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Biological control of agricultural pests: principles and field applications

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ABSTRACT

Biological control, the management of pests by the use of living organisms, has a long history of application to agriculture around the world. However, the effective use of beneficial organisms is constrained mainly by social and economic restrictions, forcing researchers to adopt increasingly multi-disciplinary techniques in order to deploy successful biological control programs. This review covers the principles of biological control techniques and their implementation, and incorporates practical examples from the biological control of a variety of agricutural pests.

Palavras-chave: manejo de pragas, controle biológico, entomologia agrícola

RESUMO

O controle biológico de pragas na agricultura: princípios e aplicações em campo

O controle biológico, manejo de pragas com organismos vivos, tem uma longa história de aplicação na agricultura em todo mundo. Entretanto, o uso efetivo dos organismos benéficos é limitado, principalmente, por fatores sociais e econômicos, forçando os pesquisadores a adotar técnicas multidisciplinares para viabilizar o sucesso do controle biológico. Esta revisão aborda os princípios básicos das técnicas de controle biológico e sua implementação, e incorpora exemplos práticos com várias pragas agrícolas.

Key words: pest management, biological control, agricultural entomology

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INTRODUCTION

According to Altieri (1997) biological control was originally defined as the action of parasitoids, predators, or pathogens in maintaining another organism's population density at a lower average than would occur in their absence (De Bach, 1964). As such, biological control distinguishes itself from all other forms of pest control by acting in a density-dependent manner, that is: natural enemies increase in intensity and destroy a larger portion of the population as the density of that population increases, and vice-versa (De Bach & Rosen, 1991). In a strict ecological sense, applied biological control can be considered a strategy to restore functional biodiversity in agroecosystems by adding, through classical and/or augmentative biocontrol techniques, missing entomophagous insects or by enhancing naturally occurring predators and parasitoids through conservation and habitat management (Altieri, 1994).

Biological control is a self-sustaining strategy, through which farmers relied for pest control on the ecological services provided by the restored functional biodiversity, thus avoiding dependence on costly pesticides.

The first description of use of biological control dates from around 300 AD, when predatory ants were used for control of pests in citrus orchards in China, a method which is still used today in Asia. In the 1750s, the British and French transported mynah birds from India to Mauritius to control locusts. Early applied biological control programs began under the USDA's Department and later Bureau of Entomology, established in 1881. The first importation of an exotic braconid wasp parasite, *Cotesia glomerata* (Hymenoptera: Braconidae), against the imported cabbageworm, *Pieris rapae* (Lepidoptera: Pieridae), into the United States occurred in 1883 and the introduction of the famous predaceous vedalia beetle, *Rodolia cardinalis* (Coleoptera: Coccinellidae) to control the cottony cushion scale, *Icerya purchasi* (Hemiptera: Margarodidae), followed in 1888 (Clausen, 1978). The Department's first large-scale biological control program did not begin until 1905 and involved explorations in Europe and Japan for natural enemies of the gypsy moth, *Lymantria díspar* (Lepidoptera: Lymantriidae), and browntail moth, *Euproctis chrysorrhoea* (Lepidoptera: Lymantriidae), introduced into New England (Vail *et al*., 2001).

Natural (biological) control is constantly active in all world ecosystems on 55.5 billion hectares. Most of the potential arthropod pests (95%, 100,000 arthropod species) are under natural (biological) control; all other control methods used today are targeted at the remaining five thousand arthropod pest species. This ecosystem function of natural biological control is estimated to have an annual minimum value of 400 billion US$ per year, which is an enormous amount compared to the only 8.5 billion US$ annually spent on insecticides. Classical biological control is applied on 350 million hectares (10% of cropped lands), and has very high benefit-cost ratios of 20-500 : 1. Augmentative, commercial biological control is applied on 0.016 billion hectares (0.046% of land under culture), and has benefit-cost ratios of 2-5 : 1, which is similar to chemical pest control (van Lenteren *et al*., 2006).

The history of biological control may be divided into 3 periods:

1. The preliminary efforts when living agents were released rather haphazardly with no scientific approach. Little precise information exists on successes during this time. Roughly 200 A.D. to 1887 A.D.;

2. The intermediate period of more discriminating biological control which started with the introduction of the Vedalia beetle, *R. cardinalis*, for control of the cottony cushion scale in 1888. Period extended from 1888 to ca. 1955; and

3. The modern period characterized by more careful planning and more precise evaluation of natural enemies. Period extending from 1956 to the present.

It must be pointed out that from 1930 to 1940 there was a peak in biological control activity in the world with 57 different natural enemies established at various places, but World War II caused a sharp drop in biological control activity, so it did not regain popularity after war due to the production of relatively inexpensive synthetic organic insecticides. Entomological research switched predominantly to pesticide research. In 1947 the Commonwealth Bureau of Biological Control was established from the Imperial Parasite Service. In 1951 the name was changed to the Commonwealth Institute for Biological Control (CIBC). Headquarters are currently in Trinidad, West Indies. In 1955 the Commission Internationale de Lutte Biologique contre lês Enemis des Cultures (CILB) was established. This is a worldwide organization with headquarters in Zurich, Switzerland. In 1962 the CILB changed its name to the Organisation Internationale de Lutte Biologique contre les Animaux et les Plants Nuisibles. This organization is also known as the International Organization for Biological Control (IOBC), which initiated the publication of the journal "Entomophaga", in 1956, devoted to biological control of arthropod pests and weed species.

The International Organization for Biological Control of Noxious Animals and Plants (IOBC), celebrated its 50th anniversary in 2006. The mission of IOBC is to promote the development of biological control and its application in integrated control programs, where biological control means the use of living organisms or their products to prevent or reduce the losses or harm caused by pest organisms (or, in short, the use of biota to control biota). During its short history, IOBC has been an effective advocate of biological control, applying its considerable influence as an independent, international, professional body to assist policy making in FAO, EU, OECD, World Bank and other international lending banks, NGOs and national agricultural and environmental ministries.

IOBC will continue to play an important role in realizing sustainable and environmentally friendly food production worldwide. In those areas with overproduction of food (e.g. Europe, North America, Australia and New Zealand) biological control will be increasingly used because its contribution to the maintenance or augmentation of biodiversity, and also because the consumers' demand for pesticide-free food. In these areas, biological control will be the corner-stone of Integrated Protection and Production of food. In areas where food production does not yet meet demands, biological control can be used to reduce the production costs, increase production, and contribute to improved health and safety of farmers and a cleaner environment.

SEQUENCE OF STEPS IN BIOLOGICAL CONTROL

There is a sequence of steps that should be taken in any biological control project. These steps ensure that the so-called beneficial does not turn out to be a pest in itself. The importation of *Pueraria lobata* (Fabales: Fabaceae) for soil conservation is an example of this problem. Though it is effective in soil conservation, kudzu is now a serious pest. Under most conditions, none of the following steps should be eliminated.

Study

The first step is to study the literature. Look for other areas where the "pest" is not a pest. One usually needs to look no farther than the origin of the host plant. In their native habitat, host and pest have usually reached a natural balance. When an area is found where host and pest live in harmony, a team of scientists is usually sent to study why the pest is not a serious problem there. The search nearly always includes exploration for natural enemies. Finding effective natural enemies in the host plant's native habitat concludes the first step.

Importation or introduction

The next step in the biological control process involves importation of the natural enemy/enemies. This involves a quarantine period for all imported organisms. Such questions as where it can live and reproduce, the spectrum of potential hosts, etc., must be answered. This step is necessary so that we do not import "solutions" that become more serious than the "problems."

Augmentation

This step, quite simply, is the rearing and release of natural enemies or entomopathogens. Natural enemies are generally reared in large numbers in laboratories and released in target areas. This step and the remaining step apply equally to natural enemies that are imported from other areas and to those that are already here. Release of natural enemies may take one of these forms: inundation or inoculation. With inundation, the target area is flooded with a large number of the natural enemies. Ideally, such a release will bring the pest(s) under control quickly and it is hoped that the natural enemies will become permanently established in the area. Inoculation of an area usually involves much lower numbers. It is designed to allow establishment of a biological control agent in an area. Or, such a release may be used merely to improve the natural enemy/ pest ratio.

Conservation

The final step in the biological control process is one that is frequently overlooked. Yet, it is just as important as any of the others. If we do not conserve our natural enemies once established, we must continually introduce more, and this quickly becomes uneconomical. Through conservation practices, there are conditions that enable the control agent to stay and live in the target area. There are conditions that favor natural biological control because ideally, once established, the biological control agent should stay and continue to provide natural control indefinitely without further intervention. Knowing the biology and ecology of the natural enemies is important, for this will enable the researchers to provide suitable protective sites for survival, especially during the off-season. Cultural practices and selective use of pesticides can help conserve natural and introduced biological control agents.

CLASSICAL BIOLOGICAL CONTROL

Classical biological control involves the introduction of natural enemies from the center of origin of an insect herbivore that has become an exotic pest elsewhere (van Driesche & Bellows, 1996). Throughout history this has involved hundreds of exchanges between various world regions of natural enemies used against agricultural insect pests. The analysis conducted by Altieri (1991), provides a measure of the "biological control contribution" of each of six regions to world agriculture and also a measure of the "biological control dependence" of each region on non-indigenous sources of natural enemies. It is clear that the six regions are interdependent in terms of biological control agents. It is also obvious that there are countries disproportionately more dependent than others for natural enemies (USA and Canada) and that other regions have made more significant contributions (Asia, including India).

If the regions are clustered into industrialized countries (USA, Canada, Western Europe, and Australia) and developing countries (Latin America, Asia, and Africa), it is observed that the industrialized countries have significantly benefited from the natural enemy richness of the developing countries. Up to 1965, industrialized countries had received 49 species of natural enemies from developing countries for the control of various agricultural insect pests, whereas the developing countries received only 30 species from the industrialized countries. Asia (including India) has provided 21 different species of natural enemies to the USA and Canada, but in return they have only received one species from North America.

When more recent data on the inter-regional introductions of parasitic insects against arthropods of agricultural, forestry, and medical importance are analyzed, it reinforces the point about the world's interdependence on biological control agents (Luck, 1981). When examining data from the 1970s and 1980s, the industrialized countries-developing countries dependence relationship still holds and again appears highly dependent on foreign natural enemy sources. Over 1981, developing countries donated 353 species of natural enemies to industrialized ones, whereas developing countries received only 260 natural enemy species from the industrialized ones. Again, Africa, Asia, and Latin America stand out as net contributors.

Data on inter-regional exchanges suggest that because there has been more transfer of natural enemies species from developing to industrialized countries than vice-versa, it could be argued that industrialized countries have accrued a "biological control debt" with developing countries. It could also be argued that such debt is related to the fact that the agriculture in industrialized countries is based on introduced plant material and therefore vulnerable to exotic pests amenable for classical biological control (i.e., by 1970 there were 212 insect pests of foreign origin in the USA) or that intensive transfers were the result of a much greater financial and scientific capacity of the industrialized countries to do so. Another argument could be that given the ecological vulnerability of high-input agricultural monocultures, industrialized countries have a greater need to utilize natural enemies to patch up unstable agroecosystems than developing countries. It is possible that with the expansion of monoculture-based agroexports in developing countries, this need may also increase in all such regions. Thus far in these countries, pest problems in export agriculture have been dealt mainly with pesticides, large number of which have been restricted or banned in the industrialized countries (Conway & Pretty, 1991).

A closer look at biological control programs judged to be "agronomically successful" may show that they are not so successful in social terms. For example, the vast majority of the classical biological control efforts conducted in developing countries (several of which were sponsored by the governments of industrial countries) have been primarily directed at commercial, industrial and export tree crops such as coffee, coconut, citrus, cocoa, and banana and not local food crops (Hansen, 1987). This trend was particularly notorious in British Commonwealth sponsored projects during colonial times. Given the structural realities of developing countries, it is obvious that these efforts were mostly for the benefit of large-scale commercial farmers, and not for the large masses of peasants and the rural poor people in these countries (Murray, 1994). Notable exceptions are the biological control programs against wheat aphids in Brazil and Chile, against Rice pests in southeast Asia and against cassava pests in Africa. These projects, in addition to targeting crucial food crops, also emphasize building indigenous capabilities to implement pest management programs, encouraging the use of simple and low-cost techniques easily adaptable by small farmers (Hansen, 1987; Thrupp, 1996).

Another issue that illustrates inequities in the interregional exchange of biological resources and that is compounded by the contradictory nature of the contemporary structure of the world economy, is the fact that while developing countries were supplying biological control agents to industrialized countries, chemical companies from the industrialized countries were engaged in a massive export of pesticides to developing countries. From 1974 to 1978, imports of pesticides by developing countries increased from $641 million to almost $1 billion. Up to the late 1970s, 38 percent of the international trade in pesticides occurred in developing countries (Weir & Shapiro, 1981). In a period of just two years, US companies increased their pesticide exports from $615 million to $1 billion. Tragically, 30 percent of all pesticides exported from the USA were unregistered, that is, not approved for use in the USA by the Environmental Protection Agency (EPA). In other words, developing countries became a kind of dumping ground for the USA and other industrialized countries (Murray, 1994). Similarly, UK pesticide exports (mostly to developing countries) grew by 211 percent in value over the 1975– 79 period, reaching about 66,000 tons by 1979 (Conway & Pretty, 1991). Latin America's share of the global pesticide market, currently around 10 percent, is steadily increasing. Brazil alone accounts for nearly 50 percent of the total sales in the region, followed by Mexico, Argentina, and Colombia (Belloti *et al.*, 1990).

In many developing countries, governments until recently subsidized pesticide production and sales. The median level of subsidy was about 44 percent of total retail costs. Such subsidies make pesticides considerably cheaper, thus encouraging farmers to use more chemicals than they would if they had to pay the full costs (Murray, 1994). These subsidies undermine efforts to promote more ecologically-sound pest control methods such as biological control. International assistance agencies based in industrialized countries, including the World Bank and US Agency for International Development (USAID), have in the past been involved in promoting pesticide use in developing countries, either directly through agricultural development loans, or indirectly though support for local agricultural credit programs or technical assistance programs (Repetto, 1985). Although international agencies have announced new policy guidelines governing pesticide use in development projects, such guidelines have been implemented unjustifiably slowly. Such sponsored assistance hinders biological control in developing countries and promotes use of pesticides, while these countries continue supplying beneficial organisms to industrialized countries. Such a situation is unethical and suggests a type of “ecological imperialism.” It should be noted, however, that many biological control workers in the industrialized countries actively oppose such policies, and are working hard to develop and promote more equitable alternatives. Further inequities may arise with the emergence of biotechnology, financed mostly by private interests in the industrialized countries. As interest in genetically engineered biological control agents increases, it is possible that developing countries may be caught in purchasing “patented natural enemies” at a high cost. The final irony is that such novel biotic agents be based on genetic resources originally obtained at no cost from developing countries (Kloppenberg & Kleinman, 1987).

INUNDATIVE BIOLOGICAL CONTROL

Augmentative biological control is applied worldwide, and more than 150 species of natural enemies are now commercially available for augmentative biological control. Data on current use of augmentation are very hard to obtain and, thus, the estimates given below are incomplete. The latest comprehensive worldwide review dates from 1977 (Ridgway & Vinson, 1977), which provides data about the use of natural enemies in the USSR (on 10 million hectares), China (1 million hectares), West Europe (< 30,000 hectares), and North America (<15,000 hectares). Since the time of that review, more than 100 new species of natural enemies have become available and are commercially produced or mass reared by governmental institutes (van Lenteren, 1997, van Lenteren, 2003).

Concerning the use of egg parasitoids, the former USSR ranked first in application of *Trichogramma* (> 10 million hectares), followed by China (all crops: 2.1 million hectares, 2 million hectares of the Asian cornborer, *Ostrinia furnacalis* (Crambidae: Pyraustinae), with *Trichogramma dendrolini* (Hymenoptera: Trichogrammatidae) in 2004; and Mexico (1.5 million hectares) (Filippov, 1989; Li, 1994; Dominguez, 1996; Wang *et al*., 2005). The former USSR claimed to have treated more than 25 million hectares annually with *Trichogramma* in the 1980s (Filippov, 1989), but others have questioned the way in which these areas were calculated: it seems that fields which had received for example three treatments of *Trichogramma*, were included three times in the estimates. Therefore, the area under biological control in the previous USSR was reestimated as maximally 10 million hectares. Application with *Trichogramma* in Japan, South East Asia, South America, USA, Canada and Europe is limited because of economic reasons (high labour costs involved in mass production) and more intensive use of pesticides that have a negative effect on natural enemies. Estimates of applications with *Trichogramma* in all other countries with the exception of the former USSR, China and Mexico are in the order of 1.5 million hectares. Inundative releases of *Trichogramma* for control of lepidoptorous pests are being studied in more than 50 countries. Other egg parasitoids, like *Trissolcus basalis* (Hymenoptera: Scelionidae), are used on much smaller areas (Corrêa-Ferreira, 2002).

Also, natural enemies attacking larval and pupal stages are not used to a large extent in augmentative biological control in field crops, with the exception of the use of *Cotesia flavipes* (Hymenoptera: Braconidae) against sugarcane borers in Brazil and several other Latin American countries. In Brazil 23.6 million cocoon masses of *C. flavipes* and 1.5 million adults of the tachinid fly *Paratheresia claripalpis* (Diptera: Tachinidae) were released over an area of 200,000 hectares of sugar cane in 1996 (Botelho & Macedo, 2002).

A substantial number of mycoinsecticides and mycoacaricides have been developed worldwide since the 1960s. At least 12 species or subspecies (varieties) of fungi have been employed as active ingredients of mycoinsecticides and mycoacaricides for inundative and inoculative applications, although some are no longer in use. Products based on *Beauveria bassiana* (33.9%), *Metarhizium anisopliae* (33.9%), *Isaria fumosorosea* (5.8%), and *B. brongniartii* (4.1%) are the most common among the 171 products commercialized worldwide. Approximately 75% of all listed products are currently registered, undergoing registration or commercially available (in some cases without registration), whereas 15% are no longer available. Insects in the orders

Hemiptera, Coleoptera, Lepidoptera, Thysanoptera, and Orthoptera comprise most of the targets, distributed among at least 48 families. A total of 28 products are claimed to control acarines (mites and ticks) in at least 4 families, although only three products (all based on *Hirsutella thompsonii*) were exclusively developed as acaricides. Eleven different technical grade active ingredients or formulation types have been identified, with technical concentrates (fungus-colonized substrates) (26.3%), wettable powders (20.5%) and oil dispersions (15.2%) being most common. Approximately 43% of all products were developed by South American companies and institutions. Currently, what may be the largest single microbial control program using fungi involves the use of *M. anisopliae* for control of spittlebugs (Cercopidae) in South American sugarcane and pastures (Faria & Wright, 2007).

Historically in China, large-scale production of the microbial insecticide *Bacillus thuringiensis* occurred in communes through solid or liquid fermentation in tanks. Wheat bran, corn meal, soybean, defatted cotton seed cake, and peanut bran are the main medium components used in Bt production. In the pilot plant at Hubei Academy of Agricultural Sciences, production grew from 26 tons in 1983 to 90 tons in 1984, and to 900 tons in 1990. Under government sponsorship, Bt is now widely used in 30 provinces for the control of various pests of agriculture and forests (Entwistle, 1993).

Since Cuba's trade relations with the socialist bloc collapsed in 1990, pesticide imports dropped by more than 60 percent, fertilizers by 77 percent, and petroleum for agriculture dropped by 50 percent. In order to deal with such shortages, massive efforts were initiated to find ways to reduce chemical use and to develop alternatives for management of plant diseases, insect pests, and weeds. The production of biopesticides and biological control agents are at the heart of this new quest with the creation of about 220 Centers for the Production of Entomophages and Entomopathogens (CREEs) where decentralized, "artesanal" production of biocontrol agents takes place (Rosset & Benjamin, 1994). The centers produce a number of entomopathogens (*Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and *Lecanicillium lecanii*), as well as one or more species of *Trichogramma*, depending on the crops grown in each area. In 1994, production levels of *Bt* and *B. bassiana* reached 1300 and 780 metric tons respectively. CREEs are maintained and operated by local technicians, many of them sons and daughters of owners of companies, which produce and distribute these products to local, state, cooperatives, and private farmers. CREEs are thus biofactories that produce low priced microbial products for local use (Rosset & Benjamin, 1994).

Opening Latin America and other developing countries' markets to Cuba's biotechnology products and expertise can provide poor and dependent countries access to alternative and cheaper technologies. In fact, Cubans are willing to train people from Lesser Developed Countries (LDC) in biotechnology, thus enabling them to develop their own appropriate biotechnology and to escape the technological control and treadmill imposed by multinationals. As rural communities within LDCs benefit from Cuban technological advances, a parallel technological path to the prevailing corporate model can be developed, thus providing farmers with more alternatives, and even with the possibility of becoming technologically independent through the creation of simple community managed insectaries, microbial insecticide, and biofertilizer manufacturing facilities.

The FAO-initiated IPM program for rice in south and southeast Asia has become a major model for how to establish farmers' networks to implement participatory IPM and is touted as one of the most sustainable crop protection alternatives for the future. The program emphasizes an innovative approach of farmers' learning about IPM, natural enemies, and rice agroecology through practical experience and in "Farm Field Schools" that enhance farmers' knowledge on beneficial biodiversity and scientific crop-management skills. By 1986, about 17,000 farmers had been trained per season in Sri Lanka. In Kasakolikasan, Philippines, 3,800 farmers have been trained, and their use of pesticides dropped between 60–98 percent and rice yields had increased between 5–15 % (Thrupp, 1996). TheBIOS (Biologically Intregrated Orchard Systems) program in California implemented by dozens of almond and walnut growers, demonstrates that biologically integrated systems (orchards with an undergrowth of selected cover crops), encourage natural control and thus reduce the reliance on pesticides and can be profitable (Thrupp, 1996).

BIOLOGICAL CONTROL IN BRAZIL (*Anticarsia gemmatalis Nucleopolyhedrovirus and Trichogramma spp.*)

Brazil has implemented several programs of classical biological control, the most recent one being for control of *Sirex notilio* (Hymenoptera: Siricidae) with entomopathogenic nematodes and three parasitoids. Brazilian sugarcane farmers apply *Cotesia flavipes* against sugarcane borer *Diatraea saccharalis* (Lepidoptera: Crambidae) on about 300,000 hectares per year. The egg parasitoid *Trissolcus basalis* (Hymenoptera: Scelionidae) of soybean bugs *Nezara viridula*, *Piezodorus guildinii* and *Euschistus heros* (Hemiptera: Pentatomidae) on 20,000 hectares of soybeans per year. The predatory mite *Neoseiulus californicus* (Acari: Phytoseiidae) is released against the spider mite *Panonychus ulmi* (Acari: Tetranychidae) in 1,800 hectares of apples (Bueno & van Lenteren, 2002).

The velvetbean caterpillar, *Anticarsia gemmatalis* (Lepidoptera: Noctuidae), is a major defoliating insect of soybean in Brazil, accounting for an average of two insecticide applications on this crop every season. In the State of Rio Grande do Sul, around 70% of the insecticide applications on soybean are made against this pest. The use of a nucleopolyhedrovirus of *A. gemmatalis* (AgMNPV) as a component of the soybean integrated pest management program has been important in reducing the chemical insecticide applications on the crop and thus their negative environmental impact, crop protection costs and cases of human intoxications. Initially, the AgMNPV was produced in the laboratory for further distribution of virus samples to soybean growers for its multiplication in the field on naturally occurring *A. gemmatalis* larval populations. Farmers would apply the virus in larger areas as viral crude preparations (homogenization in water and filtration through cloth), collect AgMNPV-dead larvae and store them in a freezer for use in the following soybean season. In 1986, a viral formulation was made available to soybean growers, and from the early 1990's five private companies started production and commercialization of this formulation, which is currently widely adopted among soybean growers (Moscardi, 1983; 1986; 1989; 1999).

During the 1993/94 season, cases of low quality and efficacy of the biological product were reported, which could be related to different factors affecting its stability and efficacy under field conditions. These may include: solar radiation, particularly the UV spectrum, relative humidity and precipitation, age and population intensity of the host insect, pH of the aqueous viral suspension in the spray tank, temperature; and viral formulation, equipment and application technology (Silva & Moscardi, 2002). Due to cases of low efficacy, particularly in Rio Grande do Sul, the treated area with the AgMNPV stabilized and even decreased in this state from mid 1990's. However, overall treated area in Brazil kept increasing and currently the AgMNPV is used in 1.2 to 1.4 million ha annually (Moscardi 1999). Silva & Moscardi (2002) pointed out that treatments involving the spray suspension at pH 6, application volumes of 100, 200 e 300 L/ha, and time of application at 2:00 a.m. e 8:00 p.m. improved the efficacy of the virus against *A gemmatalis* larvae compared to the other respective treatments. Nowadays, there is a local project (State of Parana) to improve AgMNPV use due to excessive aplications of pesticides against *A. gemmatalis*.

The research on *Trichogramma* has spread throughout Brazil, resulting in the appearance of other study groups involved with this subject (Espírito Santo, Rio Grande do Sul, Paraná, Rio de Janeiro, Mato Grosso, Santa Catarina, Paraíba, Pernambuco and Minas Gerais). Studies on *Trichogramma* have to focus on collection, identification and maintenance of *Trichogramma* strains; selection of factitious hosts for mass rearing of parasitoids; biological and behavioral aspects of *trichogramma* spp.; egg dynamics of target pests, parasitoid release; numbers, places, seasons and ways; selectivity of agrochemicals; efficiency evaluation and pest/parasitoid simulation model (Parra & Zucchi, 2004).

However, except for some cases, like the use of *T. pretiosum* to control *Tuta absoluta* (Lepidoptera: Gelechiidae), the releases on cotton by Embrapa Algodão, in Paraíba State, the sporadic use of *T. atopovirilia* and *T. pretiosum* to control *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in corn and *Plutella xylostella* (Lepidoptera: Plutellidae) in cabbage, the project has not reached large areas, due to the difficulty in transferring the technology, and particularly the lack of good quality insects available for the farmer. The volume of information and results are very interesting and liable to be used in crops such as cotton, soybean, sugarcane, tomato and other vegetables, corn, stored grain pests, etc. In addition, Garcia (1998) and Molina (2003) demonstrated the potential of use of *T. pretiosum* in citrus to control *Ecdytolopha aurantiana* (Lepidoptera: Tortricidae), the citrus fruit borer; in avocado, the parasitoid is being studied to control (Lepidoptera: Elachistidae) (Hohmann & Meneguim 1993); in agricultural crops, *T. pretiosum*, *T. atopovirilia*, and *T. galloi* have shown the greatest potential for use in Brazil (Parra & Zucchi, 2004).

Futher information on biological control program´s in Brazil are available in Alves & Lopes (2008), Parra *et al*. (2002), Pinto *et al*. (2006) and Polanczyk *et al*. (2008).

FARMERS' ATTITUDES TOWARDS BIOLOGICAL CONTROL

Until very recently, only few farmers (organizations) asked for, or stimulated, development of non-chemical control methods. The adoption of insecticides was rapid because they allowed the farmer to decide when and where they should be used. Decision criteria were clear, the method was easily understood, it was effective (at least in the short term), reduced labor costs, and was a practice the farmers could control and decide upon independently of their neighbors, institutions or agencies. Initially it was a straightforward technology. In contrast, integrated control is more complicated because of the requirement for the monitoring of various pests, the integration of different control methods and situation specific prescriptions.

The latter systems require a degree of knowledge and sophistication much greater than pesticide technology demands. Initiatives for development of IPM programs were made before and must still come from researchers and policy makers. Being unable to control a pest with chemicals is a stronger reason for farmers to change their ideas on IPM than ideological reasons. As soon as farmers realize that chemical control is no longer sufficient for complete control, their interest for an integrated approach was generated. We should not reproach the farmer for not being interested in IPM, because governments legislate the use of chemicals and often state that when chemicals are used as advised, they do not contaminate food or the environment and do not harm plants, animals or humans. Currently, the attitude of several groups of farmers is changing. European fruit growers and producers of greenhouse vegetables, for example, have experienced the positive aspects of integrated control and seriously worry about the increasing public concern on pesticide usage. Therefore, at present they generally prefer to use IPM methods (van Lenteren & Woets, 1988, van Lenteren 1993, van Lenteren, 2000). Therefore, it is the governmental bodies who should be the leaders here and who are in fact the only ones capable of changing the pest control scenario through measures that make some types of chemical control less attractive or impossible (by measures concerning registration, taxation, side-effect labeling etc.), and by stimulating other control methods (by funding research, but above all by teaching on all levels in order to change the attitude towards nature, and improvement of the extension service). It is a rather bizarre situation that public money is used for the development of alternatives for chemical control when, at the same time, their application is often not encouraged by governmental bodies, and due to the overall presence of (too) cheap broad-spectrum pesticides.

GENETICALLY MODIFIED CROPS AND BIOLOGICAL CONTROL

On a global scale, the area planted with genetically modified (GM) crops is steadily increasing, surpassing 114 million hectares in 2007 (James, 2007). While the majority of the crops have been modified for herbicide tolerance, more than 42 million hectares express the insecticidal trait Cry proteins (δ-endotoxins) derived from the soil bacterium *Bacillus thuringiensis* (Bt). Since the commercial introduction of the first GM variety in 1996, a vast body of research on the potential environmental impacts of such crops has been conducted and has not revealed any harm beyond that encountered with traditional pest-resistant crops and far less harm than caused by conventional pesticides (Sanvido *et al*., 2007).

Host plant resistance is one of the major tactics used to protect crops against pests and diseases and is an important part of IPM systems that aids to keep herbivore densities below the economic injury level. Insect-resistant GM crops may be considered as having a specific form of host plant resistance and there is no reason to hypothesize that GM host plant resistance will affect biological control agents in any other way than conventional resistance (Kennedy & Gould, 2007).

Most IPM systems aim to enhance biological control through conservation of existing natural enemies, or to introduce new ones through inoculation or inundation (Bale *et al*., 2008). It is, therefore, important to minimize the non-target effects of other IPM components, such as pesticides, GM plants or habitat manipulation. Expectations that biological control can act effectively as a sole method of pest management in field crops are generally unrealistic. Biological control, however, is an important component of IPM systems. Conserving beneficial organisms along side other crop managements requires that the pest manager understands the role of biological control agents in regulating pests, their biology, environmental requirements and the ways in which they can be adversely affected by other practices (Romeis *et al*., 2008).

Insect-resistant plants, whether produced by conventional breeding or through genetic engineering, can have impacts on natural enemies (Kennedy & Gould, 2007). Such effects can stem from changes in the plant structure or primary and secondary plant metabolites. Adverse effects can occur, for example, if the natural enemy is exposed to the plant-born insectidal factor and is susceptible to it. Theses factors can cause population level effects which might lead to changes in true level of biological control that natural enemies provided (Romeis *et al*., 2008).

CONCLUDING REMARKS

The future of biological control agents is bright but depends on technological advancements and market opportunities. Commercial interest and user acceptance of biological control agents as pest management tools is dependent on the development of low-cost, stable products which provide consistent efficacy. Solutions to key technical problems and implementation of optimization and design strategies will require research contributions from a variety of subjects. International academic, industrial, and government scientists must all work together so that significant advances in the commercialization of biological control agents can be achieved.

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