BIOLOGICAL CONTROL IN THE NEOTROPICS: A SELECTIVE REVIEW WITH EMPHASIS ON CASSAVA

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INTRODUCTION

Today, there is ample biological control (BC) research in the Neotropics. Moreover, many integrated pest management (IPM) projects in crops such as potatoes, cotton, soybeans, maize, vegetable crops and fruits include BC as a key component. Cassava cultivation is a good example of where BC has had an important role in managing the main pests, not only in the Americas but also in other continents such as Africa.

BIOLOGICAL CONTROL RESEARCH IN THE NEOTROPICS

In a literature review (1995-2003), a large number of publications on BC research in various countries of the Neotropics was found. Of these publications, the following synthesis can be made: (1) much of the research on BC is primarily on arthropod pests (60%); but there is also considerable research on plant pathogens (30%), as well as nematodes (6%) and weeds (4%). (2) With respect to the BC of arthropods in South America, 50% of the articles reviewed (578 total) report on research done in Brazil; 25% in Colombia, 11% in Chile and 9% in Argentina. In North and Central America most of the publications are from Mexico (169) and only 23 articles are produced in the other countries of the region. (3) The crops of major economic importance on which BC research is being done in South America are cotton, tomatoes, soybeans, maize, cereals, potatoes, coffee, fruits, vegetable crops, sugarcane, cassava and legumes (Table 1).

In general, the group of pests that was target of the highest number of BC projects was Lepidoptera (>40%), followed by Coleoptera (20%) and Homoptera/Hemiptera (19%) (Table 2). The complex of Lepidoptera species is quite numerous and includes genera such as *Spodoptera, Diatraea, Heliothis* and *Anticarsia* (Table 3). With respect to Coleoptera, the pests where most BC research was done were the white grubs (Melolonthidae), the coffee berry borer and the cotton boll weevil. Other BC research includes mites and fruitflies (particularly in Brazil and Colombia), and aphids and whiteflies (Table 4).

Table 1. Articles on BC of Arthropod pests, by crop, in South America (1995-2003).

Crop	Articles	Principal Pest
Cotton	42	Cotton boll weevil, leaf-eating caterpillar
Tomatoes	40	Whiteflies, leaf miners
Soybeans	36	Velvetbean caterpillar (Anticarsia sp.), especially in Brazil
Maize	33	Fall armyworm
Cereals	32	Lepidoptera/Aphids
Potatoes	29	Potato moths
Coffee	26	Coffee berry borer, especially in Colombia
Pastures	25	Orthoptera/ants/spittlebugs
Fruits	25	Aphids/Lepidoptera
Citrus fruits	23	Fruitflies/scales
Vegetable crops	20	Aphids, whiteflies/Lepidoptera
Forests	19	Lepidoptera/Coleoptera
Sugarcane	17	Sugarcane borer
Cassava	16	Mites, mealybugs
Stored products	12	Grain moth
Common beans	10	Leafhoppers, whiteflies
Legumes	10	Aphids
Ornamentals	7	Mites/thrips
African palm	6	Coconut weevil
Others (grapes, olives, bananas)	18	Various
Total	**446**	

Sources: Agricola, Agris and CAB databases, 1995-2003.

Table 2. Biological control of arthropod pests in South America (1995-2003).

Order	Articles	%
Lepidoptera	212	41.5
Coleoptera	103	20.2
Homoptera/Hemiptera	99	19.4
Acari	31	6.1
Diptera	21	4.1
Hymenoptera	18	3.5
Orthoptera	16	3.1
Isoptera	8	1.5
Thysanoptera	3	0.6
Total	511	100.0

Sources: Agricola, Agris and CAB databases, 1995-2003.

Table 3. Lepidopteran species pests that have been target of BC in South America (1995-2003).

Principal Pest	Common Name
Spodoptera frugiperda	Fall armyworm
Spodoptera spp.	Cutworms
Diatraea saccharalis	Sugarcane borer
Heliothis virescens	Tobacco budworm
Helicoverpa zea=Heliothis. zea	Corn earworm, tomato fruitworm
Anticarsia gemmatalis	Velvetbean caterpillar
Tuta absoluta	Tomato leafminer
Plutella xylostella	Diamond-back moth; leaf-eating caterpillar
Alabama argillacea	Cotton leafworm
Tecia solanivora	Guatemalan potato moth
Phthorimaea operculella	Potato tuber moth

Sources: Agricola, Agris and CAB databases, 1995-2003.

Table 4. Principal pests reported in articles on BC in South America (1995-2003).

Order	Principal Species	Common Name
Homoptera/Hemiptera	*Myzus* spp. and *Aphis* spp.	Aphids
	Bemisia tabaci	Whiteflies
	Trialeurodes vaporariorum	Whiteflies
	Empoasca spp.	Leafhoppers
	Aeneolamia spp.	Spittlebugs
	Mahanarva spp.	Spittlebugs
Coleoptera	Melolonthidae (Scarabaeidae)	White grubs
	Hypothenemus hampei	Coffee berry borer
	Anthonomus grandis	Cotton boll weevil
	Epicaerus spp.	Potato grub
	Tribolium spp.	Granary weevil
Diptera	*Anastrepha* spp.	Fruitflies
	Liriomyza sativae	Leaf miners
Acari	*Mononychellus tanajoa*	Cassava green mite
	Tetranychus spp.	Red mites

Sources: Agricola, Agris and CAB databases, 1995-2003.

The organisms most studied and used in BC were entomopathogens (about 40% of the articles), parasitoids (35%) and predators (18%). Within the group of entomopathogens, the most researched were fungi, followed by bacteria (primarily *Bacillus thuringiensis*) and baculoviruses. The fungi evaluated most frequently belonged to the genera *Metarhizium, Beauveria* and *Lecanicillium* (*Verticillium*). The most studied parasitoids were in the families Trichogrammatidae (40% of the articles) and Encyrtidae (Hymenoptera). The predators studied the most were Chrysopidae and Phytoseiidae (predators of mites).

In Mexico and Central America, the crops in which there was a greater concentration of BC research were fruits, vegetables, maize, coffee, cotton and tomato. Lepidoptera and Coleoptera were the groups of insect pests where there were more studies; and within the Homoptera, whiteflies. The BC organisms studied the most are parasitoids and entomopathogens, especially *B. thuringiensis.*

BIOLOGICAL CONTROL IN THE NEOTROPICS: CASE STUDIES

Biological control is the most important IPM component in tropical and subtropical zones. Although the potential for using BC is high, the use of chemical pesticides continues to increase (Yudelman *et al*. 1998), especially in developing countries. The use of these products above all, their abuse has had adverse effects on both natural and applied BC (Van Driesche and Bellows 1996). In many cases pesticide use has destroyed the natural enemies of the secondary pests, resulting in severe outbreaks of insects that do not normally cause economic levels of damage (yield losses and quality reduction) to crops. In the case of vegetable crops and fruits for exportation, there is a need to reduce or eliminate the toxic residues of the chemical pesticides so that they meet international market requirements (Peña 2002). To extend the use of BC in pest management, there is a need to increase the level of research and funding in the same. The literature review showed that there is increased interest in BC in various countries of the Neotropics. Some cases of success can be cited:

BIOLOGICAL CONTROL WITH BACULOVIRUSES

Baculoviruses have been successful in controlling important pests of various crops, especially soybeans, potatoes and cassava. In the case of potatoes, research at the International Potato Center (CIP) in Peru has led to good control of the potato tubermoth, *Phthorimaea operculella* Zeller (Alcazar *et al*. 1993). Research on the use of baculoviruses to control the cassava hornworm, *Erinnyis ello* L Linnaeus) (Lepidoptera: Sphingidae), and their implementation in the field by CIAT in Colombia are documented below. In soybeans, the use of baculoviruses to control the velvetbean caterpillar (*Anticarsia gemmatalis* Hübner) is one of the most successful examples of BC in the Neotropics (Moscardi 1999). *Anticarsia gemmatalis* can cause severe damage and reduction of soybean crop yields. Research done by EMBRAPA (Brazilian Agricultural and Livestock Research Entity) indicated that the baculoviruses had good potential for controlling *A. gemmatalis*, resulting in the development of a commercial product, which first came into use in 1980. In 1983-1984 applications were done on approximately 20,000 ha and progressively increased until 1.2 million ha in 1997-1998 (Moscardi 1999); in 2001-2002, applications were done on up to 1.5 million ha (Moscardi pers. comm.). This project has had many benefits for the soybean growers. The cost of using baculoviruses is 20-30%

lower than the cost of applying insecticides. The cost per ha is only US$7, which meant a savings of US$10 million in 2001-2002. Up to 2002, the baculoviruses had been applied to 17 million ha, for a total savings of US$120 million. In addition, it is estimated that the use of insecticides has decreased by 1.7 million lt, a benefit for both the environment and human health (Moscardi pers. comm.).

BIOLOGICAL CONTROL IN COTTON

Managing pests in cotton has had a long history in Colombia and illustrates the difficulties of combining BC with the use of insecticides. During the 1960s and 70s, up to 26 applications of insecticides were made per cycle, primarily for the tobacco budworm *Heliothis virescens* (F.)(Lepidoptera: Noctuidae). The insecticides were applied according to a pre-established schedule, without determining the levels of economic damage. Despite the high number of applications, cotton yields declined. By 1977, *H. virescens* had developed resistance to the available insecticides, particularly to methyl parathion (FEDEALGODON 1988). The production of cotton declined, the costs rose, and the crop was abandoned in some zones. In 1980, ICA (Colombian Agricultural and Livestock Institute) and FEDEALGODON (National Federation of Cotton Growers) began research on IPM to lower the use of insecticides. Levels of economic damage were established, and a sampling program to measure the levels of pest populations was implemented. The program was based on BC, especially the increased releases of the hymenopteran parasitoids *Trichogramma* sp. and *Apanteles* sp., lowering the populations of *H. virescens* dramatically. The use of insecticides was reduced to only 2-3 applications, and the yields of cotton rose (Bellotti *et al*. 1990). This program was a good example of the potential of IPM and BC (Smith and Bellotti 1996). This system worked well up to the 1990s when the boll weevil *Anthonomus grandis* Boheman (Coleoptera: Curculionidae) was introduced to Colombia (Díaz 2003). During the period 1991-2002, Colombia experienced a reduction of 83% in the area planted to cotton (Rodríguez and Peck 2004). The 2002-2003 harvest included only 46,514 ha in the two cotton-growing regions of Tolima-Valle and the Atlantic Coast-Meta (DANE 2004). One aspect that has greatly influenced the loss of area planted to cotton in Colombia is the high incidence of pests. The greatest losses are caused by the boll weevil, which affects 89% of the growing area in the provinces of Córdoba, Cesar and Tolima, causing 15% loss of flower heads. The tobacco budworm affects 100% of the cotton-growing area of Colombia, causing damage to 15-20% of the flower heads and bolls. Some 10% of the cultivated area is additionally affected by the Colombian pink bollworm (*Sacadodes pyralis*, Lepidoptera: Noctuidae) and whiteflies (Homoptera: Aleyrodidae).

Control of these pests is largely based on extensive use of agrochemicals, which represent 23% of the direct costs of the crop for the Colombian producer. In the Atlantic Coast, there was an average of 26 applications of pesticides per crop cycle, with 69.2% of those directed toward the control of lepidopterans. In the Cauca Valley, the number of applications has been reduced 73%, to an average of 7 applications per crop cycle, with 57.1% directed towards the control of lepidopterans (CIAT 2004). The apparent solution for this problem is to use transgenic varieties with *Bacillus thuringiensis*. Recent research indicates that the use of the transgenic varieties makes it possible to lower insecticide applications to 8-9 or even less. The use of transgenic varieties combined with BC offers a good opportunity for lowering insecticide applications (Díaz 2003).

BIOLOGICAL CONTROL IN COFFEE

The coffee berry borer *Hypothenemus hampei* (Ferrari) (Coleoptera: Scolytidae) is one of the world's major pest problems in the coffee crop. Major damage is caused by the larvae penetrating the coffee berries and tunneling in the beans, causing fruit drop. Infested berries are the sources of future attacks (Baker *et al*. 1992). The pest is well adapted to the coffee agroecosystems, and once established, is very difficult to eradicate. Yield losses can range from 5 to 24%, depending on pest infestation, and losses as high as 50% have been reported (Ramirez and Mora 2001).

Hypothenemus hampei was originally reported from Africa and introduced into Colombia in 1988. The Colombian Institute of Coffee Research (CENICAFE) initiated an IPM program, based on BC, to reduce or manage damage by this pest (Bustillo *et al*. 1998). Biological control of coffee berry borer in Colombia has concentrated on the combination of parasitoids and entomopathogens. Since *H. hampei* originated in Africa, several parasitoid species were introduced from that continent. These included *Heterospilus coffeicola,* Schneideknecht *Prorops nasuta,* Waterson *Cephalonomia stephanoderis* Betren and *Phymastichus coffea* La Salle (Borbon 1991). *Prorops nasuta* has been introduced into several countries of the Americas (Mexico, Guatemala, Brazil, Colombia, Honduras and others). Parasitism rates by *C. stephanoderis* have been recorded as high as 65% in Mexico (Barrera *et al*. 1990). Parasitism rates of *P. coffea* on *H. hampei* in Colombia reached 77.6 and 85%, 90 and 150 days respectively, after introduction (Jaramillo *et al*. 2002).

In Colombia, the coffee berry borer is infected with native strains of *Beauveria bassiana* and *Hirsutella eleutherathorum* (Bustillo 1998). Field results with applications of *B. bassiana* in Colombia and other countries have been variable, ranging from 48% to levels above 75% (Bustillo 2002). Present strategy for *H. hampei* control includes the combination of cultural and biological control practices, including the periodic release of parasitoids and the applications of entomopathogens (Bustillo 1998).

BIOLOGICAL CONTROL IN CASSAVA

Cassava (Euphorbiaceae: *Manihot esculenta*) is a perennial shrublike plant that has a 1-2 year cropping cycle. It is usually cultivated on small farmers' fields in tropical and subtropical regions of the world, where it is often intercropped or planted in cycles that overlap with other crops. These and other agronomic characteristics contribute to the diversity of arthropod pests that feed on cassava and to the complex of natural enemies associated with them.

The cassava crop originated in the Neotropics; consequently, there is a great diversity of arthropods that have been recorded attacking the crop in the Americas (Bellotti *et al*. 1999; 2002). Almost all the principal pests of cassava are found on this continent (Table 5). The accidental introduction of the cassava green mite *Mononychellus tanajoa* (Bondar) (Acari: Tetranychidae) (CGM) and the mealybug *Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae) from the Americas into Africa has caused considerable losses throughout the African cassava belt and has been the object of a massive BC effort.

In the Neotropics an ample complex of natural enemies exercises a certain level of control on the crop's principal pests (Table 6). There are more than 250 species of natural enemies, including parasitoids, predators and pathogens associated with the pests in the cassava

Table 5. Global distribution of the arthropod pests of importance in the cassava crop, adapted from Bellotti (2002).

Pest	Principal Species	Americas	Africa	Asia
Mites	*Mononychellus tanajoa*	X	*X*	
	Tetranychus urticae	X		
Mealybugs	*Phenacoccus manihoti*	X	*X*	
	Phenacoccus herreni	X		
Whiteflies	*Aleurotrachelus sociales*	X		
	Aleurothrixus aepim	X		
	Bemisia tabaci	X	*X*	
Cassava hornworm	*Erinnyis ello*	X		
	E. alope	X		
Lacebugs	*Vatiga illudens*	X		
	V. manihotae	X		
Burrower bugs	*Cyrtomenus bergi*	X		
Thrips	*Frankliniella williamsi*	X	*X*	
	Scirtothrips manihoti	X		
Scales	*Aonidomytilus albus*	X	*X*	
Fruitflies	*Anastrepha pickeli*	X		
	A. manihoti	X		
Shootflies	*Neosilba perezi*	X		
	Silba pendula	X		
Gall midges	*Jatrophobia* (Eudiplosis) *brasiliensis*	X		
White grubs	*Leucopholis rorida*	X	*X*	X
	Phyllophaga spp.	X	*X*	X
	Others	X	*X*	X
Termites	*Coptotermes* spp.	X	*X*	X
	Heterotermes tenuis	X		
Stemborers	*Chilomima* spp.	X		
	Coelosternus spp.	X		
	Lagochirus spp.	X	*X*	X
Leaf-cutting ants	*Atta* spp.	X		
	Acromyrmex spp.	X		
Root mealybugs	*Pseudococcus mandioca*	X		
	Stictococcus vayssierei		*X*	
Grasshoppers	*Zonocerus elegans*	X	*X*	
	Zonocerus variegatus			

Table 6. Reports of natural enemies of some of the principal pests of cassava, (adapted from Melo 2002).

Pests	Parasitoids	Predators	Pathogens
Cassava green mite		60	2
Cassava hornworm	18	15	15
Whiteflies	17	5	6
Mealybugs	25	46	2
Borers			
Chilomima clarkei	5	2	5
Lagochirus sp.	2		
Burrower bugs		1	5
White grubs	2	1	3
Lacebugs		1	
Thrips		1	
Scales	4	9	2
Total	**73**	**141**	**40**

crop (Melo 2002). Sixty-two species of natural enemies are associated with mites, 48 with the cassava hornworm, 73 with mealybugs and 28 with whiteflies.

Biological control is one of the components in an IPM program, in which varietal resistance (genetic component) and cultural practices (agronomic component) also play an important role. The use of chemical pesticides in traditional agroecosystems of cassava is minimal, due to their high cost and adverse effects on natural enemies, human health and damage to the environment. In addition it has been shown that in some cases, as with whiteflies, the use of pesticides is not economically viable for the small farmers (Holguín and Bellotti 2004).

RECENT ADVANCES IN BIOLOGICAL CONTROL OF MAJOR CASSAVA PESTS

Applied BC has had a major role in managing certain harmful pests of cassava. A brief description of this research, the results and accomplishments follow. Emphasis is on mites, mealybugs, the cassava hornworm, whiteflies, the burrower bug and white grubs.

Cassava green mite. Mites are considered a universal pest of cassava because they cause crop losses in both the Americas and Africa. The CGM (*Mononychellus tanajoa*) is the most important species, especially in lowland tropical regions with prolonged (3 to 6 months) dry seasons. It is native to the Americas, possibly from northern South America or Northeast Brazil, where it was reported for the first time in 1938. The mite attacks young leaves and meristems, preferably feeding on the underside of the leaves, which develop a mottled to bronzed appearance in the form of a mosaic with chlorotic spots until the leaves become deformed. *Mononychellus tanajoa* was introduced accidentally to the African continent during the 1970's, where it caused 13-80% yield loss (Yaninek and Herren 1988).

Research on the control of CGM has been based on two principal strategies: varietal resistance (VR) and BC. Research on VR has identified low-to-moderate levels of resistance in cassava clones. Programs at CIAT, IITA (International Institute of Tropical Agriculture) and EMBRAPA/CNPMF incorporate this resistance to cultivars. As VR is highly complementary with BC, a great deal of emphasis has been placed on evaluating the role of natural enemies. In order to develop a BC program to combat the CGM, explorations, evaluations and taxonomic recognition were carried out at more than 2,500 sites in 17 countries of the Americas (Bellotti *et al.* 1987; Bellotti 2002). An ample complex of the predator mites (Phytoseiidae) were found preying on mite pests. In cassava 66 species of Phytoseiidae were collected, of which 25 were new for science and 13 were very common in other crops. *Typhlodromalus manihoti* (Moraes) was collected most frequently, being found in over 50% of the fields sampled. It is followed by *Neoseiulus anonymus,* Chant and Baker *T. aripo,* De Leon *Galendromus annectens,* (De Leon) *G. helveolus* (Chant) and *Amblyseius aerialis*, (Muma) among others (Fig. 1). *Typhlodromalus aripo, T. manihoti* and *N. idaeus* play an important role in the control of *M. tanajoa* in Africa, where they were introduced from Brazil during the 1980s and 1990s. *Typhlodromalus aripo* has proven to be the most promising species. Field evaluations in Africa indicated that *T. aripo* can reduce the CGM population from 30-90%, bringing about a 30-37% increase in cassava production (Table 7) (Yaninek *et al*. 1993).

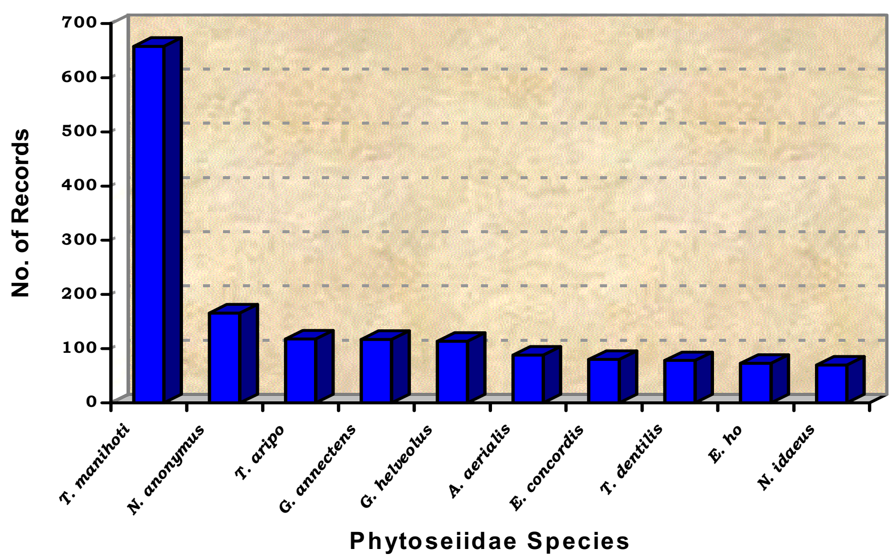

Figure 1. Species of Phytoseiidae reported on the cassava crop in the Americas.

Results of field experiments in Colombia showed the importance and the effect of the diversity of Phytoseiidae species associated with the CGM. In Colombia the production of fresh cassava roots was reduced by 33% when the natural enemies were eliminated; whereas, applications of acaricides did not increase the production, which shows the important role of BC (Braun *et al*. 1989). Explorations also found some insect predators of the CGM, especially the staphylinid *Oligota minuta* and the coccinellid *Stethorus* sp. *Oligota minuta* Cameron has been catalogued as an important predator of *M. tanajoa* populations. In research done at CIAT and in Uganda, *Oligota* populations were found between the fifth and eighth leaves,

Table 7. Establishment of Phytoseiidae species in Africa.

	N. idaeus	*T. manihoti*	*T. aripo*
Year of First Release	1989	1989	1993
No. of countries where established	2	4	11
Rate of dispersion (km/year)	0.01	2.5	12.5
Region occupied (km^2)	< 10	1300	150 000
Reduction in CGM (*M. tanajoa*) population	0%	50%	30-90%

Source: IITA (1995, 1996).

coinciding with the places where the highest populations of the pest are found. In the larval stage they can consume 49-70 mites and 44-61 eggs; in the adult stage they consume 97-142 eggs and adults in 7-16 days. *Stethorus* sp., on the other hand, is mostly found in association with *Tetranychus urticae* Koch. In severe attacks of this mite, 98% of the predators were *Stethorus* and only 2% *Oligota* (CIAT 1982). In laboratory and field observations, the predator *Chrysopa* sp. (Neuroptera) has proven to be very effective, consuming different stages of the pest.

Other natural enemies of mites are the pathogenic fungi belonging to the genera *Neozygites* (Zygomycetes: Entomophthora) and *Hirsutella* (Hyphomycetes: Monilia). The former is a pathogenic fungus that appears sporadically in Colombia and Northeast Brazil (*Neozygites cf floridana)*, causing up to 100% mortality of the CGM in 1-2 wk (Delalibera *et al.* 1992). Some strains are specific to the genus *Mononychellus* (Moraes and Delalibera 1992). In evaluations done in Africa, *Hirsutella* sp. has proven to be very effective controlling mite populations (Odongo *et al.* 1990; Yaninek *et al*. 1996) (Table 8).

Table 8. Natural enemies of the CGM *Mononychellus tanajoa* (Acari: Tetranychidae).

Predators	**Pathogens**
Neuroptera	Fungi
Chrysopa sp.	*Neozygites floridana*
Coleoptera	*Hirsutella thompsonii*
Stethorus sp.	Virus
Oligota spp.	Not identified (found in
Acari (114 strains)	Colombia, unpublished
Typhlodromalus manihoti	information)
T. aripo	
Neoseiulus idaeus	
Others	

Cassava mealybugs. More than 15 species of mealybugs have been found feeding on cassava in the Americas, Africa and Asia. The two most important species are *Phenacoccus manihoti* and *P. herreni* (Hemiptera: Pseudococcidae), which, cause significant reductions in cassava yield. Both species are of Neotropical origin. The former is found in Paraguay, certain areas of Bolivia and in the State of Mato Grosso in Brazil, but causes no economic damage in these regions. When *P. manihoti* was inadvertently introduced into Africa at the onset of the 70s, it dispersed rapidly, causing considerable losses in yield (up to 80%) (Herren and Neuenschwander 1991). *Phenacoccus herreni* is distributed in northern South America (primarily in Colombia and Venezuela) and in Northeast Brazil, where high populations can cause considerable losses. The damage produced by both species is similar: feeding of the nymphs and adults causes yellowing, curling of the leaves, formation of rosettes on the growing points, necrosis, defoliations, distortion of the stem, and death of the shoots (Bellotti 2002).

Management of mealybugs is a well-documented example of classical BC, especially in Africa, where *P. manihoti* is being controlled successfully by the parasitoid *Apoanagyrus lopezi* De Santis, which IITA introduced to Africa from Paraguay. Although *P. herreni* is distributed in northern South America, it causes serious yield losses only in Northeast Brazil (Bellotti, *et al*. 1999) (up to 80% yield reduction reported). Thus *P. herreni* can be an exotic species in this region, probably coming from Colombia and Venezuela (Williams and Granara de Willink 1992).

Numerous species of parasitoids, predators and entomopathogens of *P. herreni* have been identified in Colombia and Venezuela. Various parasitoids have shown a specialty or preference for *P. herreni*. Three Encyrtidae (*Apoanagyrus diversicornis* Howard, *Aenasius vexans* Kerrich and *Acerophagus coccois* Smith) have been evaluated as parasitoids (Van Driesche *et al.* 1988; 1990). All three species were observed having higher percentages of parasitism on *P. herreni* in laboratory studies in Colombia than on *P. madeirensis* (Table 9). Through the combined efforts of CIAT and EMBRAPA (Brazil), the three species were exported from CIAT and released by EMBRAPA/CNPMF (National Center of Research on Cassava and Fruits) in Northeast Brazil, primarily in the States of Bahia and Pernambuco from 1994-1996. More than 35,000 individuals of the three species were released. Although all three species became established, *A. diversicornis* and *A. coccois* had the most rapid and extensive dispersion (Fig. 2). Observations indicate that the mealybug populations have been reduced substantially and that the cassava crop has returned to areas that had been abandoned due to *P. herreni* infestations (Bento *et al*. 1999; 2000). *P. herreni* outbreaks have not been observed in Northeast Brazil in recent years (Farias pers. comm.)

Table 9. Parasitism (%) of three parasitoids (Encyrtidae) on two mealybug species (*Phenacoccus herreni* and *P. madeirensis*) under laboratory conditions.

Parasitoids	***P. herreni***	***P. madeirensis***
Acerophagus coccois	32	27
Apoanagyrus diversicornis	32	16
Aenasius vexans	38	2

Figure 2. Dispersion of three parasitoid species of the cassava mealybug (*P. herreni*) in Bahia, Northeast Brazil (Bento *et al*. 2000).

The cassava hornworm. *Erinnyis ello* is one of the most important cassava pests in the Neotropics. The species is not reported from Africa or Asia. The migratory capacity of the adults, their broad climatic adaptation and range of hosts contribute to their extensive distribution throughout the cassava-growing zones of the Americas and their sporadic attacks. In addition to its migratory capacity, the explosive appearance of *E. ello* occurs because of its great reproductive potential. A female can lay up to 1,800 eggs (avg of 800/female). Given the foregoing, many plantations have suffered severe defoliations for various cycles until reestablishing the balance between the pest and its natural enemies.

The hornworm's life cycle has a duration of 32-49 days (25-30°C). The larva passes through five instars in its development. The larval stage, which has a caudal horn (thus its name), lasts from 12-15 days and is responsible for the damage to the cassava plants, causing complete defoliation with up to 60% losses in yield when consecutive attacks occur. The voracity of the larva is such that it can consume up to 1100 cm^2 of leaf surface, 75% of which is consumed during the last (fifth) instar (Arias and Bellotti 1984).

Resistance to *E.* ello has not been identified in landrace varieties of *M. esculenta*; however, there are numerous natural enemies with some 40 species of parasitoids, predators and pathogens identified. Several have been evaluated extensively for the egg, larva and pupa stages of *E. ello* (Table 10). The effectiveness of this complex of natural enemies is limited, probably due to the great flight capacity and migratory ability of *E. ello*, which acts as a defense against the effectiveness of the natural enemies (Bellotti *et al*. 1992).

Among the entomopathogens, *B. thuringiensis* has been used successfully when applied to young larvae (first to third instar). From the onset of the 70s, CIAT identified a granulosis virus (Baculoviridae) attacking *E. ello* in cassava crops. Pathogenicity studies in the lab and field gave almost 100% mortality of hornworm larvae. The infected larvae can be collected in the field, blended, filtered through gauze, made into a solution with water, and applied in

Table 10. Principal natural enemies of the cassava hornworm (*Erinnyis ello*), adapted from Melo (2002).

Parasitoids		**Predators**		**Entomopathogens**	
Trichogramma spp.	(E)[1]	*Chrysopa* spp.	*(E,L)*	*Bacillus thuringiensis*	(L)
Telenomus sphingis	(E)	*Podisus nigrispinus*	*(L)*	Baculoviruses of *E. ello*	(L)
Cotesia americana	(L)	*P. obscurus*	*(L)*	*Metarhizium anisopliae*	(L)
Cotesia sp.	(L)	*Polistes carnifex*	(L)	*Beauveria bassiana*	(L)
Euplectrus sp.	(L)	*P. erythrocephalus*	*(L)*	*Paecilomyces* sp.	(L)
Drino macarensi	(L)	*P. canadensis*	*(L)*	*Nomuraea rileyi*	(L)
Drino sp.	(L)	*P. versicolor*	*(L)*	*Cordyceps* sp.	(P)
Euphorocera *sp.*	(L)	*Polybia emaciata*	(L)		
Sarcodexia innota	(L)	*P. sericea*	*(L)*		
Thysanomyia sp.	(L)	*Zelus nugax*	*(L)*		
Belvosia sp.	(L)	*Zelus* sp.	*(L)*		
Forcipomyia eriophora	(L)	*Calosoma* sp.	*(L)*		
		Spiders (Tomicidae, Salticidae, others)	*(L)*		

[1] E=egg; L=larva; P=pupa.

fields attacked by the hornworm (Bellotti *et al*. 1992). Baculoviruses have also been used successfully to control *E. ello* in southern Brazil (Santa Catarinha State). In Venezuela the baculovirus replaced insecticides on large plantations where the hornworm is endemic. In 2003, Biotropical, a Colombian firm, formulated, in collaboration with CIAT, a commercial product (Bio-virus) for the BC of *E. ello* that is presently being used by cassava producers.

Whiteflies. As a direct feeding pest and vectors of viruses, whiteflies cause significant damage to the cassava crop in the Americas, Africa and Asia. There is a large complex in the Neotropics, where 11 species have been recorded feeding on cassava (Table 11). The most important species is *Aleurotrachelus socialis* Bondar, which is widely distributed in northern South America: Ecuador, Colombia and Venezuela (Trujillo *et al*. 2004). Attacks of 1, 6 and 11 months have resulted in 5, 42 and 79% yield losses, respectively, in field trials in region of the Tolima Province, Colombia.

Aleurothrixus aepim, which primarily attacks cassava, but has additional hosts, is found in high populations, causing yield losses in Northeast Brazil (Farias 1994). *Bemisia tuberculata* Bondar and *Trialeurodes variabilis* (Quaintance) are reported in low populations from Brazil, Colombia, Venezuela and several other countries (Bellotti 2002).

Research on cassava whitefly management in the Neotropics initially emphasized varietal resistance. Diverse sources of VR to *A. socialis* have been identified. Clone MEcu 72 has consistently expressed a high level of resistance so it was included in a cross with MBra 12, which resulted in various high-yielding hybrids and moderate levels of resistance to *A. socialis* (Bellotti and Arias 2001). As a result of this work, the Colombian Ministry of Agriculture and Development released the whitefly-resistant hybrid Nataima-31 in 2003.

Table 11. Whiteflies associated with the cassava crop in Northeastern South America.

Species	Colombia	Ecuador	Venezuela	Brazil
Aleurotrachelus socialis	X	X	X	X
Aleurodicus dispersus	X	X	X	
Aleurothrixus aepim				X
Aleuroglandulus malangae	X			
Aleuronudus sp.	X			
Bemisia tabaci		X		
Bemisia tuberculata	X	X	X	X
Paraleyrodes sp.	X			
Tetraleurodes sp.	X	X		
Tetraleurodes ursorum	X			
Trialeurodes variabilis	X	X	X	X

Source: Adapted from Trujillo (2004).

A. socialis is not limited to dry season attacks; in the last decade damaging populations are found throughout the crop cycle. In research done with chemical insecticides, it was found that this control alternative decreased whitefly populations in the field; but for farmers with small areas of the crop, it was not the most viable alternative given that the high pesticide costs make the repeated applications needed for adequate control, uneconomical (Holguín and Bellotti 2004). These results confirm the need for finding more economic alternatives such as BC for controlling whiteflies in cassava.

In recent field explorations carried out in the Neotropics, especially in Colombia, Venezuela, Ecuador and Brazil, a considerable number of natural enemies associated with the whitefly complex in cassava have been identified. The most representative group is that of the microhymenopteran parasitoids. The richness of species in Colombia, Venezuela and Ecuador is primarily represented by the genera *Encarsia, Eretmocerus* and *Amitus*, frequently associated with *A. socialis* (Table 12) (Trujillo *et al*. 2004).

Gaps in the knowledge on the complex of natural enemies associated with the different whitefly species have limited the utilization and determination of their effectiveness in biological control programs. Consequently, there is little knowledge on levels of parasitism, rates of parasitism by species, specification of the host and its effect on the regulation of whitefly populations.

More than 20 species of entomopathogens have been reported infecting whiteflies, including *Aschersonia* sp., *Lecanicillium* (*Verticillium*) *lecanii, Beauveria bassiana* and *Paecilomyces fumosoroseus*; however, a careful selection of the species is required, as well as the identification and evaluation of native isolates of entomopathogen fungi. Greenhouse experiments at CIAT with isolates of *L. lecanii* resulted in 58-72% *A. socialis* nymphal mortality (depending on nymphal stage) and 82% egg mortality (Aleán *et al*. 2004). At present *L. lecanii* is being formulated into a commercial product that should be available to cassava growers

Table 12. Parasitoids of whiteflies collected from cassava in diverse agroecosystems of Colombia, Ecuador and Venezuela.

	Colombia				Ecuador		Venezuela
Species	Caribbean	Andean Zone	Inter-Andean Cauca Valley	Inter-Andean Magdalena River Valley	Coast	Sierra	Plains
Amitus sp.					X		
Eretmocerus sp.	X	X	X	X	X	X	X
Encarsia sp.	X		X	X	X	X	
E. híspida	X	X	X				X
E. pergandiella	X	X					X
E. bellotti	X	X	X				
E. sophia	X		X				X
E. luteola	X		X				
E. cubensis							X
E. americana					X		
E. strenua	X						
Encarsia sp. prob. *variegata*	X						
Metaphycus sp.	X						X
Euderomphale sp.		X			X		X
Signiphora aleyrodis		X		X	X		X

in Colombia during 2005. An integrated strategy for *A. socialis* management based on host plant resistance, the release of parasitoids and predators, and applications of entomopathogens is now being implemented in selected regions of Colombia.

Cassava burrower bug. *Cyrtomenus bergi* Froeschner, a polyphagous insect found in a subterranean habitat, is considered one of the principal pests of diverse crops such as cassava, onions (*Allium* strain), sugarcane (*Saccharum officinalis*), asparagus (*Asparagus officinalis*), sorghum (*Sorghum vulgare*), peanuts (*Arachis hypogaea*) and forage peanuts (*A. pintoi*). Since its appearance feeding on cassava at the onset of 1980, basic studies have been conducted on its biology, behavior, population dynamics and feeding preferences. Trials have been conducted on chemical, cultural and BC with fungi and entomopathogenic nematodes (EPNs). The potential of BC of *C. bergi* is presently being researched. Recent studies with entomopathogenic fungi and EPNs indicate that they have a potential importance in a BC program; however, this research has only been done in the lab and glasshouse so field studies are needed before recommending the most acceptable technology.

Steinernema carpocapsae 'All strain' was the first EPN species evaluated to control *C. bergi.* Caicedo (1993) reports that the adult stage was susceptible to all nematode doses evaluated with 60% parasitism and very low mortality, while the youngest instars were less susceptible, with 3-17% parasitism.

Evaluations of native species (*Heterorhabditis* sp.) and *Steinernema* sp., found in field samples in Colombia, together with exotic strains from the USA and UK, on fifth instar and adults under lab conditions, showed that both *C. bergi* stages were parasitized by all entomopathogenic nematode species. *Steinernema* sp. SNI 0100 was the species that showed the highest parasitism in the fifth instar and adult stage of *C. bergi* with 77 and 100% parasitism respectively. *Heterorhabditis* sp. HNI-0198 resulted in 28 and 49% parasitism in the fifth instar and adult stage respectively, 10 days after inoculation. Although the highest mortality (22%) occurred in the fifth instar, no correlation with parasitism (77%) was observed. The lowest mortality was observed with *Heterorhabditis* sp HNI-0198 with only 4% (Caicedo *et al*. 2004).

There were no significant differences among all the nematode species and doses evaluated in greenhouse studies against *C. bergi* adults. When adults were exposed to 1,000 nematodes of *Steinernema carpocapsae*, *Steinernema* sp. SNI 0100 and *Heterorhabditis* sp. HNI-0198, the parasitism was 21, 18 and 10% respectively and mortality was not observed. The parasitism and mortality caused by *S. carpocapsae* and *Heterorhabditis* sp. HNI-0198 was increased with the dose of 25,000 nematodes to 55 and 45% parasitism and 29 and 9% of mortality respectively. The adults exposed to 100,000 nematodes showed an increase in the mortality caused by *Steinernema riobrave, Steinernema* sp SNI0100 and *Heterorhabditis* sp. CIAT of 33, 28 and 26% respectively. These low mortalities suggest that it could be possible that *C. bergi* is showing immune response against all six nematodes species evaluated (Caicedo *et al*. 2004b).

Work with fungal entomopathogens, primarily *Metarhizium anisopliae*, was done in lab and glasshouse studies for three years. The most successful strains were evaluated in the field, where the best strain was selected, based on its mortiferous capacity, which reached 61% for the fifth nymphal instar of *C. bergi*. Thus this BC agent was selected for its potential management of this pest. At this time there is a specific commercial product, whose active ingredient is the strain evaluated at CIAT that is available to cassava producers. Positive results with *C. bergi* control on asparagus have been reported.

OTHER PESTS OF CASSAVA

Rhizophagous white grubs. *Phyllophaga* spp., *Anomala* sp., *Plectris* sp. and others are soil pests that feed directly on cassava roots and stem cuttings. Strains of fungi, bacteria and EPNs, which cause high mortality to the white grub larvae in the lab, are being identified (CIAT 2003) (Table 13).

Scales. *Aonidomytilus albus* Cockerell and *Saissetia miranda* (Cockerell and Parrott) are the two species that are frequently found feeding on cassava. There is natural BC for both species due to numerous parasitoids. The misuse of pesticides can, however, eliminates this advantage and results in increased scale populations.

Diptera. For some pests such as the fruitfly (*Anastrepha* spp.), shootflies (*Neosilba perezi* (Romero and Ruppell), *Silba pendula* (Bezzi)) and gall midges (*Jatrophobia brasiliensis* Rubsaaman), BC agents have not been identified. Fortunately under normal circumstances these pests do not cause economic damage to the cassava crop.

Stemborers. Especially *Chilomima clarkei* (Amsel), and the lacebugs (*Vatiga* spp.) can cause losses in cassava yield in serious attacks. To date, effective natural enemies have not been identified (Table 13).

Table 13. Other pests of cassava and their natural enemies.

Species	Parasitoids	Predators	Pathogens
White grubs *Plectris* spp. *Phyllophaga* spp. *Anomala* spp.	Diptera Tachinidae Asilidae	Coleoptera Elateridae	Fungi *Metarhizium anisopliae* *Beauveria bassiana* Bacteria *Bacillus popilliae* Bolentimorbus *Serratia* spp. Nematodes *Heterorhabditis* spp. *Steinernema* spp.
Stemborers *Chilomima clarkei* *Lagochirus* spp.	Hymenoptera *Bracon* sp. *Apanteles* sp. *Brachymeria* sp.		Fungi *Spicaria* sp. Bacteria *Bacillus thuringiensis* Virus Unidentified
Lacebugs *Vatiga manihotae*		Hemiptera *Zelus nugax*	
Thrips *Scirtothrips manihoti*		Acari *T. aripo*	

CONCLUSIONS

Biological control has been successful against certain cassava pests, especially introduced species of mites and mealybugs in Africa. Natural enemies have been used to reduce populations of the cassava hornworm (baculovirus), the mealybug in the Americas and Africa (parasitoids), and mites (ample complex of Phytoseiidae predators). The success of natural enemies depends to a great extent on the minimal use of pesticides, which can destroy the effectiveness of the BC.

In general pesticide use in traditional cassava agroecosystems is minimal, primarily due to their high cost. Farmers in the Neotropics can, however, respond with pesticides to pest population explosions. Given that the production of cassava is changing to larger plantations, the tendency to apply more pesticides for controlling these pest outbreaks has increased. There is considerable potential for replacing the use of chemical pesticides by biopesticides for managing pests in cassava. Further research is needed to develop biopesticides and methodologies for their effective implementation. This perennial crop has advantages for implementing BC given its long vegetative cycle, cultivars adapted to given agroecosystems, tolerance to drought, profitability, no specific periods of economic damage, and high potential for recovering from the damage produced by some of these important pests. The use and success of BC as an important component in an IPM program require a significant initial investment in research and collaboration among scientists, extension agents and farmers if it is to be sustainable. The role of private industry will be of key importance for biopesticides based on entomopathogens and/or botanical derivates before they can be successfully employed in a cassava IPM strategy.

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