Chapter 9
Biological Control and Integrated Pest Management

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Abstract The manipulation of beneficial organisms remains a very important tool in integrated pest management programs of insect pests worldwide. This chapter describes the approaches to using biological control and a historical perspective of each. Recent developments in genetics, systematics, population dynamics, pesticide chemistry, and public opinion have led to increased scrutiny and inclusion of beneficial insects into IPM programs. This chapter describes these developments and the variety of approaches that have been used to implement biological control as a useful tactic in IPM. It also describes how biological control interacts with other IPM tactics, and the potential for better integration into IPM programs.

Keywords Beneficial organisms · Importation biocontrol · Augmentation · Conservation biocontrol · Predators · Parasitoids

9.1 Introduction

Biological control has been a valuable tactic in pest management programs around the world for many years, but has undergone a resurgence in recent decades that parallels the development of IPM as an accepted practice for pest management. This chapter is not intended to be an exhaustive review of research involving biological control. Instead, it will try to focus on implementation of biological control practices in insect pest management programs. It will begin with an overview of the general concepts and challenges facing the use of beneficial organisms within each of the general approaches to biological control. A brief historical perspective of biological control follows. Next, the interaction of biological control with the various elements of integrated pest management programs is considered. Existing implementation, as well as potential uses of biological control in IPM are also considered.

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9.2 Approaches to Biological Control

Natural enemies have been utilized in the management of insect pests for centuries. However, this last 100 years has seen a dramatic increase in their use as well as our understanding of how they can better be manipulated as part of effective, safe, pest management systems. Recent advances in molecular systematics are shedding new light on classification of groups of beneficial insects such as the Hymenoptera (e.g. Sharkey, 2007), and delivery of this information on the internet makes it quickly and widely available (e.g. The Tree of Life Web Project at http://tolweb.org). Recent advances in the study of beneficial organism behavior (e.g. parasitoid foraging: Smid et al., 2007; van Nouhuys and Kaartinen, 2008) and reproductive biology (e.g. symbionts in parasitoids: Clark, 2007) are revealing surprising complexities in the life histories of these organisms. Understanding this complexity should lead to potential new methods for their manipulation.

Despite the long history of utilizing natural enemies, it wasn't until 1919 that the term biological control was apparently used for the first time by the late Harry Smith of the University of California (Smith, 1919). There has been debate regarding the scope and definition of biological control brought about by technological advances in the tools available for pest management. (see Nordlund, 1996). In this chapter I will follow the definition presented by DeBach (1964) as the "study, importation, augmentation, and conservation of beneficial organisms to regulate population densities of other organisms". Biological control efforts conducted with predators and parasitoids still can be organized under three general approaches: importation, augmentation and conservation of natural enemies (Debach, 1964; Bellows and Fisher, 1999). Each of these approaches has been used to varying degrees in integrated pest management programs (see Fig. 9.1).

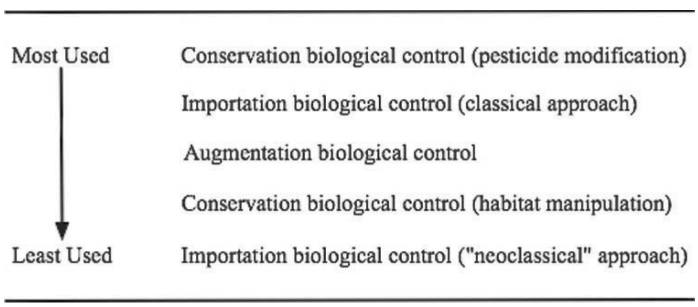

Fig. 9.1 Relative frequency of implementation of various biological control practices in IPM

9.2.1 Importation Biological Control

Importation biological control is often referred to as "classical biological control", which reflects the historical predominance of this approach to utilizing beneficial insects. It usually involves the re-uniting of natural enemies with pests that have escaped them into a new geographical area. Although the practice of introducing biocontrol agents from a related host species for the control of native arthropod pests has been used, in some cases effectively, this approach has been strongly criticized for its potential non-target impacts (see discussion below, this section).

9.2.1.1 Success Rates

From 1890 through 1960, approximately 2300 species of parasitoids and predators were introduced in approximately 600 different situations worldwide for suppression of arthropod pests (Hall et al., 1980). The overall level of establishment of these natural enemies was calculated to be 34%, with complete suppression of target pests occurring in 16% of situations, and some level of pest suppression achieved in an additional 42% of situations (Hall and Ehler, 1979; Hall et al., 1980). These rates have apparently not increased over the last 100 years (Hall and Ehler, 1979; Hall et al., 1980), although the percentage of successful projects that are complete successes has reportedly risen since the 1930's (Hokkanen, 1985). A more recent analysis has shown that the percentage of agents that establish is between 20 and 55%, and the percentage of introductions contributing to success falls within the range 5 ± 15% (Greathead and Greathead, 1992; Gurr and Wratten, 1999).

9.2.1.2 Economics

Economic assessments of the use of introduced natural enemies are not common, but have been made for several arthropod pests (Ervin et al., 1983; Voegele, 1989; Tisdell, 1990; Jetter et al., 1997; Zeddies et al., 2001; Kipkoech et al., 2006). The most common method of determining the economic benefits of biological control programs is cost-benefit analysis, which offers a systematic way of determining if the use of biological control results in a net gain (Headley, 1985; Tisdell, 1990). Classical biological control programs have produced some of the highest benefit-to-cost ratios of any pest management approach, exceeding billions of dollars in terms of total savings (Tisdell, 1990). Several highly successful individual projects have produced exceptional ratios. For example, a recent introduction program initiated against the ash whitefly in California resulted in a benefit: cost ratio ranging between \$270:1 and \$344:1 (Jetter et al., 1997). Zeddies et al. (2001) estimated the benefit to cost ratio of biological control targeting the cassava mealybug *Phenacoccus manihoti* Mat.-Ferr. (Homoptera: Pseudococcidae) in sub-Saharan Africa ranged from 200: to 740:1, depending on the market price used for cassava. Marsden et al. (1980) reported an average benefit-cost ratio (for the period 1960–2000) of 9.4:1 for three importation biological control programs conducted by CSIRO Division of Entomology against insect pests in Australia, compared to a 2.5:1 benefit-cost ratio for non-biological control projects conducted by the agency during the same time period. However, these numbers do not reflect the average of all projects that have been done, i.e. both successful and unsuccessful. Since the success rate of classical biological control has ranged between 5 and 15% for the last 100 years (Gurr and

Wratten, 1999), the average cost-benefit ratio of all importation programs combined is undoubtedly lower than for only the successful programs. Regardless, economic benefits that are provided by successful classical biological control are enhanced by the fact that programs are self-sustaining and permanent, so that benefits continue to accrue annually without additional cost.

9.2.1.3 Non-target impacts

Because importation biological control has historically been targeted primarily towards exotic pest species, it is particularly suited as a pest management tactic for exotic invasive pests. This approach continues to play an important role in this area. An example is the recent successful control of glassy-winged sharpshooter in the South Pacific (Grandgirard et al., 2008). However, because these agents are exotic, there is the possibility for non-target impacts.

Some controversy had developed over the last two decades regarding these potential non-target impacts (see reviews of this subject by Follett and Duan, 2000; Bigler et al., 2006; Van Lenteren et al., 2006). Simberloff and Stiling (1996) summarized the controversy and highlighted potential risks such as predation or parasitism of non-target species, competition with native species, community and ecosystem effects, and unexpected effects such as loss of species dependent on the target of biological control efforts. The significance and practical impacts of these potential non-target impacts has been thoroughly debated in the literature (Simberloff and Stiling, 1996, 1998; Frank, 1998; also see articles in Follett and Duan, 2000; Bigler et al., 2006), and conclusions vary depending on individual perspective. Many biological control scientists view these impacts as a real concern, but primarily as a problem of the past currently considered and dealt with by existing rules and regulations. They also feel that the benefits provided by importation biological control far outweigh the few negatives resulting from occasional cases of non-target impacts. Simberloff and Stiling (1996) argued that the few documented cases of non-target impacts, compared with the number of natural enemy introductions, may have been more the result of a lack of monitoring and documentation than a lack of actual impacts. This suggestion may be supported by the database on non-target effects of importation and augmentation compiled by Lynch and Thomas (2000). These authors found that from the relatively few cases where data had been collected in biocontrol projects, there appeared to be a number of non-target effects, although these were primarily from very early importation efforts and were mostly relatively minor.

There is one example of a biological control agent that became a widespread and well known pest following its release. The ladybeetle *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae) was released in North America and Northwest Europe as a predator of aphid pests (Roy and Wajnberg, 2008; Koch and Galvan, 2008). However, it has become not only a threat to native biodiversity and possibly ecological services through intra-guild and inter-guild predation, but also a noxious household pest, and minor agricultural pest (Roy and Wajnberg, 2008; Koch and Galvan, 2008).

9.2.1.4 Pest Resistance

Although importation biocontrol has been practiced for more than 100 years, there has only been one documented case of a target pest developing resistance to a biological control agent. The introduced larch sawfly, Pristophora erichsonii (Hartig) (Hymenoptera: Tenthredinidae), improved its defenses against the parasitoid Mesoleius tenthredinis Morley (Hymenoptera: Ichneumonidae), after the parasitoid was introduced into Canada for suppression of the pest (Messenger and van den Bosch, 1971; Pschorn-Walcher, 1977). This suggests that importation biological control is a highly sustainable practice for management of insect pests.

9.2.2 Augmentation Biological Control

Augmentation biological control includes activities in which natural enemy populations are increased through mass culture, periodic release (either inoculative or inundative) and colonization, for suppression of native or non-native pests. Augmentation is a practice that has been widely recognized by the general public for some time in the United States mainly as a result of widespread availability of arthropod natural enemies such as lady beetles (especially *Hippodamia convergens* Guerin-Meneville) and mantids through garden catalogs and nurseries (Cranshaw et al., 1996). The expansion of the internet in recent years has only increased this awareness.

9.2.2.1 Scientific Basis of Augmentation

Augmentation biological control has recently been criticized (Collier and van Steenwyk, 2004) and debated (van Lenteren, 2006; Collier and van Steenwyk, 2004, 2006) in the literature regarding the scientific foundation, efficacy, and cost effectiveness of its use in pest management. Some of these issues have been discussed in the past. Several authors have called for development of predictive models to assist in implementation of augmentation biological control (Huffaker et al., 1977; Stinner, 1977; King et al., 1985; van Lenteren and Woets, 1988; Ehler, 1990), but this has only rarely been done (see for example Parrella et al., 1992). Because of the lack of supporting data for many augmentation approaches, (Parrella et al., 1992) stated that recommendations could not be made regarding rates and application methodologies that provide predictable results. Poor quality of released natural enemies or incorrect release rates can lead to unsatisfactory pest suppression and contribute to the unpredictability of augmentation biological control (Hoy et al., 1991). However great strides have been made recently to improve this situation (see articles in van Lenteren, 2003a).

Several explanations have been offered for the lack of experimental work supporting augmentation. One is certainly the tremendous logistical difficulties involved in conducting the large-scale, statistically valid, detailed studies that are required to effectively evaluate natural enemy augmentation (Luck et al., 1988). Another may be a perceived similarity between augmentative releases and the insecticide paradigm that has discouraged research interest in this area (Parrella et al., 1992). In this regard, augmentation could be considered the least sustainable of the three types of biological control, because it does require continued external inputs.

9.2.2.2 Implementation of Augmentation

Despite these concerns, as van Lenteren (2006) points out there are numerous examples of successful implementation of augmentation (Gurr and Wratten, 2000; van Lenteren and Bueno, 2003; Shipp et al., 2007). Van Lenteren (2003b) estimated that approximately 17.1 million hectares are under some form of augmentation. A significant industry has developed that supplies these organisms (van Lenteren, 2003b). Hunter (1997) reported 142 commercial suppliers and over 130 different species of beneficial organisms, of which 53 were arthropod predators and 46 were parasitoids. An annually updated list included in the "Directory of Least Toxic Pest Control Products" produced by the Bio-Integral Resource Center of Berkeley, California (www.birc.org) includes natural enemies and the companies that provide them. These products are focused on the greenhouse market, and only four pest groups (whiteflies, thrips, spider mites, and aphids) account for 84% of expenditures on augmentation (van Lenteren, 2003b). The augmentation biological control industry is supported by a sizeable scientific community (see for example articles in van Lenteren, 2003a; Enkegaard, 2005; Castañé and Sánchez, 2006).

In addition to larger scale commercial sales, there are a number of state and farmer operated insectaries (van Lenteren, 2003c). The bulk of these insectaries apparently rear *Trichogramma* spp. wasps for release against lepidopteran pests (Smith, 1996). An intriguing example of widespread use of augmentation comes from Cuba where trade embargos prevented other pest management tactics from being practicable (Dent, 2005).

9.2.2.3 Non-Target Impacts

Augmentation biological control often utilizes exotic natural enemy species that have broad host ranges, and undoubtedly have some effect on populations of non-target insects. However, augmentation does not face the same scrutiny as importation biocontrol over these potential non-target impacts. This is at least in part due to the temporary, non-persistent activity of released natural enemies (Lynch and Thomas, 2000; van Lenteren et al., 2006).

9.2.3 Conservation Biological Control

Conservation biological control seeks to understand human influences on resident natural enemies in a system, then manipulate those influences to enhance the ability of natural enemies to suppress pests. DeBach (1964) considered conservation biological control to be environmental modification to protect and enhance natural enemies. These activities range from modification of pesticide use practices to manipulation of beneficial insect habitat within an agroecosystem (for reviews, see Barbosa, 1998; articles prefaced by Pimentel, 2008).

9.2.3.1 Pesticide Use Modification

Probably the most common pest management activity that negatively impacts beneficial organisms in agroecosystems is pesticide application. As a result, modifications of pesticide use practices are the most commonly implemented form of conservation biological control (Ruberson et al., 1998), and have long been considered an important component of integrated pest management programs (Stern et al., 1959; DeBach, 1964; Newsom and Brazzel, 1968).

Pesticide use can be modified to favor natural enemies in a variety of ways, including treating only when economic thresholds dictate, use of active ingredients and formulations that are selectively less toxic to natural enemies, use of the lowest effective rates of pesticides, and temporal and spatial separation of natural enemies and pesticides (Hull and Beers, 1985; Poehling, 1989; Ruberson et al., 1998). Decisions regarding pesticide use for insect pests in IPM programs are typically based on sampling pest populations to determine if they have reached economic threshold levels (Pedigo, 1989), although some work has been done to incorporate natural enemy sampling into these pesticide use decisions.

9.2.3.2 Other Approaches to Conservation Biocontrol

A variety of other approaches to conservation biological control have been studied, and are comparatively complex. These include management of soil, water and crop residue; modification of cropping patterns; manipulation of non-crop vegetation; and direct provision of resources to natural enemies (see review by Barbosa, 1998; articles introduced by Pimentel, 2008). In general, these approaches are aimed at enhancing the density of resident natural enemy populations or communities to increase their effectiveness in pest suppression. As highlighted by Ehler (1998) and Jonsson et al. (2008) many of the management techniques developed for conservation biological control (other than pesticide use modification) have been of academic, rather than practical interest, and are not widely implemented in IPM programs. However, a considerable amount of research has been conducted in this area recently and there appears to be great potential for future applications in IPM programs (Jonsson et al., 2008).

One possible explanation for the low rate of success in importation biological control compared with establishment rates of introduced natural enemies is the lack of resources available for enemies in agroecosystems (Gurr and Wratten, 1999). Provision of these resources through conservation biological control methods has been suggested as one way to improve the success rate for both importation and augmentation, an approach referred to as integrated biocontrol (Gurr and Wratten, 1999).

9.2.3.3 Economics

Unlike importation and augmentation biological control, economic assessments of conservation biological control programs are not only rare, but uniquely difficult to conduct (Cullen et al., 2008). These authors, however, suggest an approach for conducting such an assessment.

9.3 Historical Perspective of Biological Control

The first accounts of predatory insects being used as insect management tools date back as early as 300 AD when Chinese citrus growers placed paper nests of ants (*Oecophylla smaragdina* F.) on trees to protect them from other insects (van Lenteren, 2005). These early augmentation efforts were apparently helped along by the conservation biological control practice of aiding inter-tree movement of the ants by placing bamboo rods as runways or bridges between trees (DeBach, 1974). These ants reportedly were still available for purchase up to at least the 1970's (DeBach, 1974).

While the predatory behavior of some insects was recognized long ago and taken advantage of for pest management, the recognition and utilization of the less obvious parasitic insects did not occur until much later. Parasitism by tachinid flies was first correctly interpreted in China in the 11th century, while ichneumonoid parasitism was correctly interpreted in Europe in the 17th century (Cai et al., 2005; van Lenteren and Godfray, 2005). The difference in time between these two events was likely the more complex life history of the latter group.

The first deliberate movement of parasitoids from one location to another was conducted by C.V. Riley, who distributed parasitoids of the weevil *Conotrachelus nenuphar* (Herbst) around the state of Missouri in 1870 (Doutt, 1964). The first parasitoid successfully moved and established from one continent to another, however, was *Cotesia (=Apanteles) glomeratus* (L.), which was shipped from England to the United States for suppression of *Pieris rapae* (L.) by the U.S. Dept. of Agriculture in 1883 (Riley, 1885; Riley, 1893). Transcontinental shipment of a predatory arthropod soon followed with the transport of the predatory mite, *Tyroglyphus phylloxerae* Riley &. Plancon, from the United States to France in 1873 for suppression of the grape phylloxera, *Daktulosphaira vitifoliae* (Fitch) which it did not suppress (Fleschner, 1960; Doutt, 1964). While a variety of international movements of insects for pest control occurred in the late 1800s, none of them achieved complete economic control (Fleschner, 1960).

It is generally accepted that the first case of complete and sustained economic control of an insect pest by another insect was control of the cottony cushion scale, *Icerya purchasi* Maskell, in California during the late 1800s (Fleschner, 1960; Doutt, 1964; Debach, 1974; van den Bosch et al., 1982). *Icerya* was introduced into Californiai in 1869, and by 1886 it threatened to destroy the entire southern California citrus industry (DeBach, 1974). Two insects, the vedalia beetle, *Rodolia cardinalis* Mulsant (Coleoptera: Coccinellidae), and a parasitic fly, *Cryptochetum* *iceryae* (Williston) (Diptera: Cryptochètidae), were imported to California from Australia in 1877 and 1888. Within two years, *I. purchasi* was under complete biological control throughout the state. Although the vedalia beetle is mostly credited for controlling the cottony cushion scale, once established, the parasitic fly became the major control factor of the pest in the coastal areas of the state (Van Driesche and Bellows, 1996). This classic example is presented in many books dealing with insect biological control (e.g. DeBach, 1964, 1974; van den Bosch et al., 1982; Van Driesche and Bellows, 1996), and set the stage for future biological control programs. Probably because *I. purchasi* provides suppression of *C. iceryae* only over a limited portion of the pests' range, Greathead (1986) considered the importation of *Encarsia berlesi* (Howard) into Italy from USA in 1906 for control of the mulberry scale, *Pseudaulacaspis pentagona* Targioni-Tozzetti to be the first successful introduction of a parasitoid from one country to another for insect pest control.

Following the success of the cottony cushion scale project, numerous biological control efforts ensued worldwide (Clausen, 1978; Luck, 1981; van den Bosch et al., 1982; Greathead, 1986; Greathead and Greathead, 1992) some of which were just as successful. Although the primary focus of early efforts in biological control was importation of natural enemies, other methods of manipulating parasitoids and predators were also considered. While the concept of mass rearing insects for future releases was proposed as early as 1826 by Hartig, the first practical attempt towards augmentation of natural enemies in western Europe was probably made in 1899 by Decaux who devised a complete management program for apple orchards, including releases of field-collected inchneumonid wasps (Biliotti, 1977). The first sustained, large-scale, and successful augmentation biological control project involved mass-production of the ladybeetle *Cryptolaemus montrouzieri* Mulsant, targeting the citrophilus mealybug, *Pseudococcus calceolariae* Fernald (= gahani Green), a pest of citrus in southern California (Luck and Forster, 2003). Large-scale releases began in the early 1920's, and continued for decades, with as many as 40 million beetles being produced annually. This beetle is still available through commercial insectaries in both the United States and Europe (van Lenteren, 2003b).

The history of conservation biological control has been one of mainly potential practices developed by researchers that do not appear to have become widely adopted (Ehler, 1998). However, organic and sustainable farming systems have tried to take advantage of these practices to some degree (Altieri et al., 2005).

9.4 Interaction of Biological Control with Other IPM Tactics

In integrated pest management programs, specific tactics often do not act independently of one another. This may be especially so for biological control since the agents of insect biological control such as parasitoids and predators are susceptible to environmental perturbations such as pesticide applications. This section will examine how biological control interacts with the various tactics employed in IPM programs.

9.4.1 Population Monitoring

Pest population monitoring is a cornerstone of many IPM programs. Pesticide use decisions for insect pests are typically based on sampling pest populations to determine if they have reached economic threshold levels (Pedigo, 1989), although some work has been done to incorporate natural enemy sampling into these pesticide use decisions. Sampling for natural enemy populations or their effect on pests can be used to revise economic thresholds to more accurately determine the need or timing for pesticide applications within a pest generation (Ostlie and Pedigo, 1987), or to predict the need for treatment of a future pest generation (Van Driesche et al., 1994). An example is a sequential sampling plan that takes into account parasitized *H. zea* eggs when estimating this pest's population levels in tomatoes (Hoffman et al., 1991). Formal revised economic thresholds incorporating natural enemy numbers are not common in IPM programs. However, consultants and other pest management professionals probably informally incorporate natural enemy numbers into decision making more frequently, such as with cotton aphid management in the mid-Atlantic region of the United States (Orr and Suh, 1999). However, the use of economic thresholds alone in IPM doesn't necessarily lead to natural enemy conservation, if for example a broad-spectrum pesticide is used for treating pest populations when they exceed threshold levels (Ruberson et al., 1998). Consideration of natural enemy numbers, as well as careful selection of pesticide use practices (discussed below) can lead to a more integrated approach to IPM.

9.4.2 Cultural Controls

A variety of cultural practices such as management of cropping patterns, soil, crop residue, and non-crop vegetation are used in management of insect pests. These practices in some cases can be manipulated to enhance natural enemies of insect pests. In general, these approaches are aimed at increasing the density of resident natural enemy populations or communities to increase their effectiveness in pest suppression.

9.4.2.1 Habitat Stability

It has long been recognized that perennial cropping systems such as orchards are more favorable to natural enemies and biological control because of the habitat stability they provide (DeBach, 1964). Habitat stability can also be provided in situations where crop cycles overlap throughout the year in a substantial portion of the landscape so that individual fields are not too far apart for enemies to move between them (e.g. Mogi and Mayagi, 1990). Although there are several examples of harvest modification to allow for conservation of beneficials such as alfalfa strip harvesting (Stern et al., 1976), hay strip-harvesting (Nentwig, 1988), alternate row pruning (Rose and DeBach, 1992), and relay cropping or intercropping (e.g. Bugg et al., 1991; Parajulee and Slosser, 1999), logistical concerns prevent widespread adoption of these practices (Hokkanen, 1991; Ehler, 1998; Jonsson et al., 2008).

9.4.2.2 Crop Rotation

Crop rotation is a foundation for pest management in some cropping systems, dissociating pest populations from continued food supply from one year to the next. Although not common, crop rotation can also affect populations of beneficials such as ground-dwelling rove beetles (Lubke-Al-Hussein and Al-Hussein, 2006). Placement of rotated crops in relation to prevailing wind direction and previous years crops may influence the ability of parasitoids to locate and colonize the new crop (Williams et al., 2007)

9.4.2.3 Intercropping

The increased vegetational diversity provided by intercropping was proposed by Root (1973) as a possible means to reduce pest discovery and retention in crops, and to enhance natural enemy populations and activity (Root, 1973). Andow (1986, 1988) reviewed intercropping studies in the literature and noted that pest densities were reduced in 56% of cases, increased in 16%, and not affected in 28%. Russell (1989) reviewed natural enemy activity in intercropping studies, and reported increased pest mortality due to natural enemies in 70% of cases, lowered mortality in 15%, and no effect in another 15%. The responses of both pest and beneficial insects to intercropping are not well understood, because the underlying mechanisms at the behavioral level have not been well studied (Bukovinszky, 2007). An understanding at this level is important to develop intercropping systems with more predictable outcomes.

9.4.2.4 Trap Cropping

Trap crops are deployed to intercept dispersing pests before they can enter the main crop, allowing control measures to take place in a smaller area (Hokkanen, 1991). Natural enemies invariably follow these pests, and may be affected as well. These effects may be positive, where natural enemy populations are able to build up on concentrated pest populations and then move into the main crop (Hokkanen, 1991), although this does not necessarily lead to increased pest reductions in the main crop (Tillman, 2006a). The trap crops may also act as a sink for insect pest populations as a result of increased natural enemy activity (Tillman, 2006b). However, control measures taken for pests in trap crops have the potential to negate these positive effects by eliminating natural enemies as well. (Hokkanen, 1991), although this is not necessarily the case. Barari et al. (2005) found that parasitism of the oilseed rape (*Brassica napus* L.) pest *Psylliodes chrysocephala* (L.) (Coleoptera: Chrysomelidae) by the ichneumon wasp *Tersilochus obscurator* Aub. was not affected by insecticide treatment of a bordering trap crop of turnip rape (*Brassica rapa* L.). This was at least in part due to temporal separation of insecticide treatment and peak parasitoid activity. Even if control measures are used in traps crops, the main impact of trap cropping on beneficial insects may be the reduction in pesticide usage in the main crop resulting in conservation of beneficial insect populations.

9.4.2.5 Cover Cropping

Cover crops are employed in crop production systems for a variety of reasons including soil fertility, erosion control, and in some cases, pest management (Mangan et al., 1995; Teasdale, 1996). In a number of agricultural systems, cover crops have been shown to disrupt behavior of pest insects and reduce their abundance (Bugg, 1992; Bugg and Waddington, 1994; Teasdale et al., 2004). It is less clear how cover crops influence natural enemies, and as a result the pest insects they attack. For example, clover cover crops have been shown in some studies to enhance natural enemy populations in cotton (Tillman et al., 2004), while other studies have found no effect (e.g. Ruberson et al., 1997). Buckwheat (*Fagopyrum escalentum* Moench) has been shown to enhance natural enemy activity in crops as diverse as cabbage and grapes (e.g. English-Loeb et al., 2003; Lee and Heimpel, 2005), but in very few cases have effects on pest densities been associated with this enhancement (e.g. Nicholls et al., 2000). When mulched, cover crops can provide microhabitats favorable to insect natural enemies and increase their numbers (Altieri et al., 1985; Stinner and House, 1990; Orr et al., 1997). There does not appear to be any study that links enhancement of natural enemy populations by cover crops with economic suppression of insect pests.

9.4.2.6 Manipulation of Non-Crop Vegetation

Because cultural control practices may include consideration of non-crop vegetation, it's appropriate to outline some considerations of this vegetation by workers in biological control. Research examining the manipulation of vegetation, or habitat, within agroecosystems on a variety of scales has come to dominate studies of conservation biological control recently (see articles introduced by Jonsson et al., 2008). The goal is to build populations of beneficial insects to reduce pest populations, and increase crop yields. There are few studies where all three goals have been met, but this work appears to hold much promise. In addition to natural control, Gurr and Wratten (1999) argue that success levels of importation (classical) and augmentative releases of biological control agents could be increased through habitat manipulation. They suggest that little consideration is given to these enemies beyond their host range, host/prey consumption rates and climatic requirements. They point out that poor availability of key ecological resources such as nectar, pollen, moderated microclimate, or alternative hosts may constrain the ability of enemies to regulate host populations following their release.

While IPM practitioners have often focused on implementing biological control on a more local scale, such as an individual field, studies have indicated that landscape structure may be quite important in determining the levels of natural control provided by beneficial insects (Thies and Tscharntke, 1999; Tscharntke et al., 2007).

Fiedler et al. (2008) suggest that the goals of conservation biological control may be more easily met by combining multiple ecological service goals. This might be accomplished by looking for synergies in various activities such as biodiversity conservation, ecological restoration, human cultural values, tourism, biological control and other ecosystem services

The concept of agrobiodiversity (see series of 22 articles in van Rijn, 2007) has recently been promoted for not only the practical values provided by ecological services such as biological control and pollination, but also for preserving or enhancing biodiversity in agricultural landscapes for its own sake. Likewise, concepts such as farmscaping (Dufour, 2000) and permaculture (Mason, 2003) have tried to incorporate similar ideas to enhance ecological values such as natural controls in agricultural or residential settings.

While there is limited information on how fertilization affects natural enemies, parasitoid activity may be lowered under reduced nitrogen conditions (Fox et al., 1990; Loader and Damman, 1991; Bentz et al., 1996). However, Chen and Ruberson (2008) reported that increasing levels of nitrogen fertilization in cotton in field conditions decreased predation, but did not affect parasitism. Thomson and Hoffmann (2007) found that even though mulches increased populations of both soil dwelling predators as well as canopy dwelling predators and parasitoid, they had no effect on pest populations.

9.4.3 Mechanical or Physical Controls

9.4.3.1 Tillage

Tillage is the primary means of disturbance in agroecosystems, and is central to many agricultural practices such as preparation of seedbeds, incorporation of organic material and fertilizer, and suppression of weeds and some diseases and insect pests (Gebhardt et al., 1985). Tillage practices can have significant influences on arthropod populations, including natural enemies, and in turn pest management (Hammond and Stinner, 1999).

A significant amount of research has been directed toward understanding the influence of reduced tillage systems on arthropods, including natural enemies. In some cases, conservation tillage has been shown to increase natural enemy populations (e.g. Gaylor et al., 1984; McCutcheon et al., 1995; McCutcheon, 2000; Tillman et al., 2004), while in others they were either not affected (Ruberson et al., 1997; Gencsoylu and Yalcin, 2004), or reduced (Ruberson et al., 1995).

Much of the work dealing with soil-dwelling insect natural enemies has focused on carabid beetles (Coleoptera: Carabidae), which are significant generalist predators in annual row-crop agricultural systems (Thiele, 1977; Kromp, 1999; Menalled, 2007). Tillage affects carabid populations through direct mortality from tillage events, or indirectly through loss of prey resources and changes in microclimate (Hance et al., 1990; Thorbek and Bilde, 2004). Shearin et al. 2007 reported that entomophagous carabid beetles were more sensitive to tillage than herbivorous carabids. While diversity and abundance of carabids appears to be favored by reduced tillage (see review by Shearin et al., 2007), there are examples where entomophagous beetles are significantly more abundant in conventional tillage systems (e.g. Carcamo, 1995; Menalled, 2007).

Interpretation of results of these studies is complicated by the sampling method employed. Populations of carabids are usually sampled with pitfall traps with trap catches expressed as activity-density (Thomas et al., 1998). However, there are significant constraints to using this method, and care should be taken when designing studies and interpreting results (Thomas et al., 2006). In addition, dispersal of beetles between experimental plots may mask treatment effects (Thorbek and Bilde, 2004; Shearin et al., 2007). More work appears to be needed to gain a clearer understanding of the effects of tillage on ground-dwelling arthropod natural enemies. What is less clear, and needs even more work perhaps, is the link between population changes in enemies from tillage practices and suppression of target insect pest populations.

Tillage has also been found to affect foliage dwelling arthropod predators (House and Stinner, 1983; Troxclair and Boethel, 1984; Funderburk et al., 1988; Hammond and Stinner, 1999; Marti and Olson, 2007) as well as parasitoids (Nilsson, 1985; Ellis et al., 1988; Runyon et al., 2002; Weaver, 2004; Williams, 2006; Rodriguez et al., 2006) either directly from soil disturbance, or indirectly by altering weed communities. This is especially important where natural enemies pupate in soil. For example, an outbreak of cereal leaf beetle, *Oulema melanopus* (Coleoptera: Chrysomelidae), in Canada was linked to a change in tillage practices that killed parasitoids of the beetle overwintering in the soil (Ellis et al., 1988).

In addition to tillage, other practices used to manage crop residues can affect natural enemies. Several studies have shown that leaving crop residues behind, in cases where there is no good pest management (or other) reason to remove them through tillage or other means, can conserve populations of parasitoids and predators (Joshi and Sharma, 1989; Mohyuddin, 1991; Shepard et al., 1989).

9.4.3.2 Traps and Barriers

Traps and barriers are frequently employed in IPM programs to either reduce pest numbers directly or deny them access to crops (Pedigo, 1989). However, there are cases where they may have side effects on beneficial organisms that may interfere with pest management.

Semiochemicals, including pheromones and kairomones, are commonly utilized in host-finding by natural enemies such as parasitoids (see reviews by Vet and Dicke, 1992; Powell, 1999). They may have potential for manipulating populations of natural enemies to benefit pest management (e.g. Powell and Pickett, 2003; Quarles, 2007; Khan et al., 2008). These same semiochemicals in turn can have non-target impacts on natural enemies when traps employing them are used in IPM programs (e.g. Franco et al., 2008; Perez and Sierra, 2006).

In mass-trapping efforts or even monitoring with traps such as colored sticky traps, attraction and effect on natural enemy populations should be considered prior to implementation (e.g. Blackmer et al., 2008). Frick and Tallamy (1996) found that electric traps, using ultraviolet light as an attractant killed almost exclusively non-target insects, rather than the targeted biting flies, with approximately 13.5% of the catch predatory and parasitic insects.

Mesh size of insect barriers require testing to determine the size that excludes pest, but does not also exclude natural enemies that may be attacking other pests in a cropping system (Hanafi et al., 2007). The use of UV blocking films has potential for use in IPM programs against insect pests in greenhouse crop production, through interference with insect visual receptors and behavior (Doukas and Payne, 2007). However, these films also have the potential to interfere with biological control, and more studies examining effects on natural enemies should be undertaken (Doukas and Payne, 2007).

In the 1980's and 90's vacuum systems became popularized for management of insect pests organically, and a few systems are still available for this purpose (Kuepper and Thomas, 2002). Studies conducted to date have not demonstrated any negative impact on beneficial insects in crop field treated with the vacuums (Kuepper and Thomas, 2002).

9.4.4 Plant Breeding and Transgenic Crops

Both biological control and host plant resistance are important components of many IPM programs. However, these two methods do not necessarily act on target pests independently of one another, and IPM practitioners should consider their interactions when designing management programs (Bottrell et al., 1998). Pest resistant plants can have a variety of positive and negative influences on natural enemies (see reviews by Boethel and Eikenbary, 1986; Dicke, 1999; Ode, 2006). Likewise enemies can contribute to the sustainability of plant resistance by slowing pest adaptation to resistant plants (Gould et al., 1991; Gould, 1998).

9.4.4.1 Conventional Plant Breeding

Conventionally bred resistant plants affect natural enemies either directly through chemical or physical plant traits such as trichomes, or indirectly through plant mediated effects on host or prey characteristics such as quality (Godfray, 1994; Kennedy, 2003; Ode, 2006). These effects can be either constitutive, or inducible as a result of herbivore attack (Dicke et al., 2003; Kennedy, 2003; Pieterse and Dicke, 2007).

Although the interactions between natural enemies and pest-resistant plants have been studied for decades (see for example Boethel and Eikenbary, 1986), most attention in this field has been focused recently on genetically-modified or transgenic plants. This is especially timely now, given the expansion of transgenic crops into areas where they were previously excluded (Pollack, 2008).

9.4.4.2 Transgenic Plants

Transgenic plants currently deployed act on natural enemies directly, in a manner similar to antibiosis (Gould, 1998). The majority of studies done to date have not reported profoundly negative effects of transgenic plants on arthropod natural enemies (Callaghan et al., 2005). Lovei and Arpaia (2005) in reviewing the literature dealing with laboratory studies of the effects of transgenic plants on arthropod predators and parasitoids, reported that roughly one third of these studies indicated significantly negative effects of genetically modified plants on life history parameters of predators (30%) and parasitoid (39.8%). However, they note that there were inadequacies in the experimental methods used for these studies, including: artificial test conditions not at all related to those insects would experience under field conditions, small range of taxa tested, and variability in the types of measured parameters. Romeis et al. (2006) reviewed laboratory, greenhouse, and field studies that examined effects of transgenic crops expressing *B. thuringiensis* toxins on arthropod predators and parasitoids. They conclude that there were no direct toxic effects, and negative effects only occurred where Bt susceptible, sublethally damaged herbivores were used as prey or hosts. Several reviews have concluded that Bt cotton has a minimal impact on beneficial insect communities in cotton worldwide (Sisterson et al., 2004; Naranjo, 2005; Whitehouse et al., 2005).

Field studies reviewed by Romeis et al. (2006) indicated that abundance and activity of predators and parasitoids were similar in Bt and non-Bt crops. Romeis et al. (2006) suggest that Bt crops have fewer adverse effects on natural enemies than conventional insecticides, and can reduce insecticide use through incorporation into IPM programs with strong biological control components. A meta-analysis conducted by Marvier et al. (2007) reviewed 42 field experiments and found that non-target invertebrate populations generally were more abundant in Bt versus insecticide treated field crops, although some non-target invertebrate populations were less abundant in Bt versus non-Bt fields not treated with insecticides. A review of the economic, ecological, food safety and social consequences of transgenic Bt-expressing plants concluded that the risks of deploying transgenic Bt plants were lower than many current or alternative technologies, and the benefits greater (Shelton et al., 2002). The same pattern of results seen with Bt transgenic crops has also been reported for genetically modified crops based on insecticidal proteins other than the *B. thuringiensis* delta-endotoxin (Callaghan et al., 2005; Whitehouse et al., 2007).

Deployment of transgenic crops has resulted in lower insecticide use. Over the nine year period from 1996 through 2004, insecticide use on the genetically engineered corn and cotton grown in the US dropped by 5% (7.08 million kg) (Benbrook, 2004). Bt cotton has significantly reduced pesticide inputs wherever it has been commercially adopted, such as Australia where a 50% reduction was reported in comparison with conventionally sprayed cotton (Whitehouse et al., 2007). In contrast, from 1996 through 2004, herbicide use on genetically engineered corn, cotton, and soybeans grown in the US increased by 5% (Benbrook, 2004). However, the use of transgenic herbicide-tolerant soybeans does not appear to have any significant effect on arthropod communities (Buckelew et al., 2001).

A difficulty with making larger analyses of non-target effects of transgenic plants has been the variability in experimental approaches. To help make the evaluation process systematic, Romeis et al. (2008) propose a scientifically rigorous procedure to evaluate the risks of insect-resistant genetically modified crops to non-target arthropods that provide ecological services such as biological control, pollination, and decomposition.

The debate over the safety of genetically modified crops is likely to continue (Thies and Devare, 2007). Despite early concerns over sustainability (e.g. Gould 1998), insect pest management using transgenic crops appears to be working quite well. Concerns over impacts on non-target beneficial arthropods in transgenic crops are largely uncorroborated by the data collected to date. By reducing insecticide applications, the use of transgenic herbivore resistant crop plants likely outweighs any specific negative effects they may have on natural enemy biology. The primary means by which conservation biological control of arthropods is implemented is through the modification of insecticide applications (Ruberson et al., 1998). Rather than having anticipated negative effects, transgenic varieties appear to have resulted indirectly in the conservation of beneficial insects in crops in which they are used.

9.4.5 Pesticide Use

Probably the most common pest management activity that negatively impacts beneficial organisms in agroecosystems is pesticide application. Although herbicide use can influence both pest and natural enemy populations (see for example Shelton and Edwards, 1983; Taylor et al., 2006), this section will focus on insecticide effects since they are so much more significant.

Pesticide products used for pest management in agriculture have been changing so that use of the oldest and most toxic cyclodienes, carbamates and organophosphates is slowly decreasing worldwide (Devine and Furlong, 2007). For example, in the United States between 1992 and 2000, the use of these materials had declined by 14% (by weight of active ingredient), even though overall agricultural pesticide use had not declined in that same period (GAO, 2001). However, these materials still retain a 50% worldwide market share (Devine and Furlong, 2007; Singh and Walker, 2006). Synthetic pyrethroids, with their vastly improved mammalian and avian toxicity profiles, now account for 20% of global insecticide sales (Devine and Furlong, 2007).

9.4.5.1 Side Effects on Natural Enemies

Studies examining the side effect of pesticides on natural enemies have been reviewed several times (Haynes, 1988; Croft, 1990; articles in Vogt and Brown, 2006; Desneux et al., 2007). These side effects are manifested in several different ways. Indirect effects include habitat destruction, and damage to nesting, oviposition, resting, and mating sites (Desneux et al., 2007). Direct lethal effects of insecticides are the most well known and have typically been estimated by determining a median lethal dose (LD50) or median lethal concentration (LC50) that enemies are directly exposed to. Sublethal effects of insecticides on beneficial arthropods include deleterious side effects of direct pesticide exposure on physiology and behavior (Desneux et al., 2007). The physiological effects extend to general biochemistry and neurophysiology, development, adult longevity, fecundity, sex ratio and immunology, while behavioral effects extend to mobility, navigation/orientation, feeding behavior, oviposition behavior, and learning performance (Desneux et al., 2007). In addition to direct lethal and sublethal effects, insecticides may also lead to pest population resurgence, often attributed to the removal of a target pests natural enemies by the application of broad-spectrum insecticides (Hardin et al., 1995).

Taking sublethal effects of pesticides into consideration when choosing pesticides for an IPM program can result in great improvements in natural enemy performance (e.g. Desneux et al., 2005). In some cases, sublethal doses of pesticides have been shown to have favorable effects on arthropod physiology and/or behavior, a phenomenon known as hormoligosis (Luckey, 1968). Although hormoligosis has been reported in a beneficial arthropod, the predatory mite *Amblyseius victoriensis* (Womersley), this phenomenon appears very uncommon for natural enemies and likely of little widespread value in the integration of chemical and biological controls (James, 1997).

9.4.5.2 Modification of Pesticide Use Practices

Because of the widespread use of pesticides in agricultural systems, it follows that modifications of pesticide use practices are probably the most commonly implemented form of conservation biological control. This approach has long been considered an important component of integrated pest management programs (Stern et al., 1959; DeBach, 1964; Newsom and Brazzel, 1968). The use of pesticides can be modified in a variety of ways to minimize their impact on natural enemies. These include treating only when economic thresholds dictate, use of active ingredients and formulations that are selectively less toxic to natural enemies, use of the lowest effective rates of pesticides, and temporal and spatial separation of natural enemies and pesticides (Hull and Beers, 1985; Poehling, 1989; Ruberson et al., 1998). While the concepts behind modifying pesticide use are relatively straightforward, implementing these modifications is not necessarily straightforward. One obstacle is that the primary source of information regarding IPM is probably extension services, yet at least in the United States, there are a variety of competing sources from which growers can get information regarding pesticide use (Rajotte et al., 1987).

The practice of IPM has been shown under large-scale field conditions to be favorable to beneficial insects. Furlong et al. (2004) determined the impact of IPM practices at different farms on beneficial insects in *Brassica* crops in the Lockyer valley, Australia. Their study clearly demonstrated increased natural enemy abundance and diversity, as well as significantly greater predator and parasitoid efficacy at farms practicing IPM compared with farms that frequently treated with insecticide.

9.4.5.3 Reduced Risk Pesticides

Newer insecticide classes have been introduced over the last 15 years in response to increasing environmental concerns and more difficult registration processes. These "reduced-risk pesticides", including insect growth regulators, neonicotinoids, antibiotics, and oxadiazines are considered by the US Environmental Protection Agency (EPA) to be safer for human health and the environment than older pesticides. Their low mammalian toxicity allows for a shorter pre-harvest interval, and most are less likely to harm natural enemies and other non-targets making them more compatible with IPM programs. A definition has been provided for these materials and a procedure established to facilitate their registration in the United States (EPA, 1997). This definition includes the following characteristics: "not harmful to beneficial insects, highly selective pest impacts". Studies have demonstrated these compounds are less harmful to natural enemies than organophosphates, carbamate and pyrethroid insecticides (Balazs et al., 1997; Dhadialla et al., 1998; Pekar, 1999; Hewa-Kapuge et al., 2003; Hill and Foster, 2003; Studebaker and Kring, 2003; Williams et al., 2003a; Thomas and Mangan, 2005; Arthurs et al., 2007). However, some toxic effects on beneficial arthropods have been reported from exposure to reduced-risk insecticides such as imidacloprid and thiamethoxam (Williams et al., 2003a; Nasreen et al., 2004; Richter, 2006), indoxacarb (Haseeb et al., 2004; Galvan et al., 2006), and spinosad (Suh et al., 2000; Nowak et al., 2001; Cisneros et al., 2002; Schneider et al., 2003; Williams et al., 2003b; Wang et al., 2005). Although these reduced risk pesticides have a number of advantages over older pesticides, their use does not necessarily lead to natural enemy conservation. Sarvary et al. (2007) concluded that the use of reduced risk insecticides in individual crop fields within an agricultural landscape did not result in increased natural enemy activity in those fields, even when suitable natural habitat was interspersed with cropland.

9.4.5.4 Selectivity

The use of selective pesticides is perhaps the most powerful tool by which pesticide use decisions can be modified to favor natural enemies (Hull and Beers, 1985), and the one most readily available to growers (Ruberson et al., 1998). Selecting the best insecticides for pest management that have minimal impacts on beneficials can be challenging. To assist in this effort, a variety of databases and ranking systems have been developed which incorporate insecticide toxicities to non-target species and other information such as human toxicity and environmental contamination potential (van der Werf, 1996). These systems can be used to compare relative impacts of different pesticides on non-target organisms and to estimate probable effects on non-target environments (Reus and Leendertse, 2000). However, they have rarely been used to consider insecticide impacts on predators and parasitoids in the crop environment at a landscape level (Ferraro et al., 2003). In an effort to make this process more user friendly a beneficial disruption index (BDI) was developed by Hoque et al. (2002) to provide a generalized measure of insecticide impacts on beneficial arthropods in Australian cotton crops. This index was tested by Mansfield et al. (2006), who concluded that the BDI is an effective measure of insecticide impacts on beneficial insects in Australian cotton crops.

Pesticide exposure of natural enemies may also be reduced by applying materials only where they are needed within crop fields. Coll (2004) reviewed the future potential for reducing the negative impacts of pesticide use on natural enemies through the use of precision agriculture technologies.

9.4.5.5 Resistant Natural Enemies

Efforts have been made over the last several decades to develop natural enemies that are pesticide-resistant with the goal of better integration of chemical and biological control (Beckendorf, 1985; Croft, 1990). Genetically manipulated arthropod natural enemies have been used only a few times in IPM programs (Havron et al., 1995; Hoy, 1996). Only one transgenic arthropod natural enemy has been released on an experimental basis (i.e. with only a molecular marker), a transgenic strain of the predatory mite *Metaseiulus occidentalis* (Nesbitt) (Acarina: Phytoseiidae) (McDermott and Hoy, 1997). While this approach may have potential for improving resistance to pesticides, as well as other traits of natural enemies, a variety of scientific, regulatory, and political issues remain to be resolved before transgenic arthropod natural enemies can be used in practical pest management programs (Ashburner et al., 1998; Hoy, 2000, 2005). Meanwhile, traditional selective breeding programs attempting to develop pesticide resistant strains of beneficial insects continue to be explored (e.g. Devi et al., 2006; Ingle et al., 2007). While some authors have advocated the use of resistant beneficial insects in IPM programs (e.g. Graves et al., 1999), it could be argued that this approach is counterproductive to the goals of IPM because it could encourage more pesticide use as with herbicide resistant soybean cultivars.

9.4.5.6 Market Demands

Consumers are becoming a driving force in determining pest management practices, with retailers increasingly requesting horticultural or agricultural practice standards from farmers (Warner, 2006; Dent, 2005). Public opinions on pesticides have become polarized, with measures such as organic agricultural production gaining popularity. Global sales of organic produce are rising approximately 20% per year, with 97% of that market in North America and Europe (Davidson, 2005). However, approximately 70% of organic production occurs outside of North America and Europe, primarily in Oceania and Latin America (Davidson, 2005), meaning the effects of this organic demand will not be restricted to western countries. However, organic production still only represents a small fraction of total agricultural sales (Kiplinger, 2007; Willer and Yussefi, 2006), which means that synthetic pesticides can be used on the vast majority of agricultural production, and remain a critical component of IPM programs worldwide.

9.5 Conclusions

The use of biological control in pest management systems has had a long, rich history. While there are a variety of impediments, there also exist many opportunities for the continued use and expanded role of natural enemies in the management of insect pest problems. Changes in pest management tactics are resulting from a variety of factors, including environmental and human safety concerns, development of insecticide-resistance, increases in pesticide cost and availability, and market demand. However, pesticides will likely remain a major component of IPM programs into the foreseeable future. Modification of pesticide use practices will also probably remain the most commonly implemented form of biological control in agricultural IPM. The continual influx of alien arthropod species resulting from increased international trade presents new pests of agriculture annually (see review by Roll et al., 2007). This influx also ensures that importation biological control will continue to play an important role in IPM practices. As the scientific foundation of augmentation biological control develops, so too should its implementation. As IPM evolves to more ecologically based practices (Koul and Cuperus, 2007), the biological control practice that probably has the greatest opportunity for expanded use is conservation biological control involving agroecosystem modification.

Agriculture as a whole is facing a variety of challenging changes. Global climate change is beginning to affect agricultural systems worldwide, and biological control practices may have to altered to adapt to these changes (Stacey, 2003; Hance et al., 2007). Recent losses of conservation land and changing markets resulting from crop-based biofuels (Streitfeld, 2008), increased use of genetically modified crops (Pollack, 2008), and rising demand for organic produce (Davidson, 2005) make it clear that market forces are a major and sometimes unexpected driving force in agricultural production. Regardless of the production system, IPM will have an important role to play, and the use of biological controls can be an integral part of IPM.

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