concern to the TWF-IPM Project for humanitarian reasons. The USAID Office of Foreign Disaster Assistance (OFDA) granted special funding for the Emergency Programme to Combat the Cassava Mosaic Disease Pandemic in East Africa. The objective of this disaster assistance is to boost production of cassava in Uganda, Kenya and Tanzania and enhance both short- and longer-term food security through the implementation of an emergency program to multiply and disseminate CMD-resistant cassava (Output 4 activities). And DFID funded the project on Promotion of and Technical Support for Methods of Controlling Whitefly-borne Viruses in Sweet Potato in East Africa; sweetpotato (*Ipomoea batatas* [L.] Lam.) served as the principal food security crop in the midst of the CMD epidemic.

Whiteflies and Whitefly-Borne Viruses in the Tropics: Building a Knowledge Base for Global Action reports the results from Phase 1 of the CGIAR TWF-IPM Project. The purpose of Output 2 (problem characterization) was to gather, review, generate and analyse baseline data relevant to the diagnosis and characterization of whitefly and WTV problems in the tropics, in order to propose a sound research agenda for improved understanding of pest and disease dynamics, IPM development and IPM implementation. Several of the project coordinators have published review articles (Polston and Anderson, 1997; Legg, 1999; Morales, 2000; Bellotti and Arias, 2001; Morales, 2001; Morales and Anderson, 2001; Morales and Jones, 2004). Baseline data were generated through extensive survey work in each of the participating tropical countries. Surveys included the collection and identification of biological specimens (whitefly species, whitefly biotypes, geminiviruses, and *B. tabaci* natural enemies) and collection and analysis of socio-economic data and IPM practices, based on producer interviews. All partners have presented preliminary results of the extensive survey work and IPM measures in international, regional and national meetings. This book is the first presentation of detailed results generated by the Phase 1 projects contributing to the CGIAR TWF-IPM Project. For further information on specific methodologies used to produce the results published in this book, please contact the information and communication assistant of the project (www.tropicalwhiteflyipmproject.cgiar.org).

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