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).

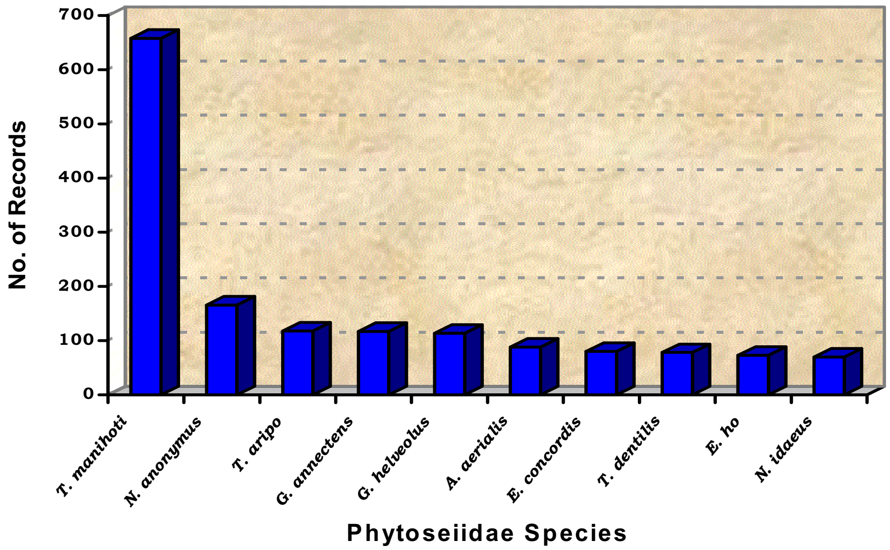

Figure 1. Species of Phytoseiidae reported on the cassava crop in the Americas.

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 Colombia, unpublished information)
Acari (114 strains)	
Typhlodromalus manihoti	
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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HUNGER, POVERTY, AND PROTECTION OF BIODIVERSITY: OPPORTUNITIES AND CHALLENGES FOR BIOLOGICAL CONTROL

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ABSTRACT

The role and contribution of biological control to hunger and poverty alleviation, and protection of biodiversity are discussed in context of the global development agenda. These linked themes are projected to continue occupying the global development agenda for the foreseeable future. Hunger and poverty alleviation efforts have frequently focused on improving agricultural production *inter alia* with a view to provide adequate but safe food to meet local and export demands especially to northern markets. Such markets have increasingly put stringent requirements on imported food including minimum acceptable pesticide residue levels. Recent years have also seen a rise in demand for organic food, providing more opportunities for export of tropical produce. Implicit in these trends has been the growing need for ecological crop management. From this context, it is inferred that there is a demand for biological control as a tool to manage the large number of native and alien pests. Another area for application of biological control is the management of invasive alien species (IAS) in the context of biodiversity conservation, under article 8h of the Convention on Biological Diversity. An assessment of the trends in biological control research and application suggest that there has been little growth despite increased opportunities and challenges.

INTRODUCTION

Biological control in its various forms has made major contributions to global development especially in dealing with the myriad arthropod pests that affect agricultural production. Pests are a major constraint for instance, Oerke *et al.* (1994) estimated that for eight major crops (rice, wheat, barley, corn, soybeans, potatoes, cotton and coffee), 42 percent of attainable production was lost due to pests. The estimated losses in Africa and Asia were just below 50%. Not surprisingly, mitigation of these losses has been a major preoccupation of many agencies over the years. The 1960s onwards saw the emergence of integrated pest management (IPM) approaches for pest mitigation and with it the important role of biological control as a fundamental component. Since then there have been many striking advances such as the spectacular success achieved in rice systems in Asia where over and misuse of pesticides had led to emergence of *Nilaparvata lugens* Stal (Hemiptera: Delphacidae) as a serious constraint to rice production (Wardhani 1992). The 1980s saw a redirection of IPM efforts especially focusing on technology delivery and this emphasis continues today in many parts of the developing world (Heinrichs 2005; Waage 1996).

Biological control has also been a central feature of the fight against the increasing spate of invasive alien species. Introduced alien species (IAS) have the potential to cripple crop production. For instance, in the 1970s, two cassava feeding arthropod pests native to South America, the cassava mealybug, *Phencacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudoccidae) and the cassava green mite, *Mononychellus tanajoa* (Bondar) (Acari: Tetranychidae) were accidentally introduced to Africa. Populations built up quickly causing crop losses ranging from 35-40% and as high as 80 % in some parts. The two pests were successfully brought under control through the introduction of specialist natural enemies (Zeddies *et al.* 2001). Similar successes have continued to be achieved as with the recent control of the hibiscus mealybug, *Maconellicoccus hirsutus* Green (Hemiptera: Pseudoccidae) in the Caribbean, Central America, northern South America and Florida (Kairo *et al*. 2000). The pest attacks a wide range of fruit, vegetables, ornamentals and forest trees.

In recent years, the importance of IAS as a threat to biological diversity has also come to the forefront (McNeely *et al.* 2001). While preventative measures are more cost effective, it is almost certain that some species will escape and become established, requiring mitigation. Classical biological control is one of the main tools available to deal with such species (Wittenberg and Cock 2001).

The important role of biological control in global development can therefore not be understated. This paper begins by looking at some key issues driving the global development agenda with particular reference to areas where biological control can play an important role. Next, it examines the demands for biological control. Given the issues and demand, this paper then examines the growth of biological control research with a view to identify how the technology can be more effectively applied.

GLOBAL DEVELOPMENT AGENDA

On 8th September 2000, 187 world heads of state and government gathered for the 55th session at the United Nation's Headquarters in New York made a number of bold declarations in response to Agenda 60 (b) (United Nations 2000). The declaration was organized around eight main themes including: values and principles, peace and security, human rights, democracy and good governance, protecting the vulnerable, meeting the special needs of Africa, strengthening the United Nations, development and poverty alleviation, and protection of the environment. The following year at the 56th session, the UN Secretary General outlined a series of strategies for action towards meeting the goals (United Nations 2001).

Among the areas addressed by the declaration were global development and poverty eradication, familiar to most as the 'Millennium Development Goals' (MDGs) as well as protection of the environment. The goals were time bound with the anticipation that by 2015 significant milestones towards addressing extreme poverty in its many dimensions including income poverty, hunger, disease, lack of adequate shelter, and exclusion, while promoting gender equality, education, and environmental sustainability would have been achieved. Thus it was targeted that by 2015, the proportion of people who suffer from hunger would have been halved. The environmental components of the Millennium Declaration spoke to issues such as global warming, forestry, the Convention on Biological Diversity (CBD), Convention to Combat Desertification, and water use among others. In July 2002, the UN Secretary General launched the 'Millennium Development Project' with a view to prepare strategies to help countries achieve the various goals (United Nations 2002). A number of task forces were set up to address the various goals and one focused on hunger. This task force made seven recommendations and while several of these have relevance to biological control, one was particularly about increasing the agricultural productivity of food for insecure farmers. This recommendation identified among other things, the need to improve soil health (mainly through access to organic and inorganic fertilizers, access to better seeds and crop diversification including a focus on crops such as vegetables. Although not mentioned as a key recommendation, the management of pests will have to be an integral component if success is to be realized.

THE DEMAND FOR BIOLOGICAL CONTROL

HUNGER AND POVERTY

Poverty and hunger are inextricably linked. At the global level, 852 million are chronically hungry and this is a slight reduction from the 1990 levels (UN Millennium Project 2005a). Agriculture is the largest economic activity for the estimated 75% of the world poor (Majid 2004). 204 million people in sub-Saharan Africa are hungry and this number is rising. Among the causes for hunger are poverty and low food production. The management of pests and by extension, use of biological control, forms part of the technical suite of solutions.

Biological control offers technical solutions to secure food production against indigenous as well as non-indigenous pests. In addition to the obvious cost advantages, biological control within an IPM framework offers a way to minimize requirements for expensive pesticides. More importantly, it increases the scope for market access in countries with the increasingly stringent requirements for minimum acceptable residues (MRLs) of pesticides on food.

In addition to traditional exports of tropical produce, new niche markets are opening up with potential for higher income to farmers. For instance, during the last years of the 1990s, sales values of organic products grew by 20-30% following major food scares such as bovine spongiform encephalopathy (BSE) (FAO, 2001). While it is not envisaged that the high growth rates will persist, nevertheless, the demand is projected to grow, and land under organic produce has continued to expand (Yussefi, 2005). Organic agriculture brings with it numerous challenges for biological control.

BIOLOGICAL DIVERSITY

Over the last couple of decades, the importance of IAS on biological diversity has become increasingly recognized (UNEP 2003). The Convention on Biological Diversity explicitly recognized the risk posed by IAS in Article 8h. This article specifically calls on Parties to "as far as possible and as appropriate: prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species." In 2002, the sixth Conference of the Parties (COP 6), adopted a set of guiding principles on how to develop effective strategies to minimize the spread and impact of IAS and a program of work for the implementation of Article 8(h). One of the principles addressed control of IAS and noted that effective control will often rely on a range of integrated management techniques, including mechanical control, chemical control, biological control, and habitat management.

TRENDS IN BIOLOGICAL CONTROL AND IPM RESEARCH

ANALYTICAL APPROACH

Given the demand for biological control and as part of the process of assessing the opportunities and challenges, the trends in knowledge generation and application based on published material abstracted for the CAB International Database (CAB abstracts) of global research in applied life sciences including, agriculture, forestry and the environment among other subjects were analyzed. Over 220,000 new records are added to the database each year, from over 6,000 academic journals and 3,500 other documents, including other serials, books, 'grey' literature and conference proceedings. The database has an international coverage, including research from over 140 countries in 50 languages.

The analysis itself was kept simple and essentially focused on number of abstracts referencing specific search terms. Firstly we examined the number of publications on 'biological control or biocontrol.' These were further categorized on basis of geographic regions. For each region 3-4 representative countries were selected based on size, history of biological control research or presence of research institutions working in the area. The regions/countries were as follows:

- Africa - Benin, Kenya, Nigeria and South Africa
- Asia - China, India and Indonesia
- South America - Brazil, Colombia and Chile
- Caribbean and Central America - Cuba, Costa Rica, Jamaica and Trinidad and Tobago
- U.S.A.

The number of publications referencing particular biological control approaches (classical and augmentation) on a global basis was also determined. This was also done for other terms which were directly relevant to biological control namely: integrated pest management, farming systems research (incorporates participatory research) and 'invasive and species'. For comparison, an assessment of the number of publications on biotechnology, being a relatively new field was also done.

It is acknowledged that the analyses might have precluded relevant material which did not reference the specific search terms used or particular geographic areas. Additionally some search terms especially invasive or species may include publications unrelated to invasive species. Additionally biases in abstracting or inherent inefficiencies or gaps might introduce further complexities. Nevertheless, it is felt that the trends generated are sufficiently robust and indicative of the real situation.

THE OUTCOMES

During the period 1995-2004, the number of publications which directly reference biological control or biocontrol has ranged between 3405 and 4530 well below the 1990 number of 4856 (Fig.1). However, the general trend appears to be one of little growth, even decline, in 2001-2004, especially when compared to the trends in other fields such as biotechnology which rose from less141 publications in 1980 to 11, 878 in 1990 and over 12,000 1995-2000 (Fig. 2). After 2000, the number of publications in biotechnology also appears to have undergone a dramatic decline.

The number of publications which make specific reference to particular country groupings ranged between 19-37% of the global total for each year (average 22%). An analysis of these by geographic areas is given in Fig. 3. For Africa, this number was 37 rising to a high of 99 in 1990. Between 1995-2004 the number ranged between 48-76 but generally there was no growth. The highest number for the Caribbean and Central America was 40 in 1985 and 2002. Between 1985 and 2003, the number fluctuated between 18-40 with the lowest being recorded in 2004. The general trend in recent years has been one of decline. South America saw a growth between 1980-1996, rising from 63 to 106. The ensuing period was characterized by inconsistent growth with a maximum of 143 being attained in 2002 followed by a decline. In Asia, there was growth from 151-445 between 1980-85 followed by a decline (1985-95). This was followed by growth over the period 1995-2000 which flattened out in subsequent years. In the U.S.A., the period 1980-85 was characterized by growth from 307 to 654 publications but subsequently there has been a general decline.

Fig. 4a gives the number of publications referencing augmentation and classical biological control specifically. For augmentation biological control, the number has remained relatively low with little growth, fluctuating between 3-26 publications. Although there was growth (2-53) in the early period (1980-90), the number for classical biological control has varied widely in subsequent years (22-60) with no clear trend. For IPM, there has generally been growth ranging from 129-1025 with a maximum being recorded in 2002 (Fig. 4b). 1980-1990 saw a growth of farming systems research publications from 20-97 followed by a relative flattening (1990-2000) and a subsequent decline. The new area of IAS has seen a consistent increase from 6-520 in 2004 (Fig. 4b).

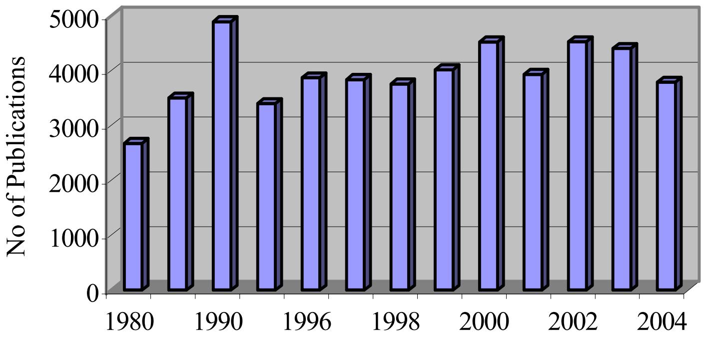

Figure 1. Publications on biological control over the period 1980-2004.

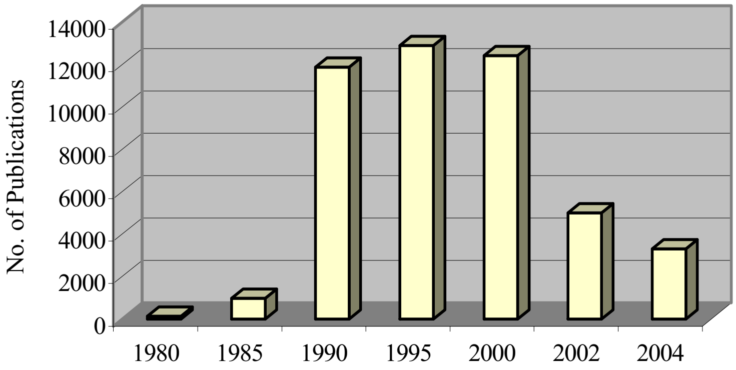

Figure 2. Publications on biotechnology over the period 1980-2004.

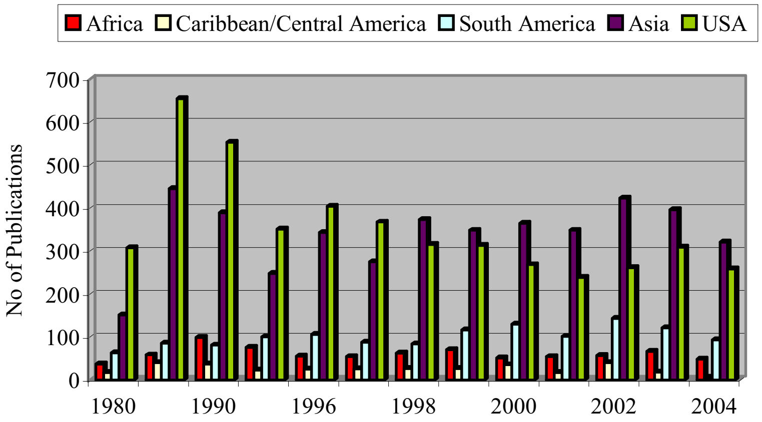

Figure 3. Distribution of publications referencing particular geographic areas.

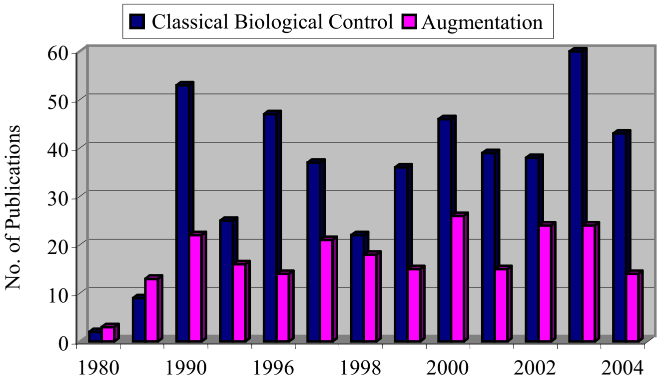

Figure 4a. Global publications on classical and augmentation biological control.

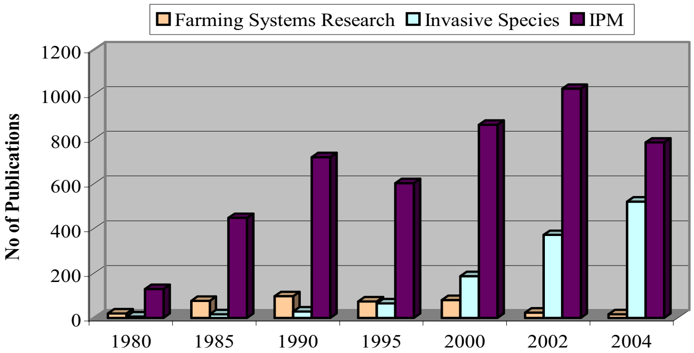

Figure 4b. Publications referencing 'farming systems research', invasive species and IPM.

DISCUSSION

Solving the problems associated with hunger and poverty or protection of biological diversity is a complex matter. Solutions will require an integrated multi-sectoral approach comprising of policy and technical imperatives. The first five years of implementation of the MDGs have elapsed. A recent assessment of progress showed that while some regions had made progress many others were largely off-track (UN Millennium Project 2005b).

Accepting that biological control is a small but nevertheless a very important component, intuitively one would expect to see increased activity as evidenced by published works. The global trends could perhaps best be described as stagnant. This pattern is also reflected in the geographical analysis and in some cases such as the U.S.A., a decline. A comparison of biological control with biotechnology, a relatively new field shows dramatic contrast.

The number of articles on classical biological control varied considerably over the study period, perhaps reflective of the opportunistic nature of such research. Overall, the number was surprisingly low while at the same time the number of articles on invasive species increased. There has been little growth in augmentation biological control over the years yet the potential for exploitation of this approach is recognized even by industry (Guillon, 2004). Indeed it is unfortunate that tremendous successes such as those achieved in the development biological pesticides against locusts have not been duplicated (Lomer *et al.* 2001). Overall, the results suggest that supporting research has not grown. There has been steady growth in IPM over the research period. While much emphasis has been placed on participatory approaches for transfer of ecological pest management strategies captured in CAB abstracts as farming systems research, there appears to have been little growth in published works on the subject.

It has been argued that much Development work is not amenable to publication in forms such as those abstracted in CAB abstracts. Notwithstanding this argument, the historical development of human endeavor in science and development has included published material on the generation as well as application of knowledge. We therefore argue that growth in a particular field should also be reflected in the published literature. This is clearly reflected in the case of biotechnology.

While diminished funding for research has been a constraint across the globe, the renewed interest in fulfilling the MDGs provides an opportunity for applying biological control. Challenges such as increased regulation for classical biological control will need to be surmounted. Overall however, the prognosis is not good and the challenge will be for biological control practitioners to ensure that the immense potential benefit from the approach is brought to bear on the pressing problems facing the world at the moment.

ACKNOWLEDGEMENTS

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CLASSICAL BIOLOGICAL CONTROL OF CITRUS PESTS IN FLORIDA AND THE CARIBBEAN: INTERCONNECTIONS AND SUSTAINABILITY

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ABSTRACT

Beginning in 1993, Florida's citrus industry has been invaded by citrus leafminer (*Phyllocnistis citrella* Stainton, Lepidoptera: Gracillariidae), brown citrus aphid (*Toxoptera citricida* Kirkaldy, Homoptera: Aphididae), and the Asian citrus psylla (*Diaphorina citri* Kuwayama, Homoptera: Psyllidae). The source(s) of these pests remain unknown but other countries in the Caribbean, as well as Central and South America, also have suffered invasions by these pests. Brown citrus aphid and Asian citrus psylla are vectors of serious citrus diseases (citrus tristeza virus and greening disease, respectively), while citrus leafminer damage provides openings for invasion of the citrus canker pathogen into the foliage. All three pests were considered suitable candidates for classical biological control. Dr. Ru Nguyen (Division of Plant Industry, Gainesville, Florida) and I have collaborated on importing, evaluating, rearing and releasing parasitoids for each pest into Florida's 860,000 acres of citrus between 1993 and the present. Two parasitoids (*Ageniaspis citricola* Logvinovskaya, Hymenoptera: Encyrtidae and *Cirrospilus quadristriatus*, which was subsequently determined to be *C. ingenuus* Gahan, Hymenoptera: Eulophidae) of the citrus leafminer were imported from Australia, Thailand, and Taiwan with the assistance of several scientists. Both parasitoids have established in Florida, and *A. citricola* has become the dominant parasitoid while *C. ingenuus* has had no apparent effect. *Ageniaspis citricola* has been supplied to colleagues in the Bahamas, Bermuda, Brazil, Chile, Mexico, Honduras, and several other countries from our rearing program. In all cases, *A. citricola* was provided free of charge along with information on rearing methods, as well as the risk assessment that we developed prior to obtaining release permits from the Florida Department of Agriculture and Consumer Services and the U.S. Department of Agriculture Animal and Plant Health Inspection Service (APHIS). Such information assisted the recipients in obtaining local release permits, thus reducing the costs of importation and release for these agencies.

Two other parasitoids were imported for control of the Asian citrus psylla: *Tamarixia radiata* Waterston (Hymenoptera: Eulophidae) and *Diaphorencyrtus aligarhensis* (Shafee, Alam and Agarwal) (Hymenoptera: Encyrtidae). The parasitoids were obtained through the kind assistance of colleagues in Taiwan. Again, we have made both parasitoids available to coun-

tries in the Caribbean, upon request, along with rearing methods and our risk assessment data.

Finally, the parasitoid *Lipolexis scutellaris*, which was later designated *L. oregmae* Gahan (Hymenoptera: Aphidiidae), was imported from Guam for a classical biological control program directed against the brown citrus aphid. This parasitoid and our data have been provided upon request from colleagues in several locations (Hoy and Nguyen 2000c).

Classical biological control historically has had an ethos that fostered cooperation, interconnections, and sharing of resources and knowledge. This ethos must be maintained if classical biological control is to be sustained as a viable pest management tactic. A few governments recently have behaved as if their natural enemies are national resources that require extensive financial remuneration; this attitude will threaten the sustainability of classical biological control. We must share information and resources in order to win our struggle to manage invasive pests.

INTRODUCTION

The objective of this paper is to provide an overview of three classical biological control projects directed against invasive citrus pests in Florida. In addition, I will provide a personal perspective on several issues limiting the sustainability of classical biological control, and make a plea that communication needs to be improved if classical biological control is to be sustainable in the region.

Beginning in 1993, Florida's citrus has been invaded by three significant pests: the citrus leafminer (*Phyllocnistis citrella*), the brown citrus aphid (*Toxoptera citricida*), and the Asian citrus psylla (*Diaphorina citri*). These invasions have created serious disruptions to the integrated pest management program, which is based on biological control of scale insects, mealybugs, mites, and whiteflies (Browning and McCoy 1994; Hoy 2000; McCoy 1985). The majority of citrus pests prior to 1993 were under substantial biological control and Florida citrus growers could manage diseases and most arthropod pests with the use of oil and copper sprays once or twice a year, especially if their crop was destined for juice production (because cosmetic damage is not an issue).

PEST STATUS OF INVADERS

After each new invasion, the introduced pests multiplied and spread rapidly throughout Florida's citrus, causing economic damage. For example, the citrus leafminer colonized 860,000 acres within a year after its detection (Heppner 1993; Hoy and Nguyen 1997). Population densities were often extremely high, despite the presence of generalist natural enemies such as spiders, lacewings, ants, and eulophid parasitoids (Browning and Peña 1995). Densities of the citrus leafminer were so high that fruits and stems, in addition to foliage, were attacked (Fig. 1) (Heppner 1993). Growers repeatedly sprayed their trees, especially nursery trees and young groves, in a futile effort to suppress the leafminer populations. Subsequently, the citrus leafminer has been implicated as exacerbating the spread of citrus canker in south Florida, where this disease is the target of an eradication program (Gottwald *et al.* 2001).

Figure 1. Citrus leafminer damage on citrus foliage (left) and fruits (right). An operational economic injury level is estimated to be less than 1 leafminer per leaf. UGA1390033, UGA1390034

The brown citrus aphid can be a direct pest of tender new citrus foliage (= flush) (Fig. 2), causing shoot deformation and production of sooty mold. The aphid completes one or two generations before the flush hardens off and then alate aphids are produced. However, the concern over the invasion of the brown citrus aphid was the fact that this aphid is a very efficient vector of *Citrus tristeza virus* and accentuated by the knowledge that approximately one-fourth of Florida's citrus was planted on rootstock susceptible to the disease caused by the virus (Yokomi *et al.* 1994). This acreage has had to be replanted on tristeza-tolerant rootstock at great expense.

Figure 2. Brown citrus aphids develop on tender new shoots of citrus. The ephemeral aphid populations make it difficult to sample for parasitoids. UGA1390035

The Asian citrus psylla is a vector of the bacterium that causes greening, one of the most serious diseases of citrus in Asia (Gottwald *et al.* 2001; Halbert *et al.* 2000; Knapp *et al.* 1998; Whittle 1992). Psyllids also can cause direct feeding damage to young shoots (Fig. 3). The pest apparently invaded Florida without the greening pathogen (Hoy *et al.* 2001), but Florida's citrus is vulnerable to the disease now that the insect vector is well established (Knapp *et al.* 1998).

Figure 3. Asian citrus psylla: orange eggs on tender flush (left) and adults feeding on mature foliage (right). Adults can survive over the winter on mature foliage, which leads to a lag in populations of their host-specific parasitoid, *T. radiata*, in Florida in spring. Psyllid nymphs, which are hosts for the *T. radiata*, can develop only on tender new growth. UGA1390036, UGA1390037

The citrus leafminer, Asian citrus psylla, and the brown citrus aphid all feed on tender new growth (flush), which can potentially reduce tree growth or yield, although economic injury levels for these pests have not been determined for all citrus cultivars in Florida. Because Florida citrus receives rainfall all year, management of pests that attack the flush is especially difficult because populations can be high between March and October each year due to the production of four or five major flush cycles.

HOW DID THESE PESTS INVADE?

The method by which these pests invaded Florida remains unknown, although it is likely that the increased trade and tourism has made invasions more frequent (Enserink 1999; Frank and McCoy 1992). It appears that Florida, and other tropical and subtropical regions are especially vulnerable to invasions and the apparent inability of quarantines and regulatory agencies to stem the flow of pest arthropods into new regions from around the world will continue to create new opportunities for classical biological control (York *et al.* 2005). Because the IPM program in Florida's citrus is so heavily dependent on biological control, I believe we are on a 'biological control treadmill', rather than the more common 'pesticide treadmill', because new pests need to be controlled in a compatible manner with the long-established biological control of our exotic pests (Hoy 2000).

CLASSICAL BIOLOGICAL CONTROL

All three invaders were considered suitable candidates for classical biological control and Dr. Ru Nguyen (Division of Plant Industry, Gainesville, Florida) and I have collaborated on importing, evaluating, rearing and releasing parasitoids for each pest into Florida's 860,000 acres of citrus from 1993 to the present.

CITRUS LEAFMINER

Two parasitoids (*A.* and *C. quadristriatus*, now *C. ingenuus*) of the citrus leafminer were imported from Australia, Thailand, and Taiwan (Hoy and Nguyen 1997, Hoy and Nguyen 2003). The first collections were made possible through the kind assistance of Dan Smith, of the Queensland Department of Primary Industries in Australia. Both parasitoids had been imported into Australia and undergone risk assessment there (Neale *et al.* 1995). Because the climate of Queensland matches that of Florida relatively well, we chose to collect parasitoids there first. Dan Smith generously provided me with field assistance and data that facilitated our efforts to obtain rapid permission to release *A. citricola* in Florida.

The release of *A. citricola* in Florida may have achieved a record for least time from importation into quarantine until release; I returned from Australia on a Monday (April 25, 1994) with large numbers of adults and pupae of *A. citricola*, and Dr. Nguyen and I recognized that we would 'waste' many of these adults due to a lack of space and hosts in our quarantine facilities. Because we had written a draft request to release *Ageniaspis* prior to my travel to Australia, based in part on the information provided by Australian scientists from their risk analysis, we were able to submit our request to release *A. citricola* to the Division of Plant Industry for review on Tuesday, which immediately submitted it to the USDA-APHIS for review. Permission to release *A. citricola* was facilitated by John LaSalle at the British National Museum, who confirmed the identity of the parasitoid after we sent specimens to him by overnight shipment. The Division of Plant Industry of the Florida Department of Agriculture and Consumer Services assisted in a rapid review, as did the USDA-APHIS, and Dr. Nguyen and I had permission to make the first releases of adults of *A. citricola* into populations of citrus leafminers by Friday (April 29) (Hoy and Nguyen 1997).

Ageniaspis citricola pupae are produced within the pupal chamber of the citrus leafminer; this encyrtid is polyembryonic and females typically deposit two eggs per oviposition event, one of which develops into a male. The second egg twins, producing two daughters (Zappalà and Hoy 2004); this reproductive strategy may contribute to its success when host populations are low. *Ageniaspis citricola* and *C. ingenuus* have both established in Florida, with *A. citricola* now the dominant parasitoid of the citrus leafminer (Hoy and Nguyen 1997; Hoy *et al.* 1995; Hoy *et al.* 1997; Peña *et al.* 1996; Pomerinke and Stansly 1998; Smith and Hoy 1995; Villanueva-Jimenez and Hoy 1998a; Villanueva-Jimenez *et al.* 2000) (Fig. 4).

Cirrospilus ingenuus has had no apparent effect in reducing citrus leafminer densities, although this eulophid has established in south Florida (LaSalle *et al.* 1999). In retrospect, however, Dr. Nguyen and I regret releasing this ectoparasitoid because we discovered, after the release, that it could hyperparasitize *A. citricola* (Hoy and Nguyen 1997).

Figure 4. *Ageniaspis citricola* pupae.
UGA1390038

Ageniaspis citricola has many of the attributes of an effective natural enemy (Rosen and Huffaker 1983). It is host specific (Neale *et al.* 1995), able to locate low-density leafminer populations and to discriminate between previously parasitized hosts (Edwards and Hoy 1998; Zappalà and Hoy 2004), although it is not able to perform well in regions with low relative humidity (Yoder and Hoy 1998) and lags behind citrus leafminer populations in the spring in Florida (Villanueva-Jimenez *et al.* 2000). Citrus leafminer populations decline to very low densities over the winter when there is no new flush and typically only a very few citrus leafminers are found in the first flush cycle in spring. Since *A. citricola* is host specific and polyembryonic, populations of *A. citricola* increase from very low densities to detectable levels by the second flush cycle in Florida and, if not disrupted by drought or pesticide applications, become the dominant parasitoid, capable of parasitizing up to 100% of the leafminer pupae by the fall, which decreases the number of citrus leafminers able to overwinter (Villanueva-Jimenez *et al.* 2000; Zappalà *et al.*, unpublished). A second population of *A. citricola* was imported from Taiwan, and this population appears to be a cryptic species (Alvarez and Hoy 2002; Hoy *et al.* 2000). Although it was released in Florida, we have no evidence of its establishment (Alvarez and Hoy 2002).

During 2000 and 2001, Florida suffered a drought that was especially serious in the spring, leading to a greater lag between populations of *A. citricola* and the citrus leafminer than before. This led us to consider release an additional parasitoid that would have the potential to suppress citrus leafminers early in the season when *A. citricola* densities are very low and a long list of potential candidates was reviewed (Heppner 1993; Schauff *et al.* 1998). Such a parasitoid ideally would tolerate lower relative humidities than *A. citricola* and might have an alternative host on which it could overwinter. With the assistance of Dr. G. Siscaro of the University of Catania in Italy, we imported the eulophid *Semielacher petiolatus* Girault (Hymenoptera: Eulophidae) (Fig. 5) for evaluation in quarantine (Hoy *et al.* 2004). This parasitoid had established in citrus in the Mediterranean and promised to have a greater tolerance of low relative humidities (Ateyyat 2002; Lim *et al.* unpublished). It was also reported

Figure 5. *Semielacher petiolatus* female.
UGA1390039

to use alternative hosts, including a dipteran leafminer in the genus *Liriomyza* (Massa *et al.* 2001), which could provide hosts for *S. petiolatus* during the winter when citrus leafminer populations are extremely low in Florida.

After importing *S. petiolatus* into quarantine we demonstrated that it could develop on the citrus leafminer, but that it often superparasitized (Lim and Hoy 2005). Additional research confirmed that *S. petiolatus* does not discriminate between unparasitized and parasitized hosts with its own progeny or with the endoparasitoid *A. citricola* and could potentially disrupt the substantial control provided by the host-specific *A. citricola* (Lim *et al.* unpublished). Also, it did not parasitize *Liriomyza trifolii* Burgess (Diptera: Agromyzidae), a common and abundant leafminer pest of vegetables during the winter in Florida (Lim *et al.*, unpublished). After this risk analysis in quarantine, we recommended against releasing *S. petiolatus* in Florida because of the information previously mentioned and also because there was no evidence that it would provide control of the citrus leafminer during the spring when populations of *A. citricola* lag behind those of its host. Although it is difficult to predict with any certainty the outcome of potential releases of *S. petiolatus* in Florida, the potential benefits do not appear to justify the potential risk. In regions where *A. citricola* is not an effective parasitoid, it is possible that releases of *S. petiolatus* are appropriate, but independent risk analyses should be conducted in each country.

Ageniaspis citricola has been supplied to colleagues in the Bahamas, Bermuda, Brazil, Chile, Mexico, Honduras, and several other countries (including Morocco, Italy, Spain) from our rearing program (Hoy and Jessey 2004; Villanueva-Jimenez *et al.* 1999). In all cases, *Ageniaspis* was provided free of charge along with information on rearing methods (Smith and Hoy 1995), studies of its biology and susceptibility to pesticides (Alvarez and Hoy 2002; Edwards and Hoy 1998; Hoy *et al.* 2000; Villanueva-Jimenez and Hoy 1998b; Yoder and Hoy 1998; Zappalà and Hoy 2004) and the risk assessment data that we developed prior to obtaining release permits from the Florida Department of Agriculture and Consumer Services and the U.S. Department of Agriculture Animal and Plant Health Inspection Service (APHIS). Such information was intended to assist the recipients in obtaining permission to make releases, thus reducing the costs of importation, evaluation and release for local regulatory agencies.

ASIAN CITRUS PSYLLA

Two host-specific parasitoids were imported for control of the Asian citrus psylla: *T. radiata* and *D. aligarhensis* (Fig. 6) (Hoy and Nguyen 1998). Both parasitoids were obtained through the kind assistance of P. K. C. Lo of the Taiwan Agricultural Research Institute and had shown efficacy in Taiwan and on Reunion Island (Aubert and Quilici 1984; Chien 1995; Chien and Chu 1996; Chu and Chen 1991). Before we could obtain permission to release these parasitoids we had to 'prove a negative', namely that they did not harbor the greening pathogen. This led us to develop a polymerase chain reaction (PCR) test with a known level of sensitivity for the greening pathogen (Hoy and Nguyen 2000a; Hoy *et al.* 1999; 2001). Both parasitoids appear to be host specific and were mass reared and released throughout Florida, where *T. radiata* is now widely distributed (Hoy *et al.* 2000; Hoy *et al.* unpublished; Skelley and Hoy 2004). The status of *D. aligarhensis* is unclear because only a few recoveries have been made (Hoy *et al.*, unpubl.).

Again, we have made both parasitoids available to colleagues in the Caribbean, upon request, as well as our rearing methods, information on the parasitoid's biology (McFarland and Hoy 2001; Skelley and Hoy 2004) and our risk assessment data.

Figure 6. Asian citrus psylla nymphs parasitized by *Tamarixia radiata* (left) and *Diaphorencyrtus aligarhensis* (right). Exit holes for *T. radiata* and *D. aligarhensis* are on the thorax and abdomen, respectively, making it easy to discriminate parasitism by the two parasitoids in the field. UGA1390040, UGA1390041

BROWN CITRUS APHID

The parasitoid *Lipolexis scutellaris*, which was later designated *L. oregmae* by Miller *et al.* (2002), was imported with the assistance of Ross Miller in Guam for a classical biological control program directed against the brown citrus aphid (Hoy and Nguyen 2000b,c). Petr Stary provided taxonomic identifications and other information, and Susan Halbert, of the Florida Department of Agriculture and Consumer Services, provided expert advice on preparing the application to release *L. scutellaris* in Florida (Hoy and Nguyen 2000c).

This parasitoid was easy to rear on the brown citrus aphid on citrus trees after the discovery of its unusual behavior of causing parasitized aphids to walk off the tree to mummify in the soil at the base of the trees (Hill and Hoy 2003). We treat the soil in the potted trees with a 2-3% sodium hypochlorite solution prior to exposing the trees to aphids and parasitoids to control fungal pathogens of the parasitoid mummies (Hill and Hoy 2003, Persad and Hoy 2003a,b; Walker and Hoy 2003b).

Laboratory analyses indicated that *L. oregmae* and *Lysiphlebus testaceipes* (Cresson), a parasitoid already established in Florida and a natural enemy of the brown citrus aphid, are not intrinsically superior to each other (Persad and Hoy 2003a). Beginning in 2000, releases were made throughout the state over several years, and *L. oregmae* seems to have established (Hoy *et al.* unpublished; Persad *et al.* 2004). However, populations of *L. oregmae* are low in Florida, perhaps because this parasitoid is preyed upon by abundant red imported fire ants, *Solenopsis invicta* Buren (Hymenoptera: Formicidae), in citrus groves (Hill and Hoy 2003; Persad and Hoy 2004; Walker and Hoy 2003). Red imported fire ants will feed on mummies in the soil and also will climb into the tree to remove parasitized aphids, leaving behind the unparasitized pests (Persad and Hoy 2004). A PCR test that allows us to sample aphids and assay them for the presence of either *L. oregmae* or *L. testaceipes* allowed us to obtain qualitative data on distribution and spread of *L. oregmae* in Florida (Persad *et al.* 2004). This technique is sufficiently sensitive that we could grind up 500 aphids of which only one was parasitized by *L. oregmae*, yet get a positive PCR product??. Once we know that *L. oregmae* is present in a grove, additional samples can be taken to ascertain the relative abundance of *L. testaceipes* and *L. oregmae*.

Because *L. oregmae* attacks black citrus aphid (*T. aurantii* Boyer de Fonscolombe), spirea aphid (*Aphis spiraecola* Patch), cotton aphid (*Aphis gossypii* Glover), and cowpea aphid (*Aphis craccivora* Koch), on citrus and other crops in Florida, it has alternative hosts that can sustain it when brown citrus aphid populations are low (Hoy and Nguyen 2000c). These aphids also are imported pests of citrus in Florida so there was reduced concern about the nontarget effects of *L. oregmae*.

Releases of *L. oregmae* were also made in Bermuda during the July of 2002, but its establishment has not yet been confirmed. Shipments of *L. oregmae* have been requested by scientists in CARDI for release in Jamaica and permits have been issued by the Jamaica Department of Agriculture.

CONSTRAINTS TO CLASSICAL BIOLOGICAL CONTROL IN THE REGION

Biological control is, in my opinion, at a turning point in its development as a discipline. It could become a more important component of pest management programs if we are able to resolve concerns about potential risks to biodiversity (Howarth 1991; Simberloff and Stiling 1996). If we are unable to resolve those concerns, there could be less classical biological control conducted in the future, rather than more. Several constraints need to be eliminated or reduced.

INTERNATIONAL COOPERATION

International cooperation is crucial to the success of classical biological control programs (FAO 1997). Such cooperation will become even more important in the future because we lack sufficient resources to conduct classical biological control projects in isolation. Scientists in Australia, Taiwan, Thailand and Guam were instrumental in our ability to respond rapidly to the three invasive species in Florida's citrus. They provided assistance, information, and resources that enabled us to respond rapidly to the threat of these invaders. Historically, classical biological control has depended on such generous international cooperation and it needs to be maintained. The belief that natural enemies are national resources that should be sold is detrimental to the continued success of classical biological control. Indeed, biological control scientists may wish to become even more proactive about cooperating in classical biological control of citrus pests and begin sharing information about the natural enemies of potential invaders in advance, perhaps using websites as a repository of information.

THE FUTURE OF CLASSICAL BIOLOGICAL CONTROL

It is ironic that, just when there is an increased focus on and potential role for biological control of arthropod pests, serious concerns about biodiversity could restrict its use. Current constraints also include the deployment of relatively few resources, at least compared to those available to develop new pesticides or transgenic crops. Most of the funding for classical biological control is obtained from public sector sources, which have not had sufficient increases in their budgets to meet the current and potential demand.

The history of biological control of arthropod pests is filled with outstanding examples of successes and a remarkably low number of ecological problems (Frank 1998; Funasaki *et al.* 1998). Despite this, we will have to embrace increased oversight and consideration of ecological issues. The question then becomes: how best can we achieve appropriate oversight without hampering the benefits of biological control?

One solution for biological control practitioners might be to focus more frequently on natural enemy species that are narrowly host- or prey-specific. Scientists working on biological control of weeds already have accepted this constraint, and undergo external reviews of the biology, behavior, and host specificity of the natural enemies they wish to release. It also will be useful to have more thorough scientific peer review before natural enemies are released for classical biological control of arthropod pests (Ewel *et al.* 1999). Despite increased peer review, it may be impossible to eliminate all risk concerns.

Risk analyses are neither simple nor easy. Blanket criticisms of biological control are of little constructive value in the absence of comparative data on the alternatives, including doing nothing (Thomas and Willis 1998). Furthermore, biological control has numerous public benefits, including relatively inexpensive and long-term control, and reduced pesticide applications, which can result in reduced negative effects on ground water, nontarget species, human health, and worker safety.

RECOMMENDATIONS

- Sharing of information is essential if classical biological control is to be cost effective; providing information on risk assessments, unpublished data on biology and ecology, and copies of hard-to-find literature on web sites would be an efficient method of sharing key information that will allow scientists and governmental agencies to evaluate potential introductions of natural enemies for classical biological control in other countries. At present, this form of sharing occurs on an *ad hoc* basis. The University of Florida has provided resources and technical support to assist us in providing information in this manner, but it may be useful to consider developing a centralized and international site where practitioners of classical biological control can deposit such information.

- If possible, scientists and organizations should provide colonies of natural enemies upon request to others at the lowest possible cost. Reimbursements for shipping and rearing costs are appropriate, but tying the request for natural enemies to large-scale funding for the donor could delay or preclude the introduction of key natural enemies in a timely fashion.
- Funding for post-release evaluations is particularly difficult to obtain because most funding is provided for collection, importation, rearing and release. Sharing of information and colonies would produce savings that could be used to obtain needed data on the effects of the imported natural enemies on the target pests subsequent to their establishment. Such studies should occur after equilibrium has developed between the pest and its natural enemies in the new environment. In addition, funding needs to become available for evaluating the impact of key importations on nontarget species. Again, this type of funding remains relatively rare, but is essential if we are to develop the data to understand the long-term costs and benefits of classical biological control.

CONCLUSIONS

Our collective responses to these challenges will determine how effectively classical biological control is maintained as a viable discipline. We have valuable new tools, including molecular genetic methods, which will allow us to answer previously intractable questions in systematics, ecology, behavior and quality control. The use of pesticides no doubt will decline and the ones used may be less hazardous to the environment. The demand for classical biological control could increase in the 21st century, especially if we respond effectively to concerns regarding potential negative environmental consequences attributed to biological control. When risks and benefits are compared appropriately, classical biological control should fare very well in comparison to the risks and benefits associated with other pest management tactics such as chemical control, cultural practices, host plant resistance (including the use of transgenic crops), and genetic control.

The potential risks and benefits of classical biological control must be calculated in a realistic manner because it is not possible to manage pests without any risk. As pointed out by Lubchenco (1998), our world is changing and we now live on a "...human-dominated planet. The growth of the human population and the growth in amount of resources used are altering Earth in unprecedented ways." Lubchenco (1998) concluded that the role of science now includes "...knowledge to reduce the rate at which we alter the Earth systems, knowledge to understand Earth's ecosystems and how they interact with the numerous components of human-caused global change, and knowledge to manage the planet". This change in perception of the status of ecosystems must become widespread among scientists and others if appropriate policy decisions are to be made. To increase awareness of this change in perception, perhaps a new term should be coined to describe our role and responsibilities as 'planet ecosystem management' or 'PEM' (Hoy 2000). Humans are, in fact, remodeling the entire global ecosystem.

Classical biological control historically has had an ethos that fostered cooperation, interconnections, and sharing of resources and knowledge. This ethos must be maintained if classical biological control is to be sustained as a viable pest management tactic. A few governments recently have behaved as if their natural enemies are national resources that require extensive financial remuneration; this attitude will threaten the sustainability of classical biological control. We must share information and resources in order to win our struggle against invasive pests.

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CONSERVATION AND ENHANCEMENT OF BIOLOGICAL CONTROL HELPS TO IMPROVE SUSTAINABLE PRODUCTION OF BRASSICA VEGETABLES IN CHINA AND AUSTRALIA

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ABSTRACT

Brassicas comprise a major group of vegetable crops in Zhejiang Province, China and southeast Queensland, Australia. In Zhejiang, heavy reliance on chemical control to manage insect pests in brassica vegetable production has resulted in insecticide resistance, increased costs of pest control and insecticide residues hazardous to human health. In southeast Queensland, reliance on chemical control has also resulted in increased cost of pest control, control failures due to insect resistance and reduced profits. To improve sustainable production of brassica vegetables in the two regions, a group of Chinese and Australian scientists have undertaken a joint project to develop practical integrated pest management (IPM) strategies for these crops.

In both regions, major efforts have been made to evaluate the complexes of endemic natural enemies under different pest management practices, and to conserve and enhance these natural enemies as the central elements of effective management programs. In Zhejiang, field trials were conducted across crops, seasons and localities to test and improve an IPM system that emphasized the use of proven action thresholds for different crop growth stages and strategic application of selective insecticides to promote the impact of natural enemies. Compared with conventional methods, IPM practices were associated with substantially higher natural enemy activity, a 20-70% reduction in input of insecticides, and no yield loss. The improved IPM system has been implemented to various degrees in major vegetable production areas in Zhejiang, and has improved the safety and profitability of production.

In southeast Queensland, as an important part of the IPM development and implementation effort, a three-year experimental field study was conducted to evaluate the impact of endemic natural enemies on independent farms practicing a range of pest management strategies. Natural enemy impact was greatest on farms adopting IPM and least on farms practicing insecticide intensive conventional pest control strategies. On IPM farms, the contribution of natural enemies to pest mortality permitted the cultivation of marketable crops with no yield loss but with an average of 70% less insecticide inputs compared to conventional farms.

The field studies and IPM implementation in China and Australia indicate that naturally occurring biological control can be substantially enhanced to form the central element of effective IPM programs and improve vegetable production. Demonstration of the effectiveness of biological control in the two regions through an international joint effort not only made the evidence more convincing but also promoted the adoption of the improved IPM strategies by farmers.

INTRODUCTION

Brassicas constitute a major group of vegetables in China. Depending on the region, brassicas account for 35-45% of all vegetable crops. In Zhejiang province, the proportion of brassica vegetables has decreased in recent years due to an increase in other vegetable crops, but they still account for approximately 30% of all vegetables and a total area of 235,000 ha was cultivated in 2004 (calculated on single crops). Brassica vegetables are mostly grown by small landholders (<0.5 ha) around urban centers, and in specialized production areas where farms can be much larger. The crop systems are complex and erratic, revolving around intercropping practices (growing more than one crop on a small piece of land at the same time) throughout the entire year. In Zhejiang, a complex of insect pests attacks brassica vegetable crops. The major species include the diamondback moth (DBM), *Plutelle xylostella* L. (Lepidoptera: Plutellidae), the cabbage white butterfly, *Pieris rapae* L. (Lepidoptera: Pieridae), the cluster caterpillars, *Spodoptera litura* F. (Lepidoptera: Noctuidae), the beet armyworm, *Spodoptera exigua* Hübner (Lepidoptera: Noctuidae), the green peach aphid, *Myzus persicae* Sulzer (Hemiptera: Aphididae), and the turnip aphid *Lipaphis erysimi* Kaltenbach (Hemiptera: Aphididae) (Liu *et al.* 1996).

The brassica industry in Queensland grows a total of 2,300 ha of crops per annum (Heisswolf *et al.* 1997). The major production region is the Lockyer Valley, a river system about 100 km inland from Brisbane and farm sizes range from 40-100 ha. Planting of crops begins in February (later summer) and weekly or fortnightly plantings are made until September (early spring), final harvests are collected in late spring/early summer. On many farms, regular weekly plantings used to be continuous and crops were grown all year around. A suite of lepidopterous pests attack brassica vegetable crops in the region. These include DBM, cabbage white butterfly, centre grub, *Hellulla hydralis* Guenee (Lepidoptea: Pyralidae), *Hellulla undalis* F. (Lepidoptea: Pyralidae), cabbage cluster caterpillar, *Crocidolomia pavonana* F. (Lepidoptea: Pyralidae), cluster caterpillar, and *Helicoverpa* spp. (Lepidoptera: Noctuidae). DBM has been the most difficult pest to manage, largely due to its resistance to a range of commonly used insecticides (Heisswolf *et al.* 1997).

In Zhejiang, the control of insect pests on brassica vegetable crops has relied heavily on the use of chemical insecticides since the 1970s, resulting in insecticide resistance, increased costs of pest control and insecticide residues hazardous to human health (Liu and Yan 1998; Liu et al. 1996). In southeast Queensland, reliance on chemical control in the 1970s and 1980s also resulted in increased cost of pest control, control failures due to insect resistance and reduced profits (Heisswolf et al. 1997). To improve sustainable production of brassica vegetables in the two regions, a group of Chinese and Australian scientists undertook a joint project to develop practical integrated pest management (IPM) strategies for these crops (Zalucki and Liu 2003).

A JOINT VENTURE IN IMPROVING BRASSICA IPM

This project was started in 1995 to build on existing studies to develop sound, sustainable brassica IPM strategies that significantly reduce pesticide hazards, and are acceptable to the growers in Zhejiang and Shanghai, east China, and Queensland, Australia. The project involved five institutes in China, working in close collaboration with two institutes from Australia (Liu *et al*. 1996; Zalucki and Liu 2003). The working strategy consisted of three overlapping and ongoing phases: problem definition, research and development, and implementation. Structured problem definition workshops, involving all groups of stakeholders and in particular farmers and extension workers, were organized at the start of the project to promote information flow, determine priority issues, address priority needs, and propose action plans (Liu *et al.* 1996). Work has since concentrated on the following five, interacting components: (1) survey and evaluation of natural enemies?, (2) rational application of insecticides, in particular promoting use of biological insecticides, (3) development of action thresholds, (4) development of management strategies through season-long in-field IPM trials, and (5) IPM implementation activities.

RESEARCH, DEVELOPMENT, AND IMPLEMENTATION IN EAST CHINA

SURVEY AND EVALUATION OF ARTHROPOD NATURAL ENEMIES

Regular sampling in both farmers' fields and unsprayed fields in Hangzhou showed that a range of parasitoids attack each of the major pests. For example, DBM is attacked by at least 8 species of parasitoids, of which *Cotesia plutellae* Kurdjumov (Hymenoptera: Braconidae), *Oomyzus sokolowskii* Kurdjumov (Hymenoptera: Eulophidae) and *Diadromus collaris* Gravenhorst (Hymenoptera: Ichneumonidae) are the major larval, larval-pupal and pupal parasitoids respectively (Liu *et al*. 2000). The cabbage white butterfly is attacked by a suite of at least 7 species of parasitoids, of which *Cotesia glomeratus* (L.) (Hymenoptera: Braconidae) and *Pteromalus puparum* L. (Hymenoptera: Pteromalidae) are often most abundant.

Insect parasitoids are active in fields despite the heavy use of chemical insecticides in the crop systems over the years. For example, in fields that have not been heavily sprayed during a growing season, parasitoids usually achieved 10-60% parasitism of DBM larvae and pupae during June to early July and September-November each year when DBM was most abundant (Liu *et al*. 2000). IPM field trials demonstrated that both parasitoids and arthropod predators were several-fold more abundant in fields that were sprayed with selective insecticides, than in fields that were sprayed with wide-spectrum chemical insecticides (Lin *et al.* 2002; Yu *et al.* 2002; Zhang *et al.* 1999).

EVALUATION OF BIOLOGICAL AND SELECTIVE INSECTICIDES

Biological and chemical insecticides were bio-assayed in the laboratory and tested in the field. A number of Bt and NPV products were shown to have high efficacy in killing the target pests with no side effects on the beneficials (Shi and Liu 1998; Shi *et al.* 2004). Other insecticides showing selectivity include abmectin, avermectin, spinosad and fipronil against DBM and *P. rapae*, chlorfluazuron and chlorfenapyr against *S. litura* and *S. exigua*, and imidacloprid against aphids (Guo *et al.* 1998; Guo *et al*. 2003; Zalucki and Liu 2003).

DEVELOPMENT OF ACTION THRESHOLDS

Laboratory and greenhouse trials demonstrated that several cultivars of common cabbage and cauliflower could endure some defoliation without reduction of head weight at harvest. There was evidence of over-compensation for defoliation at the pre-heading stage. However, the plants were more sensitive to defoliation at the cupping stage. For example, 10% defoliation of common cabbage (cultivar Jin-Feng No.1) at the pre-heading, cupping or heading stages respectively resulted in mean head weights at harvest 9.8% heavier, 4.3% lighter and 3.3% heavier than undamaged controls (Chen *et al.* 2002; Liu *et al.* 2004). These data were used to assist in developing action thresholds for practical application (Table 2). Of particular value was the characterization of crop growth stages sensitive to insect damage. Thus, farmers and extension officers were asked to monitor the insect pests more closely at both the seedling and cupping stages.

IPM FIELD TRIALS

Based on the findings of studies of various components and information from literature, management strategies were formulated and tested in the field to evaluate the effects of different management strategies on pest and natural enemy populations and to develop practical IPM guidelines and protocols. The major components in the IPM strategy included use of action thresholds in decision-making and strategic use of biological and selective insecticides (Tables 1 and 2). In each location, a field trial with a crop of approximately one ha was divided into 2-3 plots. Each plot was managed by an IPM or a conventional, insecticide intensive, approach for an entire season. Regular sampling was conducted through the season and pest control action was taken according to the guidelines in Tables 1 and 2. At the end of each trial, crop yield and quality, input of insecticides and levels of natural enemy activities of different plots were compared (Table 3). Field IPM trials with common cabbage were conducted in Hangzhou from 1996 to 2000 and in 2000 trials were conducted at five sites in Zhejiang and Shanghai (Lin *et al.* 2002; Liu *et al.* 2004; Yu *et al.* 2002; Zhang *et al.* 1999). In 2001 and 2002, field IPM trials with cauliflower, broccoli or Chinese cabbage were conducted at three sites in Zhejiang and Shanghai (Zalucki and Liu 2003). The results showed that biological and selective insecticides could offer effective control of all the insect pests and that the activities of natural enemies were promoted (Table 3). Compared with conventional practice, IPM practice could reduce insecticide input by 20-70%, with no risk of crop loss (Fig. 1; Zalucki and Liu 2003).

Table 1. Summary of designs of field IPM trials in China.

Treatment	Description	Application of insecticides
IPM	Use of action thresholds, apply biological and selective insecticides	Spray Bt for control of DBM and Pieris rapae, spray chlorfluazuron and NPV for control of *Spodoptera* spp. and spray imidacloprid for control of aphids
Conventional	Simulation of typical practice by farmers, or recording of farmer's practice	Basically calendar sprays with mixtures of broad-spectrum chemical insecticides such as chlorpyrifos, fenvalerate, methomyl, fipronil, and methamidophos

Table 2. Action thresholds (mean number of insects/plant) used in IPM treatment in China.

	Cabbage Growth Stages			
Pests	Transplants	Pre-heading	Cupping to Early Heading	Heading to Mature
Lepidoptera[a]	0.5	1.0	1.0	4.0
Aphids	5	500	500	2000

[a] Number of lepidopteran larvae were converted to "standard" insects by the following formula: 1 standard insect = 1 *Pieris rapae* = 1 *Spodoptera exigua* = 0.5 *Spodoptera litura* = 5 *Plutella xylostella*.

Table 3. Examples of results of field trials including plots managed with IPM or conventional (Con) pest control strategies in Hangzhou, China, in autumn 1998 and autumn 2000.

	1998		2000	
Assessments[a]	IPM	Con	IPM	Con
Mean head weight (kg)	1.23 a	1.11 a	1.18 a	1.02 a
% marketable heads	94.4 a	88.0 b	95.6 a	91.1 a
% heads without insect damage	52.5 a	16.7 b	76.7 b	96.7 a
Number of sprays[b]	7(8)	8(23)	3(5)	5(8)
Cost of insecticide application per ha (RMB Yuan)	2,700	3,780	680	1025
Mean % parasitization of DBM larvae	19.4 a	2.0 b	35.2 a	7.1 b
Mean % parasitization of DBM pupae	32.6 a	1.3 b	18.8 a	13.0 a

[a] Figures in the same row of the same year followed by the same letter do not differ ($p>0.05$, Student-t test).

[b] In the IPM treatment, usually one insecticide and only rarely a mixture of 2 insecticides was used per spray, while in the conventional treatment, usually a mixture of 2-3 insecticides was used per spray. Figure in brackets indicate the relative amount of insecticide input calculated on the basis of one insecticide in one spray at the recommended rates.

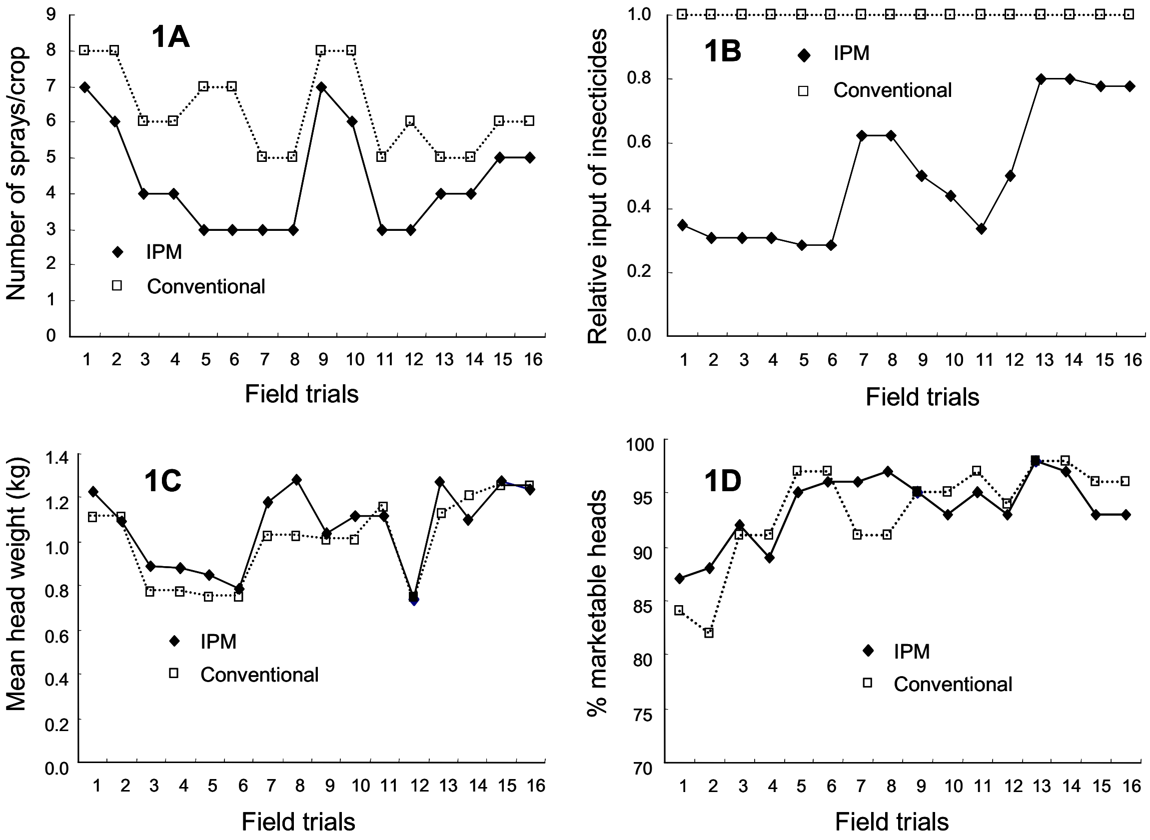

Figure 1. Comparison of insecticide input and crop yield between field plots managed by IPM or conventional approaches at each of 16 field trials at various locations in Zhejiang and Shanghai, China, from 1999 to 2001. 1A: number of insecticide applications per crop; 1B: relative quantity of insecticide input with that of conventional approaches set as unity (see footnote of Table 3 for further explanation); 1C: mean head weight in kg at harvest; and 1D: % of marketable heads.

IMPLEMENTATION

Implementation activities included grower involvement in field trials, field days and participatory workshops, frequent dissemination of fact sheets, as well as short training courses for extension officers and growers (Liu *et al.* 1996; Zalucki and Liu 2003). An independent project evaluation in the project areas showed substantial improvement in farmers' knowledge, attitude and approaches towards IPM (Liu and Qiu 2001). For example, by 2001, 36% of the growers in the project areas conducted regular monitoring of insect pests on their crops and usually tried to use biological or selective insecticides if required, compared with only about 20% in the non-project areas; growers in the project areas had more frequent contact with extension officers than growers in the non-project areas (Liu and Qiu 2001). An extensive survey by the agricultural departments in Zhejiang and Shanghai in late 2002 showed that in 10 major, project-associated production areas, which involved some 50,000 farming families and produced some 2 million tons of brassica vegetables in a year, input of chemical insecticides was reduced by 30-60% in a period of five years. Legally excessive pesticide residues on brassica vegetables from August to October (the season of the year when insecticides are mostly applied) were reduced steadily from 20-40% in the mid 1990s to 0-10% (0% in the central project areas) in 2002 (Zalucki and Liu 2003).

RESEARCH, DEVELOPMENT, AND IMPLEMENTATION IN SOUTHEAST QUEENSLAND, AUSTRALIA

DEVELOPMENT AND IMPLEMENTATION

The effort to develop an IPM approach for the control of insect pests in brassica vegetable crops in Queensland began in late 1980s when many growers encountered frequent spray failures with chemical insecticides. In many cases control failures were so severe that crops failed completely. A resistance management strategy was implemented in 1988 with widespread support of the industry. This strategy included a summer production break, improved spray application, an understanding of insecticide resistance and the need for insecticide rotation on farms (Heisswolf *et al.* 1997; Niemeyer 2004).

In the early 1990s, development work to reduce the reliance on conventional insecticides began by focusing on the crop system level of pest management and introducing Bt into the emerging IPM system. Research and extension activities involved a series of demonstration plantings at the local research station and on commercial farms. Data on pest activity, abundance of natural enemies, yields and quality of harvested products were collected. Results were then shared with growers and used to recommend improvements to management regimes with particular emphasis on spray decision making (Heisswolf *et al.* 1997; Niemeyer 2004).

Following the start of the joint brassica IPM project between Australian and Chinese scientists in 1995, more fields trials were conducted to focus on issues such as protocols for monitoring pests and parasitoids, action thresholds, insecticide spray coverage, and development of decision-making tools (Deuter and Liu 1999; Heisswolf *et al.* 1997; Zalucki and Liu 2003). Insect identification workshops were held for growers and field days were organized for growers to view the field trials and discuss the implications for improving pest management on their farms. Many growers started to appreciate the principles of IPM and recognized the potential impact of natural enemies and the capacity of crops to tolerate some damage particularly at the pre-heading stage. Seeing the benefits of IPM and the value of information exchange between growers and extension and research scientists, about 30 growers in the Lockyer Valley formed the Brassica Improvement Group in February 1998. This group met once a month during the growing season each year to share and exchange information with researchers, industry and other growers. These research and extension activities promoted the acceptance of IPM concepts and more and more growers gradually shifted from reliance on regular sprays of broad spectrum chemical insecticides to a reasonably integrated strategy, which included a combination of a summer production break, regular crop scouting, threshold-based decision making, strategic application of selective insecticides, and conservation of natural enemies (Deuter and Liu 1999; Furlong *et al.* 2004a; Zalucki and Liu 2003). One of the key elements in the IPM systems is always to start a growing season with a "soft approach", that is to spray a selective insecticide only if needed, to ensure conservation of natural enemies and to aid the promotion of their activities later in the season (Niemeyer 2004).

ON-FARM EVALUATION OF THE IMPACT OF NATURAL ENEMIES ON THE SUCCESS OF IPM

Adoption of IPM programs is usually gradual and slow (Trumble 1998), and the brassica IPM program in the Lockyer Valley has not been an exception. Despite the intensive development and implementation effort and wide support from the industry, growers varied in their perception and approaches to the alternative pest management strategies. By 2000, a wide spectrum of pest management practices, ranging from the conventional calendar sprays to reasonably sophisticated approaches, was observed on different farms (Furlong *et al.* 2004a). As many farms in the valley grow a comparable range of vegetable crops and the general features of the ecosystem (climate, soil type and non-crop vegetation) are similar throughout the area, the wide spectrum of pest management strategies on different farms offered a unique opportunity to measure the effect of pest management practices on pest and natural enemy populations and crop production at the farm level. Mechanical exclusion with cages and life table analysis were used as the major techniques in this on-farm evaluation study, and the major pest DBM was used as the target pest (Furlong *et al.* 2004a,b).

This on-farm experimental study was conducted on 10 independent farms between 2000 and 2002. Individual farms, each of an area of 45-80 ha, were assessed and the management practices (production breaks, conservation of natural enemies, regular crop scouting, threshold based decision making, use of broad-spectrum insecticides, number of insecticide applications per crop, and tank mixes of insecticides) were scored and summed to produce a management index (Furlong *et al*. 2004a). For example, as regards threshold based decision making, a farm scored -2 for no action or +3 if decisions were based on the population density of pests as well as parasitoids. Farms with an overall score of >5.2 were categorized as IPM, farms with a score <0 as conventional practices, and those in between as intermediate. Each farm operated independently and thus formed a somewhat independent crop ecosystem. Such an approach allowed the long-term management practices to be included as a single variable in the analysis, and the effects of adopting different strategies on the efficacy of natural enemies could be evaluated (Furlong *et al.* 2004a).

During the study, three species of larval parasitoids *Diadegma semiclausum* Hellén (Hymenoptera: Ichneumonidae), *Apanteles ippeus* Nixon (Hymenoptera: Braconidae) and *O. sokolowskii* and two species of pupal parasitoids *D. collaris* and *Brachymeria phya* Walker (Hymenoptera: Chalcididae) attacked immature DBM. *Diadegma semiclausum* was the only parasitoid abundant over the course of the study (Furlong *et al.* 2004a; also see Wang *et al.* 2004).The most abundant groups of predatory arthropods caught in pitfall traps were Araneae (Lycosidae) > Coleoptera (Carabidae, Coccinellidae, Staphylinidae) > Neuroptera (Chrysopidae) > Formicidae. On crop foliage, Araneae (Clubionidae, Oxyopidae) > Coleoptera (Coccinellidae) > Neuroptera (Chrysopidae) were most common. The abundance and diversity of natural enemies was greatest at sites that adopted IPM, correlating with greater DBM mortality at these sites. Over the course of the study, the mean mortality of immature DBM caused by the natural enemy complex was 73% of the original test cohorts at IPM sites but only 20% of the original cohort at conventionally managed sites (Fig. 2). At IPM sites the contribution of natural enemies to pest mortality permitted the cultivation of marketable crops with no yield loss (Fig. 3) and a substantial reduction in insecticide inputs.

On average the number of sprays per crop was 8.6 on conventionally managed farms and 2.3 on IPM farms, an impressive more than three fold difference. Furthermore, these 2.3 sprays on IPM farms were almost all Bt formulations or selective insecticides (Furlong *et al.* 2004a).

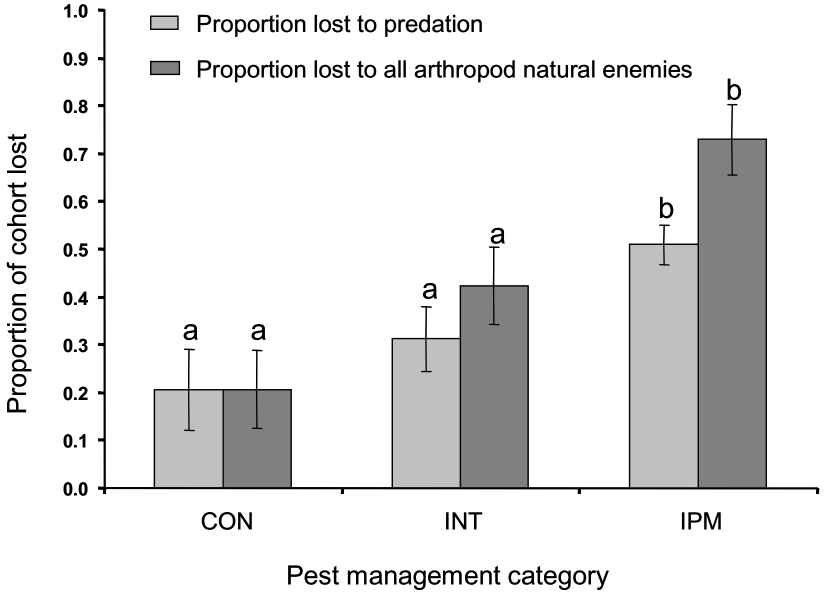

Figure 2. Estimated mean proportion (± SE) of original *Plutella xylostella* cohorts lost to predation and lost to the combined effects of the endemic arthropod natural enemy complex at sites practicing conventional (CON), integrated (IPM), and intermediate (INT) approaches to pest management (2000-2002) in the Lockyer valley, southeast Queensland, Australia. Columns of the same color marked by different letters are significantly different (LSD; $P < 0.05$) (adopted from Furlong *et al.* 2004a).

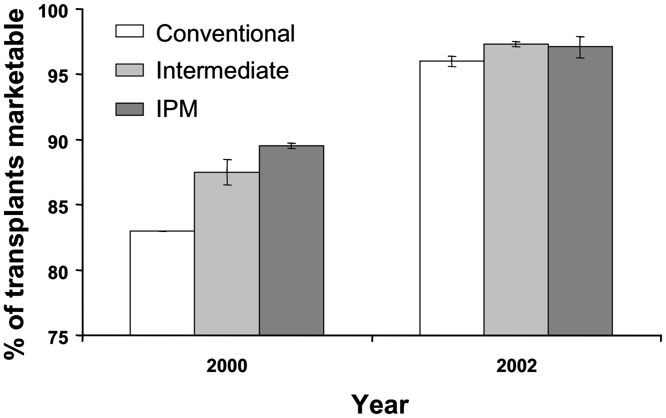

Figure 3. Cabbage yield at sites practicing conventional (CON), integrated (IPM) and intermediate (INT) approaches to pest management in 2000 and 2001 in the Lockyer valley, southeast Queensland, Australia (adopted from Furlong *et al.* 2004a).

DISCUSSION AND CONCLUSIONS

The history of pest control in the last century has repeatedly shown that sustainable pest management can only be achieved by utilizing endemic biological agents as part of a total ecosystem approach to crop management (Lewis *et al.* 1997). Many modern agricultural practices, which often reduce the ecological complexity of habitats and rely extensively on chemical pesticides, require revision. In this international cooperative project on brassica IPM, joint efforts were made to carry out research, development and implementation in two regions in Australia and China. While the brassica crops in the two regions share some of the same major pests, the crop ecosystems differ in many ways (see Introduction), and on-farm evaluation of the impact of natural enemies required different experimental setups in the two countries.

In Zhejiang and Shanghai, China, field trials were conducted for single seasons on a rather small scale, using plots within the same field, although extensive effort was made to repeat the same trials in different locations and years (Lin *et al.* 2002; Liu *et al.* 2004; Yu *et al.* 2002; Zhang *et al.* 1999). In such circumstances movement of natural enemies between treatments can confound results and the effectiveness of the natural enemy complex at the important agro-ecosystem level cannot be addressed. In the Lockyer Valley, brassica crops are grown on relatively large (50-100 ha) independent farms responsible for making their own pest management decisions. As the continuum of pest management practices included in the field study evolved over a course of approximately 10 years, the comparative experimental analysis between farms reflected the outcomes from different pest management strategies at the realistic crop ecosystem level over time (Furlong *et al*. 2004a; Heisswolf *et al*. 1997). Despite the differences in crop ecosystems between the two regions and the differences in experimental methods, the results indicate that in both regions naturally occurring biological control can be substantially enhanced to form the central elements of effective IPM programs and improve vegetable production.

One of the major features of this cooperative project has been the frequent interchange of visiting studies by both sides and frequent exchange of information. Experimental results and information on recent developments in IPM implementation in both regions were delivered to all team members through annual reports and project review meetings. Effort was made to convey the information to the growers in various extension activities (Deuter and Liu 1999; Zalucki and Liu 2003). Data on the effectiveness of naturally occurring biological control, as affected by pest management practices, in both geographic regions helped the extension scientists and growers to build up their confidence for a shift from chemical control to an IPM strategy. There is ample evidence that the improvement in pest management achieved through this joint project has promoted the sustainability of the brassica industry in the two regions of China and Australia (Zalucki and Liu 2003).

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BIOLOGICAL CONTROL OF FRUIT PIERCING MOTH (*EUDOCIMA FULLONIA* [CLERCK]) (LEPIDOPTERA: NOCTUIDAE) IN THE PACIFIC: EXPLORATION, SPECIFICITY, AND EVALUATION OF PARASITOIDS

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ABSTRACT

Adult fruit piercing moths (Noctuidae) are common pests of ripening fruit over much of tropical and subtropical Southeast Asia, Australia, and the western Pacific islands. *Eudocima fullonia* (Clerck), a target for classical biological control, occurs in that region including Papua New Guinea where it is not a pest and where it is thought to be controlled by natural enemies. Surveys conducted in Papua New Guinea revealed that two abundant egg parasitoids, *Telenomus lucullus* (Nixon) and *Ooencyrtus* sp. (*Papilionis*, species- group, Encyrtidae) were contributing up to 95% mortality of moth eggs. The host specificity of both parasitoids was studied in the laboratory by exposing them to eggs of related Noctuidae. *T. lucullus* was found to be specific to *Eudocima* spp. in the laboratory but *Ooencyrtus* sp. oviposited and developed on several non-target noctuid species in the presence of the moth host's food plants. *T. lucullus* and *Ooencyrtus* sp. were assessed as adequately host specific for release in Samoa, Tonga, Fiji and the Cook islands. However, the parasioids were not assessed with the non-target *E. iridescens* (T.P. Lucas), a rare species from northern Australia unavailable for testing. The two egg parasitoids were released on Samoa, Tonga, Fiji, and the Cook Islands but were not released in Australia due to the inability to demonstrate adequate host specificity. *T. lucullus* and *Ooencyrtus* sp. both became established in Tonga and Fiji but only *T. lucullus* became established in Samoa and the Cook islands. After establishment of parasitoids increased levels of egg parasitism and declines in the abundance of target eggs occurred in Samoa and Tonga, and decreases in the abundance of the moths and its damage to fruit were observed in Fiji and Cook Islands. The methods for conducting surveys, host specificity testing and field evaluations are described.

INTRODUCTION

Fruit piercing moths (*Eudocima* spp. [= *Othreis* spp.], Noctuidae: Catocalinae) are serious pests of ripe and ripening fruit in many subtropical and tropical countries including parts of

Africa, Southeast Asia and western Pacific countries (Waterhouse and Norris 1987). The most widespread pest species, *Eudocima fullonia* (Clerck) occurs in Australia and western Pacific countries (Waterhouse 1997) including New Caledonia (Cochereau 1977). Although cosmopolitan in the Pacific, Waterhouse and Norris (1987) suggested that the Indo-Malaysian region is the most likely area of origin of *E. fullonia*.

Both sexes of adult fruit piercing moths puncture fruit with their long, stout proboscis which is adapted to penetrate the rind of firm, intact fruit allowing moths to feed on fruit juice and pulp. Secondary invasions by micro-organisms spread into damaged tissues causing rot and premature fruit-fall (Sands *et al*. 1993). There are two different biotypes of *E. fullonia*. In Papua New Guinea (PNG) and on most Pacific islands, larvae of *E. fullonia* feed on several *Erythrina* spp. (Fabaceae) as well as vines of the family Menispermaceae, whereas in Australia, Southeast Asia, and Africa, the larvae feed only on Menispermaceae (Sands and Chan 1996; Sands & Schotz 1991).

In eastern Australia the moths migrate annually in warmer months from the tropics, to temporarily colonise the temperate regions (Sands *et al*. 1991) and their abundance varies from year to year (Mosse-Robinson 1968) with climatic variation. In New Caledonia, outbreaks mainly follow prolonged periods of drought (Cochereau 1977). In western Pacific countries, including New Caledonia, indigenous natural enemies do not prevent the build up of moth numbers that invade orchards and cause serious damage (Cochereau 1977). However, *E. fullonia* is not abundant or a pest in Papua New Guinea, where its abundance is thought to be reduced by parasitoids (Sands and Broe 1991).

In early attempts to control *E. fullonia*, a larval parasitoid *Winthemia caledoniae* Mesnil (Diptera: Tachinidae) from New Caledonia, (Cochereau 1977) was relocated within the region but it failed to become established (Kumar and Lal 1983; Waterhouse and Norris 1987). Very few other parasitoids of larvae of *Eudocima* spp. are known. However, *Euplectrus maternus* Bhatnagar from India and *E. melanocephalus* Girault from northeastern Australia have been considered to be potential biological control agents (Jones and Sands 1999).

Two egg parasitoids from PNG, *Telenomus lucullus* Nixon (Hymenoptera: Scelionidae) (= *Telenomus* sp., LPL 530 in Sands *et al*. 1993) and an *Ooencyrtus* sp. (Hymenoptera: Encyrtidae) (*papilionis* Ashmead, species-group), were recently introduced into the western Pacific (Sands and Liebregts 1992; Sands *et al*. 1993) in attempts at biological control of *E. fullonia*. The exploration, evaluation, and the release of these egg parasitoids, the introduction into Tonga of another egg parasitoid, *O. crassulus* from Samoa, and the reasons for not releasing egg parasitoids from Papua New Guinea in Australia, are discussed. Preliminary evaluation of *E. melanocephalus* from Australia, as a possible agent for the Pacific islands is also discussed.

MATERIALS AND METHODS

Exploration for parasitoids in Papua New Guinea. Surveys for parasitoids of *E. fullonia* were conducted in Papua New Guinea (PNG) in 1987 and 1988, at the edge of coastal rainforests and on roadside vegetation near Madang, northern PNG, near Vudal, New Britain, at Tep Tep in the Finisterre Ranges (alt. 2000 m), and at the edge of mesophyll vine thickets near Port

Moresby, southern PNG. In a search for any alternative hosts of *Ooencyrtus* sp. or *Telenomus lucullus* , eggs of Noctuidae (other than *E. fullonia*) were collected opportunistically near Madang, PNG and incubated in the laboratory until egg parasitoids emerged.

The host plants of *E. fullonia* were examined and any immature stages located were returned to the laboratory for rearing. Immature stages of the moth from individual eggs and egg masses deposited on leaves of the food plant, *E. variegata* var. *orientalis* L., and occasionally from vines (Menispermaceae) were collected from localities close to sea level, whereas at a high altitude (2,000 m) locality, Tep Tep, Morobe Province, stages of *E. fullonia* were collected from the menisperm vine, *Stephania japonica*.

Leaf portions of *E. variegata* or menisperm vines with single eggs and egg masses were excised and incubated in ventilated plastic containers for up to 28 days until parasitoids or larvae eclosed. Parasitoids that emerged were maintained by feeding with honey droplets smeared on wax paper. Moth larvae were provided with fresh leaves of appropriate food plants until they appeared to be parasitised, or if they pupated, until moths or parasitoids eclosed, or unparasitised pupae died. Percent parasitism of each host stage was calculated for each field locality and food plant based on the numbers of immature stages that developed fully, died or produced parasitoids. Parasitised larvae of *O. fullonia* were occasionally recovered from food plants in rainforest in PNG but none were successfully reared or positively identified. These parasitoids were thought to be a *Euplectrus* sp. (Eulophidae) (Sands unpublished).

TESTING THE HOST SPECIFICITY OF PARASITOIDS

Cultures of egg parasitoids *T. lucullus* and *Ooencyrtus* sp. (*papilionis* species-group) were established in the laboratory in Madang, PNG to provide material suitable for consignment to Australia. Parasitoids were reared in PNG through one generation using moth eggs obtained from a caged culture of *E. fullonia*. Parasitised eggs of *E. fullonia* were then separated from leaf substrates for subsequent packaging and consignment to Australia. All host specificity tests were conducted in a quarantine facility in Brisbane, Australia, where cultures of both PNG egg parasitoids were established using eggs of *E. fullonia* (Australian biotype) as hosts. Parasitoids were reared and tested in large (14 x 3 cm) ventilated plastic tubes containing a card smeared with honey as food.

Representatives of non-target, indigenous Australian Noctuidae were exposed to parasitoids for specificity tests. They were selected for testing on the basis of their taxonomic relatedness to the target genus, *Eudocima* (Noctuidae: Catocalinae), their known life histories, and the availability and practicability of obtaining fertile eggs or larvae. To obtain eggs of all species, gravid moths were held in cages and induced to oviposit on organza using the method described by Sands and Schotz (1991).

In a first group consisting of other *Eudocima* spp., eggs of *E. salaminia* (Cramer), *E. materna* (Linn.), *E. aurantia* (Moore), *E. iridescens* (T.P. Lucas) and *E. cocalis* (Cramer) were nominated for exposure to *T. lucullus* and *Ooencyrtus* sp. In a second group, eggs of less closely-related Catocalinae, species of *Ophiusa* spp., *Dasypodia* spp., *Achaea* sp., *Phyllodes imperialis* , *Donuca* sp., *Erebus terminitincta* (Gaede) and an *Anomis* sp. were tested. Immature stages of two species *Helicoverpa armigera* (Hübner)(Heliothinae) and *Spodoptera litura*

(Fab.)(Acronictinae), representating other subfamilies as their life histories well known. Cultures of these were obtained from the University of Queensland, Brisbane.

The host specificities of *Ooencyrtus* sp. and *T. lucullus* originally from PNG, were evaluated for their suitability for introduction into western Pacific islands and mainland Australia. The host specificity of the Australian *E. melanocephalus* was determined as preliminary for its proposed introduction into Fiji and Samoa, countries where the temperature and humidity were predicted to be most favourable (Jones and Sands 1999).

Egg parasitoids from PNG were tested for their host specificity by exposing to eggs of selected non-target species attached to gauze: (i) without plant material and (ii) with leaf portions of plant hosts of *E. fullonia* (*S. japonica* and *E. variegata*) to test for any different (tritrophic) responses to the eggs (Table 1).

INDIGENOUS NATURAL ENEMIES IN AUSTRALIA AND THE PACIFIC

Prior to introducing an exotic agent, the indigenous natural enemies were surveyed in each proposed receiving country, to: (i) ensure that the agent species was not already present, (ii) identify indigenous natural enemies and distinguish them from the proposed agent, and (iii) quantify impacts by each indigenous species on the target host. Information from the literature (e.g., Sands *et al.* 1993; Waterhouse and Norris 1987) and a co-ordinated program focussed on indigenous and introduced parasitoids (Table 2) of *E. fullonia* in the western Pacific.

The most abundant indigenous parasitoids of eggs that needed to be distinguished from species proposed for introduction from PNG included: *O. crassulus* Prinsloo and Annecke (Hymenoptera: Encyrtidae) and *Trichogramma* spp. in Samoa; *O. cochereaui* Prinsloo and Annecke, *Trichogramma chilonis* Ishii (Hymenoptera: Trichogrammatidae) and *Telenomus* sp. (Hymenoptera: Scelionidae) in New Caledonia (Cochereau 1977; Maddison 1982).

The impact on eggs by an important predator of eggs, *Germalus samoanus* China (Hemiptera: Lygaeidae), was quantified during the assessment of egg parasitism in Samoa.

Specimens of parasitoids reared from *E. fullonia* were retained in the Australian National Insect Collection, Canberra and others were submitted to the Natural History Museum, London for identification.

LARVAL PARASITOIDS

On the Pacific islands very low levels of parasitism were recorded from larvae during the reported study. In Australia, egg and larval parasitoids (Huber 1999) were reared from immature stages of *Eudocima* spp.. *Euplectrus melanocephalus* Girault and an unidentified *Euplectrus* sp. were identified as larval parasitoids from northeastern Queensland, but they were only abundant during the warm, humid months each year (Huber 1999). Parasitised larvae of *Eudocima* spp., mostly instars 1 and 2, were collected from menisperm vines near Cairns, northern Queensland. Using methods described by Jones and Sands (1999) they were maintained with leaves of the food plant until they pupated, died, or parasitoids developed. The suitability of *E. melanocephalus* as a biological control agent was evaluated in a secure facility in Brisbane. The effects of temperatures on immature development times were

Table 1. Host specificity tests: parasitoids of *E. fullonia* exposed to eggs of Noctuidae.

Parasitoid	Host[a]/Non-target Host[b]	Stage of Host	Pars. Oviposition	Pars. development
E. melanocephalus	*E. fullonia*	2nd, 3rd inst. larva	+	+
"	*E. materna*	2nd, 3rd inst. larva	+	+
"	*E. salaminia*	2nd, 3rd inst. larva	+	+
"	*E. aurantia*	2nd, 3rd inst. larva	+	+
"	*Erebus terminitincta*	2nd, 3rd inst. larva	-	-
"	*Spodoptera litura*	2nd, 3rd inst. larva	-	-
Ooencyrtus sp.	*E. fullonia*	egg	+	+
"	*E. materna*	"	+	+
"	*E. salaminia*	"	+	+
"	*E. aurantia*	"	+	+
"	*Erebus terminitincta*	"	+/- *	+/- *
"	*Dasypodia* spp.	"	+/- *	+/- *
"	*Phyllodes imperialis*	"	+/- *	+/- *
"	*Ophiusa* sp.	"	+/- *	+/- *
"	*Achaea* sp.	"	+/- *	+/- *
"	*Donuca* sp.	"	+/- *	+/- *
"	*Spodoptera litura*	"	+/- *	+/- *
"	*Helicoverpa armigera*	"	+/- *	+/- *
Telenomus lucullus	*E. fullonia*	"	+	+
"	*E. materna*	"	+	+
"	*E. salaminia*	"	+	+
"	*E. aurantia*	"	+	+
"	*Erebus terminitincta*	"	-	-
"	*Dasypodia* spp.	"	-	-
"	*Phyllodes imperialis*	"	-	-
"	*Ophiusa* sp.	"	-	-
"	*Achaea* sp.	"	-	-
"	*Donuca* sp.	"	-	-
"	*Spodoptera litura*	"	-	-
"	*Helicoverpa armigera*	"	-	-

*oviposition and development only in presence of *Erythina variegata* and *Stephania japonica.*

Table 2. Introductions of parasitoids for biological control of the fruit piercing moth, *Eudocima fullonia*.

Natural Enemy	Country of Origin	Country Released	Host Stage	Established	Reference
Winthemia caledoniae Mesnil	New Caledonia	Fiji (1983-84)	larva	-	Kumar and Lal 1983
Winthemia caledoniae Mesnil	New Caledonia	Tonga (1979)	larva	-	Waterhouse and Norris 1987
Ooencyrtus cochereaui	New Caledonia	American Samoa	egg	-	"
Ooencyrtus cochereaui	New Caledonia	Samoa	egg	-	"
Ooencyrtus crassulus	Samoa	Tonga (1992)	egg	+	Sands and Liebregts 1992
Ooencyrtus sp. (*papilionis* group)	Papua New Guinea	Samoa (1989)	egg	-	Sands *et al.* 1993
Ooencyrtus sp. (*papilionis* group)	Papua New Guinea	Fiji (1992)	egg	+	Sands *et al.* 1993
Ooencyrtus sp. (*papilionis* group)	Papua New Guinea	Tonga (1992)	egg	+	Sands 1996
Ooencyrtus sp. (*papilionis* group)	Papua New Guinea	Cook Islands (1996)	egg	+	Sands and Liebregts unpubl.
Telenomus lucullus	Papua New Guinea	Samoa (1989)	egg	+	Sands and Liebregts 1992
Telenomus lucullus	Papua New Guinea	Fiji (1992)	egg	+	Sands *et al.* 1993
Telenomus lucullus	Papua New Guinea	Tonga (1993)	egg	+	Sands 1996
Telenomus lucullus	Papua New Guinea	Cook Islands (1996)	egg	+	Sands and Liebregts unpubl.

determined to predict its adaptability to the tropical environments of the Pacific islands (Jones and Sands 1999). The suitability of the unidentified *Euplectrus* sp. was not evaluated.

MEASURING ABUNDANCE AND PARASITISM OF EGGS OF *E. FULLONIA*

To monitor the abundance of moth stages some variation in methodology was applied in each country, where the immature stages, mostly eggs of *E. fullonia* on the host plant *Erythrina* spp., were sampled monthly for more than 12 months, before and after release of PNG parasitoids in Samoa, Fiji, and Tonga.

Eggs and egg masses on leaves of the food plant (mostly *E. variegata* var. *orientalis* (L.) Merrill, but also *E. subumbrans* (Hask.) in Fiji and Samoa) were collected to calculate percent parasitism by indigenous egg parasitoids (before release of PNG parasitoids). Only one pre-release survey for parasitoids was carried out in Rarotonga, Cook Islands.

Low trees of *Erythrina* spp. on properties, road boundaries or fence posts were selected for sampling sites when supporting the immature stages of *O. fullonia*. After each sampling event, trees were pruned to approximately 3 m to encourage lateral and terminal growth suitable for re-sampling. From each site each month, 100 terminal or lateral stems with leaves attached were cut from each of 20 *Erythrina* plants. Leaves were removed from terminals and all attached eggs and egg masses containing living stages (moth embryo or parasitoid) were recorded, returned to the laboratory and incubated in vials until moth larvae or parasitoids emerged. If a minimum of 30 eggs or masses was not recovered each month additional leaves were collected until 30 eggs or egg masses were retrieved. From the eggs recovered, egg abundance, egg mortality and identity of the egg parasitoids were recorded. Percent parasitism of single eggs and egg masses were calculated separately.

In the receiving countries for the egg parasitoids, *Ooencyrtus* sp. and *T. lucullus,* methods for post-release studies on eggs of *E. fullonia* were based on those to monitor pre-release parasitisation and egg abundance. The appearance of parasitised and post-parasitised stages allowed estimates to be made of parasitism in the field and were applied to the sampling methods. For example, eggs parasitised by *T. lucullus* were identifiable by markings on the chorion of eggs, and *Ooencyrtus* sp. and *Trichogramma* spp. were identified by the colour of the egg, eggshell and meconium. The abundance of eggs, levels of parasitisation by indigenous parasitoids and the release dates in each country for *Ooencyrtus* sp. and *T. lucullus* were recorded as follows:

Samoa. Single eggs as well as egg masses were abundant. An indigenous *Trichogramma* sp. ranged in abundance from 4-16% of host eggs parasitised and eggs parasitised by *O. crassulus* averaged 28-35% on the islands of Savai'i and Upolu. The PNG *Ooencyrtus* sp. and *T. lucullus* were released on both islands in 1988.

Tonga. Single eggs were abundant and egg masses uncommon. An indigenous *Trichogramma* sp. varied greatly in abundance from 6-85% of eggs parasitised on Tongatapu island and from 0-53% on the island Eua. An indigenous *Telenomus* sp. was uncommon with parasitism ranging from 0-5% on Tongatapu. The Samoan egg parasitoid *O. crassulus*: was released on Tongatapu between December 1992 and June 1993, and on Eua in November 1993. The PNG *Ooencyrtus* sp. was released in August 1992 on Tongatapu and *T. lucullus* on Tongatapu and on Eua in November 1993.

Fiji. Single eggs were abundant and egg masses uncommon. *Trichogramma* sp. parasitised 2-16% of eggs and a rare indigenous *Telenomus* sp. parasitised less than 2% of eggs. The PNG *Ooencyrtus* sp. was released in October 1990 on the island Viti Levu and *T. lucullus* on Vanua Levu and Viti Levu islands in October 1993.

Roratonga, Cook Islands. Single eggs predominated over egg masses. *Trichogramma* sp. and an indigenous *Telenomus* sp. together parasitised less than 2% of eggs. The PNG *Ooencyrtus* sp. and *T. lucullus* were released in October 1996.

RESULTS

CLIMATIC SUITABILITY OF PARASITOIDS

The PNG egg parasitoids, *Ooencyrtus* sp. and *T. lucullus*, were confirmed to be well suited to tropical climates, and less suited to sub-tropical or temperate climates of the receiving countries. After they were released *Ooencyrtus* sp. and *T. lucullus* were recovered from the receiving islands, except from Samoa where only *T. lucullus* became established, and Cook Islands where only *Ooencyrtus* sp. became established. Although predicted to be suitable for release in most Pacific inland countries (Jones and Sands 1999), based on climatic and host range suitability, the Australian larval parasitoid *E. melanocephalus* was not released due to the lack of opportunity to culture it and monitor its establishment.

HOST SPECIFICITY TESTS WITH NON-TARGET NOCTUIDAE

In PNG, *Ooencyrtus* sp. or *T. lucullus* was reared only from field-collected eggs of *Eudocima* spp., and on no occasions were they recovered from eggs (35 spp. mostly unidentified) of non-target Noctuidae. Several parasitoids of the same genera emerged but their specific identities were not determined.

After the PNG parasitoids became established in Fiji, eggs of other Noctuidae and some unrelated moths with eggs of similar size to the target, *E. fullonia*, were sampled close to release sites in an attempt to find any evidence of attack on non-target species. In the Pacific, there was no evidence (monitoring discontinued in 1997) from samples of Noctuidae eggs, that *Ooencyrtus* sp. and *T. lucullus* had crossed over to attack eggs of any non-target moth species. On several occasions a similar *Telenomus* spp. were recovered from eggs including a hawk moth (probably *Agrius* sp.) but the parasitoid proved to be a species different to *T. lucullus* (W. Liebregts unpubl.).

In Australia, *Eudocima* spp. available for testing in the laboratory were confirmed suitable hosts for the complete development of the PNG egg parasitoids *Ooencyrtus* sp., *T. lucullus* and the Australian *E. melanocephalus* (Jones and Sands 1999). Eggs of other related moths (Catocalinae) failed to support complete development of the parasitoids. However, when testing eggs of Noctuidae in the presence of leaves of the hosts (*Erythrina variegata*, *Stephania japonica*) of *E. fullonia*, *Ooencyrtus* sp. (but not *T. lucullus*), oviposited in the eggs of all non-target species and some, or complete parasitoid development occurred. When eggs of the same Noctuidae attached to gauze, without leaves were exposed to *Ooencyrtus* sp., no non-target species attracted oviposition by this parasitoid.

The inability to obtain immature stages of the rare *E. iridescens* for testing, a species closely-related to the target pest species, influenced the decision not to release the PNG egg parasitoids *Ooencyrtus* sp., *T. lucullus* in Australia.

RELEASE AND ESTABLISHMENT OF EGG PARASITOIDS

Samoa. *Ooencyrtus* sp. from PNG failed to become established in Samoa. *T. lucullus* released at the same time, became established and was first recovered in Samoa in October 1988. After the establishment of *T. lucullus* on Savai'i, total egg parasitism of *E. fullonia* increased from 62% to 79% for single eggs, and from 56% to 80% of egg masses.

Tonga. *O. crassulus* became established on Tongatapu and was recovered in October 1993 and December 1994. *Ooencyrtus* sp. was recovered on the same island from 1993 with egg parasitism reaching an average of 30% in 1996. *T. lucullus* was recovered on Tongatapu in 1994 where total egg parasitism increased from 19% to 27% in 1996. On Eua total egg parasitism increased from 22% in 1994 to 69% in 1996 after release of *T. lucullus*.

Fiji. *Ooencyrtus* sp. was recovered on the island Vanua Levu from September 1992 and *T. lucullus* was recovered from both islands in October and November 1993. Quantitative data on egg parasitism after parasitoids became established were not available.

Roratonga, Cook Islands. The PNG *Ooencyrtus* sp. and *T. lucullus* were released in October 1996. Only *Ooencyrtus* sp. was recovered in April 1997. In the Cook Islands quantitative data were not collected and sampling was discontinued after establishment of the parasitoids was confirmed.

DISCUSSION

The procedure for testing exotic parasitoids with non-target species highlighted some of the difficulties in obtaining the appropriate stages of species for testing and the need to avoid testing non-target species in the presence of the certain plants to avoid 'false positive' results (Sands and Van Driesche 2000). In this example, the parasitoid *Ooencyrtus* sp. oviposited in eggs of a range of non-target hosts when portions of the food plants of *E. fullonia* were present but did not do so when the plant material was withheld. Identified also were the difficulties of making decisions about whether or not, to release an agent, when these anomalous results are obviously obtained and when the risks of releasing an agent could potentially affect a rare species closely related to the target, when it could not be obtained for testing.

Although field data show increases in total parasitism of eggs of *E. fullonia*, and decreases in the 'hatch' (moth larvae) of eggs in all countries wherever *Ooencyrtus* sp. and *T. lucullus* became established, the resulting declines in adult moth density were not easily demonstrated. However, levels of damage to fruit were reported to have decreased in all countries. For example, in Fiji in1997 levels of damage to oranges and mangoes were noted by orchard managers and agricultural research staff, to have decreased when compared with earlier years. Damage to fruit was lower since monitoring began in the early 1990's, 5 years after the parasitoids had become established (S. Lal pers. comm.). In Samoa a decline in damage to firm fruit (e.g., citrus), but not soft fruit (e.g., carambola) was noted in 1997 (unpublished data). In Rarotonga, Cook Islands, a marked decrease in moth abundance occurred after egg parasitoids had become established (M. Poschko pers. com.). Clearly more attempts are needed to quantify levels of parasitism to eggs of *E. fullonia* and damage to fruit, to determine if the introduced egg parasitoids have had a permanent beneficial impact on horticultural production in those countries.

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