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COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE

THE SUSTAINABLE MANAGEMENT OF BIODIVERSITY FOR BIOLOGICAL CONTROL IN FOOD AND AGRICULTURE: STATUS AND NEEDS

by Jeff Waage, Imperial College London[1]

This background study paper is made available to the Commission on Genetic Resources for Food and Agriculture to inform decision-making on future work on micro-organisms and insects, in the context of its Multi-Year Programme of Work.

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[1] Jeff Waage is a Professor of Applied Ecology at Imperial College, and had headed there Departments of Environment and Agriculture since 2001. Prior to that, he was Chief Executive Office of CABI Bioscience and managed its international biological control and taxonomy programme.

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1. INTRODUCTION

Agricultural production relies not only on crops but on an *associated biodiversity* in agro-ecosystems. Pests, diseases and weeds limit crop production, and are themselves limited by the action of their *natural enemies*, mostly arthropods and micro-organisms. Other invertebrates and micro-organisms are important to maintenance of soil health and fertility, and to pollination of crops. Few of these organisms are domesticated, but many are consistently associated with agro-ecosystems in such a way that those which are beneficial to crop production can be considered genetic resources for agriculture. This report considers one group of these organisms, the natural enemies of value to the biological control of pests, diseases and weeds.

1.1 Plan of Report

The first Section of this Report introduces some relevant definitions and introduces the resources for biological control in a biodiversity context. Section 2 of this report describes how natural enemies are used in biological control, identifying three approaches: conservation, augmentation and introduction. Their value to agriculture is discussed, as well as likely future trends in demand. Section 3 considers the current international environment for these approaches to biological control and the conservation and use of natural enemies which they require. Section 4 identifies challenges for future conservation and use, starting with an examination of the risk that it may lose valuable biodiversity for biological control. This section also considers the challenges to maintaining access to natural enemies and to encouraging their use. In Section 5, the conclusions of early Sections are drawn together to generate priorities and recommendations for improving conservation and use of biodiversity for biological control.

1.2 Definitions relevant to biological control

The focus of this study is on biological control in crop protection, where it has received by far the greatest applications, specifically against plant pests, diseases and weeds. Biological control has other applications, most notably in the microbial control of insect vectors of human disease and in the management of invasive alien plants and vertebrates which affect biodiversity and ecosystem processes. The processes, opportunities and constraints which described below will usually also apply to these other applications of biological control.

Biological control is defined here as the use of living organisms as control agents for pests, weeds and diseases. These control agents will be referred to as *natural enemies.* They feed on, compete with or otherwise inhibit pests and their population growth and spread. This review considers four broad types of natural enemies:

- Invertebrate predators which feed in the larval or adult stage on invertebrate pests
- Parasitic insects (parasitoids) which develop from eggs laid in or on the bodies of invertebrate pests, killing them in the process
- Parasitic organisms, like nematodes, which feed and develop in invertebrate pests, often killing them in the process
- Micro-organisms, including viruses, bacteria, fungi and protozoa, which infect and debilitate or kill invertebrate pests, weedy plants or other micro-organisms
- Micro-organisms which displace plant pathogens by competition for surfaces or by antagonistic processes, such as production of toxic substances.
- Herbivorous arthropods which consume and damage weedy plants in various stages.

These organisms are the most frequently encountered in considerations of biological control. In the rest of this paper, I will use the word *natural enemy* to denote any of the taxa mentioned above, and *pest* to denote invertebrates, pathogenic micro-organisms and weeds which are harmful to crops, unless I wish to highlight a particular pest group or groups.

Biological control is sometimes used to describe the use of chemicals of biological origin for pest control, for instance plant extracts like nicotine as pesticides or volatile chemicals from plants or insects as attractants or repellents for insect pests. These chemicals and the plant and animal genetic resources from which they come, will not be considered in this study.

In recent years, natural enemies in the taxa above have sometimes been a source of genes for the genetic manipulation of crops for pest resistance. Most significant, for instance, has been the use of the bacterium, *Bacillus thuringiensis*, or Bt, a micro-organism which produces a toxic protein which kills a range of insect pests. Bt is used as a biological control agent, e.g. as a biopesticidal spray, but the gene for toxin production has also been transferred to crops, including cotton, maize and vegetables. These "Bt crops" are now grown on 32.1 million ha worldwide, in both developed and developing countries, where over 9m smallholder farmers grow Bt crops, largely Bt cotton (James 2006).

This study will not consider natural enemies as a source of metabolites or genes for pest control. While fungi and other micro-organisms are a source of a range of commercial chemical pest control products, e.g. the strobilurin fungicides, the great majority of the organisms that have provided these products are not natural enemies (Copping 2004). Similarly, with only a few exceptions (e.g. *Bacillus thuringiensis,* genes for spider venoms) the majority of genes which have been engineered into crops to generate new crop protection products derive from organisms other than natural enemies. These may include other plant species or pests themselves, for instance genes for viral coat proteins that confer virus resistance in plants.

1.3 Resource for biological control in a biodiversity context

There are many organisms in agro-ecosystems which may have a value, negative or positive, to crop production. Natural enemies comprise a subset, the "borders" of which is sometimes difficult to define. Species in agro-ecosystems interact in food chains. Predators, parasitoids and pathogens attack insect crop pests, while plant feeding insects and pathogens attack weeds of crops. These natural enemies have a clear and direct biological control function. However, other organisms may have a biological control effect without actually killing pests directly, because of the web-like nature of relations between species in crops. For instance, crop protection may be conferred by:

- herbivores which preferentially feed on weeds which compete with crops, thereby improving crop vigour and production
- herbivores on crop or wild plants which support populations of natural enemies which also attack crop pests
- benign micro-organisms which colonize crops and their habitats, thereby reducing colonization by pathogens
- plants or invertebrates which produce chemicals repellents to pest species
- non-crop plants which are attractive to pests and thereby reduce their numbers on crops

The sheer diversity of interacting invertebrates, micro-organisms and plants in agro-ecosystems makes these indirect biological control effects likely. For instance a single rice crop in Asia may have almost 600 species of higher animals and plants interacting in food webs (Roger *et al.* 1990, not to mention the (probably greater) diversity of micro-organisms associated with these species and with soils. It is important, therefore, to note that those pest-destroying natural enemies which I will consider here represent only a fraction of the biodiversity which is important to biological control in agro-ecosystems.

Other, beneficial crop associated biodiversity, including pollinators and species which contribute to soil fertility, are, like natural enemies, often insects, fungi or other micro-organislsm, and occur in similar habitats. Hence they may be subject to similar agricultural processes. These include threats, such as pesticide use against beneficial arthropods, as well as benefits.

Because beneficial, biological control effects are generated directly or indirectly by a wide range of crop-associated organisms, not just natural enemies, and because other beneficial organisms in crops are affected by agricultural practices in a similar way to natural enemies, it is neither easy, nor perhaps desirable, to separate biological control organisms out for separate consideration of biodiversity conservation and use. A broad approach to the conservation and use of beneficial, crop-associated biodiversity may be preferable, and I will return to this concept in Section 2.1.

2. STATUS AND TRENDS IN BIOLOGICAL CONTROL

In this Section, I will consider the different ways in which natural enemies are used in biological control. However, I will start with a consideration of natural enemy diversity and function, as this is critical to understanding its conservation and use relative to other resources for agriculture.

2.1 Natural enemy diversity and function

From the perspective of genetic resource conservation and use, the most important feature of natural enemies is their remarkable diversity. It has been suggested that as much as 50% of extant species are natural enemies in the categories above (Strong *et al.* 1984). The Millennium Ecosystem Assessment (2005) estimates the total number of species on earth to exceed ten million, based on the work of Groombridge and Jenkins (2002). About 8m of these are insects and myriapods, 1.5m fungi, 0,75m chelicerates, 0.65m protoctists and 0.4m nematodes. Natural enemies constitute a substantial proportion of insects, fungi and chelicerate species, and are well represented in protoctista and 0.4m nematodes. Hence, there are probably millions of natural enemy species. For the three largest taxa, insects, myriapods, fungi and chelicerates, the analysis suggests that, of their approximately 10.25m estimated species, about 9 million (88%) are yet to be described.

By contrast, all crop species are described and thousands of specific plant genetic resource accessions and varieties have been characterized in the last decades. Even if we consider plant species generally, as a future resource for new crops, recent estimates suggest there are at most a few hundred thousand species (Scotland and Wortley 2003), the great majority of which are named. Hence, living resources for biological control are far more diverse and far less well known than plant resources for agriculture.

In order to understand natural enemies in agro-ecosystems so that we might best conserve and use them, it is also helpful to appreciate aspects of their *specificity* and *functionality*.

Natural enemy species may be highly specific, that is, they may attack and reproduce on only a single pest species. This is one explanation for the enormous diversity of natural enemies: because of their high specificity, natural enemies are *at least as* diverse as their prey or hosts. When you consider that these prey and hosts comprise insects, plants and fungi, themselves enormously diverse, it is clear how such natural enemy diversity can arise. However, other natural enemy species may attack a range of pest species, and we call these generalists. Within a particular natural enemy taxon, both specialist and generalist species may be found. For instance, for insect parasitoids, 60% of the 214 species of parasitoids in the family Braconidae attacking plant-feeding flies in the family Agromyzidae in Britain are specific to only one species, and of 514 species of parasitoids in the family Ichneumonidae in North America, 53% are recorded from only one insect host species (Price, 1980). Recent research suggests that natural enemies may not only be specific to a particular pest species, but it may be specific to only a particular situation (e.g. habitat or crop). When attacked by particular insect pests, some crops are now known to to produce very specific volatile chemicals which attract only particular natural enemies of that pest to that crop (Turlings *et al.* 2002).

Specificity is extremely important in biological control: on the one hand highly specific natural enemies are less likely to affect desirable non-target species (e.g. crops and beneficial insects) while, on the other hand, the high specificity of many natural enemies limits their commercial application by limiting the range of target species and hence markets.

Functionality describes the role of natural enemies in ecosystems and, particularly, food chains. We recognize functionality when we distinguish different kinds of natural enemies in Section 1.1 as predators, parasitoids and pathogens. Further, within these functional groups, we can define groups of natural enemy species which use a particular host in a particular way. We often call these “natural enemy guilds". For instance, a guild of predator species attacking aphid pests in a particular crop and region may include different species of beetles, spiders, flies or wasps. A parasitoid guild attacking these same pests may comprise species of flies and wasps.

Functionality is important in biological control for two reasons. Firstly, it helps us to understand how we might make use of the bewilderingly large diversity of natural enemies – it helps to sort natural enemies into functional groups which behave in a similar manner and which can be sampled, used or conserved in a similar manner. Secondly, it identifies a degree of *redundancy* in biological control systems. That is, it shows us how more than one natural enemy may make a contribution to control of a particular pest in a particular situation. This allows us to be efficient in selecting natural enemies to use in biological control. If we are re-creating a complex of natural enemies on a pest, for instance on an alien pest which has been introduced without its natural enemies, functionality allows us to be more strategic about putting together that complex. At the same time, when natural enemy diversity is threatened in a crop system (e.g. by intensive cropping practices), functionality helps us understand how many and what kind of species need to remain in a system to ensure biological control remains effective. Where taxonomy is still very poor, as for instance in soil organisms where perhaps only a very small percentage of organisms can be isolated, cultured and named, we may base our understanding and use of natural enemies on different functional groups rather than taxonomic groups. Recent techniques for extracting and analyzing genetic material from soils have created a breakthrough in our ability to characterize them biologically and functionally.

At this point, the following conclusions may be drawn about natural enemy biodiversity relevant to its conservation and use in agriculture. The use of natural enemies in biological control is made more difficult by their sheer diversity and our poor understanding of this. This contrasts greatly with plant genetic resources, and makes biological control very dependent on taxonomy and taxonomical services. Understanding specificity and functionality is crucial to dealing with this diversity and "extracting" useful species to consider for biological control, and this makes biological control very dependent on ecology and ecological research, to understand the complex, dynamic relations between natural enemies and pests.

2.2 Approaches to biological control

Natural enemies exert a continuous level of pest suppression and regulation in agro-ecosystems without any specific human intervention. This is a form of biological control. At the same time, the term "biological control" is also used to describe the deliberate application of specific natural enemies against specific pests. This usually involves their production and release, sometimes as commercial products.

Not surprisingly, much of the history of biological control has focused on its second interpretation, the active use of specific natural enemies, because this is most closely associated with solving particular pest "crises" or developing pest control products. Interest in biological control as a continuing, natural process of pest suppression has waxed and waned over the past two centuries, and has its origins in early ecological research in the 19th century which understood natural enemies as a balancing force acting on population growth and size. Interest in using specific natural enemies for controlling specific pests arose at the very end of the 19th century, and grew rapidly in the first half of the 20th century, as agriculture became more intensive and pest problems more severe. However, with the widespread introduction of synthetic organic pesticides after 1950, interest in biological control, both as an underpinning process in crop production and as a technology, waned. Subsequently, resurgence of pests, associated with pesticide effects on natural enemies, led to a renaissance of interest in this "background" level of natural enemy action, whose conservation subsequently underpinned the concept of integrated pest management (IPM). The birth of this concept then stimulated a renaissance in biological control technology, aimed at developing IPM-friendly products to replace chemical pesticides.

Across this history, three general approaches to biological control arose. I will use definitions which are in line with current textbook treatments (van Driesche and Bellows 1996; Hajek 2004, van Lenteren 2006):

- Natural enemy conservation – the protection and encouragement of local natural enemy populations by crop and habitat management measures that enhance their survival, efficiency and growth.
- Augmentation of natural enemies – the release of natural enemies into crops to suppress specific populations of pests over one or a few generations, often involving the mass production of natural enemies.
- Introduction of natural enemies – the introduction locally of new species of natural enemies with the intention that they establish and build populations that suppress particular pests, often alien pests to which they are specific. This approach has frequently been called "classical biological control", probably because of its origins in the 19th century. However, it is no more original than our other two approaches, and therefore the more descriptive term "introduction" is used in this report.

While these three approaches are distinctively different, they do interact in ways which important to natural enemy conservation. This will be considered in Section 2.6.

2.3 Conservation of natural enemies

In natural ecosystems, predators, parasites and pathogens of animals, and herbivores of plants, contribute to the maintenance of complex communities at relatively stable levels. Outbreaks of particular species may occur in nature, but these tend to be suppressed over time by the density- and spatially-dependent, regulatory processes which characterize natural biological control (van Driesche and Bellows 1996). In agro-ecosystems, where we designate many species which limit crop production as pests, their control by natural enemies may be substantial, but may still fall short of what we anticipate in order to get the maximum productivity of the crops which we plant.

There is considerable evidence that agricultural intensification affects, and often reduces, levels of natural biological control. This is probably associated with the effects of intensification on crop-associated biodiversity. Along a gradient of intensification running from shifting cultivation and species-rich home gardens through to intensive cereal production, we see a dramatic change in biodiversity within crops, both above and below ground (Swift *et al.* 1996). This may be qualitative, for instance soil tillage and loss of accumulating litter tends to increase bacteria and small invertebrates relative to fungi and larger invertebrates, without always causing a shift in overall diversity (Swift *et al.* 1996, Wardle *et al.* 1999). Or it may be quantitative, for instance, coffee grown under shade with mixed cropping has a diversity of ant and beetle communities similar to that of nearby rainforests, but this is greatly reduced in unshaded coffee monoculture. (Swift *et al.*1996). Precisely how these changes in biodiversity affect biological control will depend on the functionality of the community remaining after intensification. It is not necessarily the case that intensification reduces the contribution of biological control. Rice ecosystems are examples of intensive production where an effective insect natural enemy complex is maintained (see Section 2.3.1).

However, a range of modern farming practices have been shown to be directly antagonistic to biological control. Intensive systems based on genetically uniform, high-yielding crops and high inputs of fertilizer and pesticides, may favour pest population growth and interfere with natural enemy survival and growth, leaving biological control operating well below its potential.

The conservation of natural enemies in agro-ecosystems is targeted at maximizing the impact of local natural enemies on pests. With a knowledge of local natural enemy communities, conditions which optimize biological control can be selected. These may include maintenance of uncultivated crop margins, where natural enemies find shelter or food, or survive on other prey or hosts between crops or seasons. Similar refuges may be created in crops for natural enemies.

Multi-cropping and inter-cropping have been shown to increase insect natural enemy diversity and abundance relative to that in intensive monocultures. This, along with the effect of diversified crops on directly reducing pest populations (the "resource concentration hypothesis", Root 1973) contributes to the phenomenon of reduced pest impact on diversified systems (Altieri 1990). Recent studies of insect chemical ecology have revealed the capacity of different plants to repel pests and attract natural enemies, sometimes called a “push-pull” strategy, and this has been applield in Africa to reduce stem borer damage on maize by intercropping and companion planting (Khan *et al.* 1997, Cook *et al.* 2007)

Less intensive cropping systems may be associated with a greater diversity of soil organisms of importance to biological control, although there may not be a clear relationship between intensification and soil biodiversity in general (Wardle *et al.* 1999). Considerable research has been directed at conservation of suppressive soils, which appear to have a microflora and fauna which naturally suppresses plant diseases and soil pests. Typically for biological control, this discovery has led to more efforts to identify particular control agents for commercial development, than to understand the ecology of these complex suppressive systems, so as to manage crops to favour them (Alabouvette and Steinberg 2006). Nonetheless, suppressive soils as a conservation approach have much promise, particularly with the new molecular techniques for characterizing the genetic diversity and function of soils.

More specific crop manipulations can be made to favour particular natural enemy species or groups, including encouragement of specific pollen and nectar-rich wildflowers along crop margins (Gurr *et al.* 2006) or application of “food sprays” for predators on crops. This approach has recently been called “ecological engineering” and requires a deep understanding of natural enemy ecology and their use of animal and plant foods inside and outside the crop (Gurr *et al.* 2006).

Sometimes we discover important aspects of natural enemy conservation only when we disrupt biological control. The use of pesticides, particularly insecticides, has often been associated with resurgence of arthropod pests through the selective reduction of their natural enemy communities. Such pesticide-induced resurgence in crops as varied as cotton, tree fruit, vegetables and rice has stimulated the development of integrated pest management (IPM) systems. Similar processes, involving pesticidal disruption of natural enemy communities and actions, can be found in the management of crop diseases (van Driesche and Bellows 1996; Polazek *et al.* 1999), and IPM methods have been extended into plant disease and weed control (Kogan 1998).

IPM can be defined as “the best mix of control tactics for a given pest problem in comparison with yield, profit and safety of alternative mixes” (Kenmore *et al.* 1985). But behind this broad and sensible definition is the original impetus provided by pesticide-induced pest resurgence, which started in the 1950s. Sometimes resurgence occurred in the target pest, but often it occurred in minor pests after insecticides were used to control other species. Research at the time came up with many explanations for resurgence, but the elimination of natural enemies was probably the most important. A widespread phenomenon was resurgence of sucking insects such as scales and mealybugs. Here, the pests are somewhat protected from sprays by their concealed habits and waxy coats, but their tiny natural enemies are highly susceptible as they pick up pesticide while searching plant surfaces for their concealed hosts.

Resurgence often led to increased pesticide application, hence even more resurgence and sometimes pest resistance to chemicals, leading farmers onto a “pesticide treadmills” of spiralling input costs and falling yields. In these circumstances, the first step in many IPM programmes was simply the reduction of pesticide use, which allowed natural enemies to recover, increased yield and reduced costs, often over a very short period. Ultimately, in many crop systems, including those not showing resurgence, the IPM “best mix” of control methods reflects this combination of natural enemy conservation and limited pesticide use.

While IPM systems in developed and developing countries have different features (Waage 1996), all tend to treat natural enemy action as a “baseline” of pest control, the conservation of which may make intervention with pesticides unnecessary. When this natural biological control is insufficient, then pesticides or other interventions are used, in such a way so as not to disrupt natural enemy action. Monitoring of some kind is therefore necessary in IPM to ensure that natural enemies are present and other interventions are unnecessary. This examination is usually conducted by trained extensionists or farmers.

Hence, one of the challenges in natural enemy conservation is that it requires knowledge of natural enemies and their biology. Many farmers may not recognize the difference between insect natural enemies of insect pests or weeds and insect pests themselves, and may treat them all with insecticides. Similarly, farmers may not recognize pests which are suffering from disease caused by natural enemies, and spray unnecessarily. In many parts of the world, generations of dependence on chemical pesticides has left many farming communities without an appreciation or understanding of natural enemies and biological control, and hence an inability to make use of them in IPM.

IPM programmes therefore involve training of extensionists and/or farmers in recognition of natural enemies and understanding of biological control, empowering them to interpret changing conditions in crops and making decisions whether intervention is necessary. The cost of such training and monitoring may constrain the implementation of IPM. Farmer training in natural enemy conservation and IPM has proven effective, a model for which has been the "farmer field school" developed in the 1980s for rice IPM in Asia (Pontius *et al.* 2002, and see Section 2.7.2).

IPM systems tend to be developed by governments, in response to pesticide-induced crises in production, affecting the livelihoods of farming communities, or threatening consumer safety or the environment. In many developing countries, national IPM programmes have often developed around crops in crisis, such as cotton, rice and vegetables, and international agencies, particularly FAO, have provided technical assistance to national and regional programmes. Most development assistance agencies have modified their traditional pesticide procurement guidelines on loans and grants to encourage an IPM approach. In Europe, the IOBC has a long tradition of developing and disseminating IPM standards for crops, which have been used by the agriculture and food industries as a basis for certification standards. More recently a number of European countries have adopted pesticide reduction targets (Wattiez and Williamson 2003), while in the USA, a different approach has been taken, involving a government policy to put 75% of crop production under IPM (Ehler and Bottrell 2000). To build their natural enemy conservation elements, often from a zero baseline, all of these government IPM programmes rely heavily on agricultural research capacity in national institutes, universities and museums.

Section 2.3.1 illustrates the role of natural enemy conservation in rice pest IPM. Other crop systems where IPM has proven very important in the past 50 years includes tree crops, such as apples, citrus, cocoa and coffee, where insecticide use has disrupted natural control of scale insects, mealybugs, leafminers and other moth pests and led to pesticide resurgence. IPM has also been successful in certain field crops like cotton and brassicas, where pesticides have induced outbreaks of sucking insect and moth pests (Way and van Emden 2000).

Hence, the conservation of natural enemies for pest management today involves first and foremost the recognition of natural enemies and their role, and their conservation in IPM systems. Beyond that, conservation and natural enemy action can be enhanced by adjustment of crops and cropping practices to favour persistence and growth of their populations.

2.3.1. Case study: IPM in rice pest management in Asia

Rice is one of the world's major food crops, and has been a major beneficiary of the Green Revolution, a global initiative of the late 1900s directed at meeting the food demands of a growing world population through breeding increased productivity in staple food crops. With the introduction of short duration, high yielding rice varieties in Asia, rice production increased from about 200k per ha to 400-600 kg per ha. Along with improvements in irrigation, rice production increased dramatically (Conway 1997).

Yields of Green Revolution rice varieties were closely correlated with nutrient supply, and therefore were distributed with fertilizers. Pesticides were added to these "packages" with less justification, but became widely used in government supported programmes to implement these new varieties. In 1974, only a few years after planting programmes began, outbreaks of the rice brown planthopper, *Nilaparvata lugens*, began to occur in Indonesia. This sucking insect was, previously, very minor pest. The planthopper problem spread throughout rice production in Asia. There was much scientific debate about the cause of planthopper outbreaks, including possible indirect stimulation of plants by pesticides, emergence of pest resistance to pesticides or development and migration of new, virulent pest strains. In the 1980s, scientists at IRRI were able to demonstrate quite clearly that pesticide use was the principal cause of planthopper outbreaks (Kenmore *et al.* 1984). Natural enemies are highly exposed to sprays and have, in general, long generation times, such that a few sprays can eliminate natural enemies for long periods. Planthopper, by contrast has a part of its population, particularly in the egg stage, protected from sprays and a very short generation time, so their populations can recover quickly from pesticide sprays, particularly in the absence of predators.

The initial response to this new problem was to draw upon the technology that had successfully underpinned the Green Revolution, namely plant breeding and pesticide use. Pesticide subsidies and provision led to a "pesticide treadmill" and worsening pest problems. Varieties resistant to planthopper were developed but quickly broke down, probably because very high pest population levels, caused by intensified pesticide use, facilitated rapid selection of pest resistance to new plant defenses (Gallagher *et al.* 1994).

Reduction in pesticide use and recognition and conservation of natural enemies underpinned the development of an IPM approach to rice pest management. The deployment of IPM faced difficulties of entrenched government dependency on pesticides and the influence of the pesticide industry, and progressed at different rates and in different ways in different countries. However, an FAO-supported programme identified very quickly that delivering IPM messages via national extension systems would not bring rapid change, and embarked upon an ambitious plan for direct training of farmers through adoption and modification of participatory, community health programmes. The farmer field school approach which evolved was based on three principles: (1) grow a healthy crop, (2) observe fields weekly, and (3) conserve natural enemies. Farmers in villages participated in a season long programme of experiential learning, designing, executing and interpreting experiments in their rice crops. As a result, they developed an understanding of crop, pest and natural enemy ecology and became experts in pest management in their own fields. Millions of rice farmers have now participated in these schools throughout Asia.

Farmer field schools had a dramatic effect. Economic benefits, even within a single season, in terms of the reduction of pesticide costs against sustained or even increased yields have helped rice IPM spread from village to village and country to country (van den Berg 2004). Farmers informed by experiential learning process have also begun to undertaken research into new biological pest management methods and national research programmes have been stimiluated to look at other opportunities for IPM. IPM programmes, involving an FFS approach, have been spread from rice now into other areas of intensive pesticide use and pest resurgence, including cotton and vegetables in Asia, Africa and tropical America (Ooi and Kenmore 2006).

Many years after the beginning of the ecological research that led to the development of IPM, further ecological research has shed light on precisely why natural enemies and biological control is so important in rice systems. Work by Settle *et al.* (1996) demonstrated that the flooding of rice fields creates a diverse and abundance community of invertebrates which feed in water on detritus. Early in the season, predators invade fields and build up high numbers on these prey communities. When plant pests like the planthopper invade, predators are already present and suppress pests before their populations can grow. Hence, the capacity that planthopper has to "outrace" natural enemies is suppressed.

This research clarifies why the control of brown planthopper is particularly dependent on biological control conservation, and why it is so very sensitive to predator disruption, particularly by pesticides. It also reveals another important feature of natural enemy conservation. In this study, 765 species of organisms were found to be involved in this rice system. Of these, 145 were associated with the pre-rice environment associated with flooded fields, 127 were herbivores in the crop, and 493 (64%) were natural enemies. Only by resolving this enormous biodiversity into functional groups could experiments be designed and interpreted which revealed the role of biological control in suppressing this pest. Without knowledge of the taxonomy, biology and ecology of these hundreds of species, such research and understanding would be impossible. Hence, unlike other approaches to biological control, which require intensive research on just a few natural enemy species, natural enemy conservation requires extensive research on many species.

2.4 Augmentation of natural enemies

In many agricultural systems, useful natural enemies may not persist, due to the nature of the habitat, crop practices or seasonal effects. Even if well established in agro-ecosystems, they may not reach densities capable of delivering sufficient pest control at the right time – pathogens of insects and plants, for instance, often require specific conditions and high host densities to cause self-spreading epidemics in pest populations. Augmentation addresses this problem through application of natural enemies to crops.

Two variations of augmentation are recognized, which are effectively extremes along a continuum. *Inundation* involves release of a population of natural enemies which is large enough to suppress a particular pest generation, with no expectation that they will reproduce and exert further control. *Inoculation*, on the other hand, involves release of smaller numbers of natural enemies to establish and reproduce on a pest population, building sufficient numbers over a few generations to suppress the pest population before it becomes damaging. Inoculation is often associated with highly seasonal systems, where early release of natural enemies ensures that pest populations do not escape biological control because of the late arrival of "wild" natural enemies into the crop in question. Inoculation places less demands on production, but is more knowledge intensive and unpredictable, and perhaps for this reason it is less popular. Micro-organisms (e.g. pathogens of pests) are often used inundatively and macro-organisms (e.g. insect predators and parasitoids) inoculatively.

The practice of augmenting local natural enemy action by releasing natural enemies in crops is ancient (Konishi and Ito 1973). In the 19th and early 20th century the practice began to grow as a modern pest management option along two paths. Some insect pathogens had a saprophytic habit which allowed them to be produced by fermentation on inexpensive substrates, such as agar or nutrient broths. This allowed mass production of insect pathogenic fungi and bacteria. The first experimental mass-released pathogen, or "biopesticide" was the fungus, *Metarhizium anisopliae*, mass produced in the 1880s against beetle pests.

A second approach involved the use of arthropod (insect and mite) natural enemies for control of arthropod pests. These augmentation methods often grew out of unsuccessful efforts at introduction (Section 2.5), when introduced natural enemies failed to establish. Mass production and release of predators and parasitoids became feasible when inexpensive ways to produce their prey or hosts were developed. The most important development involved egg parasitoids of the genus *Trichogramma*, for control of moth pests (Flanders 1930). Here, the eggs of meal moths were used for mass production. They could be cheaply produced on surplus or waste grain. This practice of using cheaply produced alternate or "factitious" hosts made augmentation more affordable and competitive.

Today, augmentative approaches to biological control remain largely restricted to use of pathogens, predators and parasitoids for controlling invertebrate pests. Glasshouse systems in Europe use a wide variety of macrobial products in the form of predators and parasitoids, each product associated with the control of one or just a few insect or mite pest species. Augmentation of predators and parasitoids is also practiced in the field, particularly in orchard systems and, in the tropics, in sugar cane. *Trichogramma* is still applied against moth pests in a wide range of field crops.

For microbial products, bacteria, viruses and fungi against insect pests dominate the marketplace. Microbial products, largely fungi, have also been developed for control of plant pathogens, particularly soil competitors and antagonists, as well as "mycoherbicides" for weed control. (Van Driesche and Bellows 1999). Most biopesticides are specialised products for particular pests, but two exceptions are Bt, which is used against a wide range of Lepidoptera, Diptera and Coleoptera, and *Trichoderma* spp., which are used to suppress a range of soil inhabiting plant pathogens. Worldwide today, about 150 species of natural enemies are sold as macrobial and microbial products for insect pest control (van Lenteren 2006), but just 30 of these species account for 90% of sales.

Augmentation today is a mixture of public and private sector activity. Public sector activity grew around state programmes, particularly in state-owned production systems such as existed in China and the former Soviet Union. Many of these have now been privatized locally. Privatized production has long been a tradition in a number of crop systems, like citrus, glasshouses and sugar cane, where centralized production is efficient. In the case of sugar production, local milling companies may produce natural enemies and sell them to growers, while in the glasshouse industry in Europe, a few growers began to product natural enemies for their own use and gradually grew into major companies producing natural enemies for growers throughout the region.

Because of this mix of public and private sector activity it is difficult to estimate the scale of augmentation today. From a commercial perspective, sales are in the order of $300-400m, which is only about 1% of the approximately $30-40b market in pest control products, the rest being sales of chemical pesticides and, increasingly, transgenic crops (Gelernter 2005; van Lenteren 2006). Expectations in the last two decades that commercial biological control products would displace a substantial proportion of chemical pesticide sales, which led to much venture capital investment, are now gone. Instead, augmentation is seen today to service a stable, important, but small set of niche markets in pest control. Commonly cited reasons for biological control products not having a larger market share are the high specificity of some biological products (which limits markets), short shelf-life, problems in storage and transport, unpredictability in the field due to variable conditions on release (e.g. temperature, solar radiation, rainfall) and cost of production relative to alternative, chemical pesticides.

Underlying these shortcomings, however, is a pest control environment that has been developed around a "chemical paradigm" over the past 50 years, into which biological products fit poorly (Waage 1997). This paradigm has favoured products with high efficacy (killing effect) and rapid action, which the market now expects. Chemicals generally out-perform biological products on these criteria, while properties that give biological products their advantage, namely their capacity to reproduce, spread and protect other natural control, have not been valued in conventional pest control markets. It is not surprising, perhaps that *Bacillus thuringiensis*, which accounts for over 90% of microbial biopesticide sales (Jarvis 2001), is usually formulated as dead bacteria containing the toxic protein endotoxin – as such it is not a living biological control agent, but merely a chemical pesticide.

Augmentation has found its niche on crops where chemical pesticides are undesirable, difficult to use and/or relatively ineffective. Examples include high value horticulture production, e.g. of vegetables, fruits and flowers, and some tropical plantation systems, like sugarcane. An interesting pattern of development has emerged in some augmentative programmes, best illustrated by European glasshouse production (Enkegaard and Brodsgaard 2006). Here, up to the 1950s growers relied on synthetic pesticides for pest control, until resistance developed in the alien spider mite, *Tetranychus urticae*. Faced with no chemical control options, biological control was developed using an alien predatory mite, *Phytoseiulus persimilis*, discovered in Europe in 1960, and by the 1970s many growers were using this. Also in the 1970s, pesticide problems with control of an alien whitefly, *Trialeurodes vaporariorum* were addressed similarly with an alien parasitoid, *Encarsia formosa*. With these two biological control agents firmly established, subsequent new pests could not be treated with broad-spectrum pesticides without disrupting existing control. Without pesticides, some secondary pests became more important. IPM programmes were established which used the least disruptive pesticides, and biological control agents were found and developed for these new pests, including thrips, aphids, leaf miners. As of 2004, there were about 115 natural enemies used commercially in these systems. To some extent, this glasshouse production system has become locked into a cascading of new biological control products and IPM methods, as use of broad-spectrum pesticides becomes less feasible. Concern about pesticide residues in glasshouse crops has also contributed to keeping biological control popular, and its use has facilitated other developments, such as the introduction of bumblebees to increase pollination of tomatoes. Opportunities for such "cascading" biological control probably exist in other crop systems presently dominated by pesticides.

Because augmentation is founded on a need to repeatedly introduce natural enemies into crop systems, its success has often required that it be commercialized. Today, it is increasingly a private sector activity, practiced either by companies which supply products to farmers or by farmers or farming cooperatives which produce natural enemies in a central facility and distribute or sell them to members. Multinational agrochemical corporations made an investment in biological control products in the last few decades of the 20th century. Few lasting products emerged from this, probably because they competed poorly with chemical products from the same companies. Experience suggests that the most sustainable biological control production for augmented pathogens and invertebrate natural enemies comes from small to medium scale enterprises, often serving a regional market and particular crop systems. Many of these private producers have developed from farming operations which initially produced products for local use. Universities and government research institutions have provided critical research support to these commercial operations.

In principle, developing countries should provide excellent conditions for augmentation, because of relatively high local pesticide costs and risks, a rich biological control resource and inexpensive labour and materials. However, sustainable augmentation requires also stable local demand and supply, a favourable regulatory system and a very good research backup, and these have often been lacking in developing countries. Section 2.4.1 provides a case study on development of a biological pesticide for locusts. This is an interesting example in that it combines typical modern augmentation research with an intended developing country application.

2.4.1 Case study: a biopesticide for locust control

Locusts and grasshoppers are major insect pests of crops and pasture in semi-arid regions of the world. Their populations typically show seasonal surges, often migrations, leading to the sudden local appearance of dense swarms. Locusts and grasshoppers are a particular problem in drier regions of the developing world, where outbreaks can wipe out annual crop and pasture production threatening the food supply of poor communities over large areas. For many years, governments in affected regions have maintained locust and grasshopper control programmes, usually funded for developing countries by donor agencies. International organizations, particularly FAO, help to coordinate regional locust and grasshopper control campaigns. Control programmes usually involve truck-based or aerial application of broad spectrum chemical pesticides. These operations are often difficult to maintain in the periods between outbreaks.

In the late 1980s, outbreaks of desert locust in Africa led to a new call on development agencies to fund pesticides and resources for control. However, concerns had grown in past years that chemical locust control campaigns were often ineffective and/or not cost effective, and that the chemicals used were harmful to fragile semi-arid environments and posed disposal and pollution problems where they stored. Aerial spray units associated with locust and grasshopper control had often been mobilized between outbreaks for other kinds of pest control, e.g. on cotton or rice, often causing pest resurgence. When, in 1989, the International Institute of Biological Control proposed to donors that a safe, biological alternative to chemical locust control could be developed, funding was provided to develop a biopesticide based on local fungal pathogens.

Biopesticides had a long history of research but only limited successful development, due in part to lack of investment, particularly in developing countries. IIBC saw a programme targeting such an iconic and devastating pest, as a means to generate sufficient research support to ensure complete product development, with potential spin-offs for other tropical pests. Further, success would demonstrate the value of biological control to developing countries and undermine the widespread and damaging aerial application of chemical pesticides against many tropical pests, thereby helping the development of IPM. The specific feature of locust biological control that made it so promising was the use of oil-based pesticide formulations for locust control. Fungal spores, being hydrophobic, mix well in oil, and earlier work at IIBC had shown that oil formulations of entomopathogenic fungi can be very effective, particularly in arid environments with intense sunlight.

A programme was established between the International Institute of Biological Control (IIBC) and the International Institute of Tropical Agriculture (IITA)'s Plant Health Management division in Benin to develop and test the biopesticide, financed by Canadian, US, Dutch and British bilateral aid.African national programmes joined this effort through their established programms with IITA. The overall programme was called LUBILOSA (Lomer *et al.* 2001, and see www.lubilosa.org).

Under natural conditions, even in very arid areas, locusts and grasshoppers often exhibit very low levels of infection by the lethal fungi, *Beauveria bassiana* and *Metarhizium anisopliae*. The project discovered many strains of these fungi through international surveys, but *Metarhizium anisopliae* var *acridum* emerged as the most virulent in bioassays and affected only grasshoppers and locusts. Remarkably, besides LUBILOSA, separate research programmes in Madagascar, Australia and Brazil have all found local strains of this same fungus and chosen them for biopesticide development. Prior to this project, the existence of a widespread, virulent pathogen of these pests was quite unknown, indicating how a single research project can quickly generate new biological control opportunities.

The selected fungus was used to develop the best oil formulations for application, based on locally available vegetable oils and airplane fuel, and the best production and storage conditions. Conventional wisdom that fungi do not store well and break down in desert conditions was proven to be incorrect. Inexpensive production methods, based on liquid fermentation, were developed, which ultimately ensured that the cost of the eventual biopesticide formulation was competitive with chemical pesticides.

The first field trial was made in Benin in 1999 and led to large scale field trials with standard ground and aerial application equipment throughout West Africa. These proved highly successful and suppressed grasshopper populations to levels lower than chemical pesticide treatments and for longer periods of time. This seemed to be due in part to the persistence of the fungus in the environment, and delayed infection of later generations of pest. Environmental studies also showed that important natural enemies of these pests, including other insects, birds and reptiles, were not harmed by the biopesticide. Hence, like all biopesticides, action is both direct and indirect through natural enemy conservation, in contrast to chemical pesticides which may kill these natural enemies.

The biopesticide product, Green Muscle, had its first commercial use in Niger in 2000, on 2000 ha of grasshopper-infested land. Commercial development of the biopesticide was necessary for it to be sustainable, even if it were to be financed by development agencies. Testing was conducted to meet US registration requirements, including mammalian testing, as a “gold standard”. In order to attract private producers, some of the biopesticide technology was made exclusive, and a trust created into which LUBILOSA income from this intellectual property would go. This trust is dedicated to sharing the benefits arising from this African biodiversity with African countries. An African production facility was established in South Africa in 1998, and this has produced the product for its continued use in Africa.

There is considerable need for further uptake of Green Muscle in Africa. Locust and grasshopper control programmes have taken up this product in only a few countries, like Niger. FAO is also using and promoting Green Muscle in its control programmes in Africa. In 2000, a product called Green Guard, based on LUBILOSA technology, was released for grasshopper control in Australia. This product is being used by the Australia Plague Locust Commission because of its low cost, the absence of environmental effects, especially on aquatic organisms, and its suitability for use in organic beef production. (Milner and Hunter 2001). Technology developed for fungal biopesticides is now being adapted for the control of malaria vectors in Africa (Blanford *et al.* 2005).

The LUBILOSA programme concluded in 2002. It had demonstrated that effective, competitive biopesticides can be developed and produced for, and in, developing countries. A similar story could be told for development of insect viruses as biopesticides in Brazil, where locally produced products have been used on over 1m ha for many years (Moscardi 1999). However, success stories such as these remain few, due largely to a lack of research investment. Even where sufficient research has been possible, as with LUBILOSA, small markets, regulatory problems and competition with chemical pesticides and “pesticide-based production systems” will challenge uptake of augmentation in developing countries, as it does elsewhere.

2.5 Introduction of natural enemies

The international movement of peoples and crops has contributed for centuries to the introduction of new pests, diseases and weeds to agriculture. Often, introduced pests will exhibit devastating outbreaks, which may spread rapidly across a country. Given that many individual farm businesses are affected, governments usually step in with campaigns of pest eradication or control. Biological control introduction may be employed in these circumstances, particularly if it has been used effectively elsewhere against the pest.

Biological control introductions against alien agricultural insect pests emerged in the 19th century, stimulated by growing agricultural research in regions settled by Europeans where introduced pests on introduced crops were major problems. The first major success in biological control introduction was made in 1888, against the alien cottony cushion scale, *Icerya purchasi*, in California. The introduction of an Australian parasitoid and ladybird from the pest's area of origin was so successful that it stimulated similar introductions of ladybirds and parasitoids against other alien pests, and a long history of programmes began. In the early 1900s, the method was extended to the introduction of herbivores for the control of exotic weeds, like cactus in Australia in 1925. Greathead and Greathead (1992) and Julien and Griffiths (1998) have established databases on introduction programmes against insects and weeds, respectively, and have shown a steady increase in numbers of agents released per decade over the 20th century.

Most introduction programmes have been directed against alien insect pests or weeds. For both targets, insect natural enemies have been the preferred agents, largely because of their high host specificity and capacity for rapid reproduction and spread. Introduction programmes have been successfully implemented over a wide range of crops and habitats, but they have been most frequent against insect pests of perennial crops, such as tree crops, and against weeds of extensive habitats, such as pastures and waterways. Several factors have contributed to this bias. For insect pests, the establishment and spread of natural enemies may be more effective in less disrupted agro-ecosystems, such as orchards or forest plantations, than in field crops. Common alien insect pests, such as sucking insects and leaf miners, are more common in these systems. Similarly, weeds of pastures, plantations and waterways may provide a more stable environment for establishment and spread of biological control agents than those of arable crops. However, in both cases, competition with chemical pest control has probably also been a factor. Biological control has found a niche where chemical control is prohibitively expensive, such as in extensive pastures, ineffective, such as in dense forests or sugarcane plantations, or undesirable, such as in waterways where pollution is a concern.

However, it is important to stress that biological control introductions have wide applicability, and there have been spectacular successes for insect and weed control in annual, arable crops. In 1971, a specific strain of rust fungus gave widespread control of a weed of field crops, *Chondrilla juncea*, in Australian field crops, and heralded the start of the use of rust fungi for biological control (Evans *et al.* 2001).

Success rates of biological control for natural enemies which have been established in areas of introduction have been estimated at about 40% for programmes against insect pests and 30% for programmes against alien weeds (Waage and Greathead 1988). Success rate of all introduced agents would be lower, as some will fail to establish.

Introduction programmes require considerable research and time, hence they have high initial costs, but their benefits, where successful, are continuing. A typical programme involves a number of stages of research. First, studies are made to determine the area of origin of the alien pest, which often requires detailed taxonomy, as the target species may not be a pest in that region and may even be unknown to science. Exploration is made in the likely area of origin and potential natural enemies for introduction identified. These are characterized and studied for their potential impact on the pest in its new range and for their specificity. Safety protocols (See Section 3.3) usually require that only highly specific natural enemies are introduced, eliminating a large number of species from consideration. Taxonomic support is critical throughout this process. On more than one occasion, misidentification of target pests and/or their natural enemies has caused delay or failure in introduction programmes (Quicke 1997).

Specificity tests follow well established protocols and may be lengthy, depending on the number of non-target species to be tested. This is particularly true for weed control, where a wide range of crop and native plants are usually tested. Selected natural enemies are imported into quarantine facilities in the affected country (or into similar facilities in cooperating countries) where tests are made to ensure they are carrying no contaminants themselves. They are then mass reared and released into affected areas, and their establishment and impact on the target pest monitored. A programme against a single alien pest may involve the introduction of several natural enemies, which may take years, even decades.

A concern for environmental impact of biological control introductions has become particularly important in the past 20 years and has led to more extensive safety testing of potential agents, particularly against native species (see Section 3.3).

Introduction programmes have been almost universally government activities, for several reasons. A new alien pest, weed or disease has the capacity to spread over many farms and may indeed be well established and spread before it is discovered. Hence, collective action is necessary to control it and stop further spread, which cannot easily be done by individual farmers. Further, introduction programmes are usually prohibitively expensive for farmers to mount. They require the deliberate introduction of alien species, which must be carefully regulated by government. Finally, the benefits of successful introduction spread as the introduced natural enemies spread, and cannot be limited to the farms of any private investors. Hence, it is easy to see introduction programmes as public good activities, undertaken by government on behalf of national agricultural and food security.

Section 2.5.1, describes a specific introduction programme involving the control of the cassava mealybug, an alien pest in Africa. In this case, the national programmes in affected countries in Africa were supported by development assistance agencies and international research institutions to carry out this regional biological control programme.

2.5.1 Case study: biological control of cassava mealybug in Africa

The biological control of cassava mealybug in Africa is one of the best documented programmes of biological control introduction in history and has benefited from a level of analysis that has been sadly lacking in the great majority of introduction programmes (Gutierrez *et al.* 1988, Herren and Neuenschwander 1991, Neuenschwander 2001). Unsuccessful programmes rarely attract analysis and, paradoxically, successful programmes are also little studied because the problem is quickly forgotten.

The cassava mealybug, *Phenacoccus manihoti*, was accidentally introduced into Africa in the early 1970s from its native South America. It spread rapidly across the African cassava belt, causing losses of up to 60% of production, for a crop that was not only a staple for many communities but of particular importance in times of food insecurity. Cassava farmers could not afford pesticides to control mealybugs, nor are pesticides particularly useful against these insects. However, there was a long tradition of successful biological control of alien mealybugs of agriculture by introduced insect parasitoids and predators, which led to the idea of an introduction programme.

A biological control programme was established by the International Institute of Tropical Agriculture, in cooperation with the International Institute of Biological Control (CAB International), the International Centre for Tropical Agriculture (CIAT), national agricultural research programmes in Africa and South America and other collaborators.

Exploration began in South America in 1981. Like many alien pests, in its native range, the mealybug proved extremely rare. Precious time was lost when, due to lack of taxonomic knowledge, exploration focused on a closely related species, *P. herreni*, until it was discovered that its natural enemies did not accept *P. manihoti* from Africa. The mealybug was finally discovered, after extensive exploration, in a few locations in Paraguay. A range of natural enemies were identified, including parasitoids and predators. These were characterized and reared in quarantine at IIBC in UK, to ensure they were not contaminated, e.g. with hyperparasitoids. Normally, quarantine would be undertaken in the country of importation, but quarantine facilities in Africa were not suitable for this work at the time.

In all, nine species were released, but only one, the specific parasitoid *Epidinocarsis lopezi*, gave substantial control, despite its poor initial performance in laboratory studies. Retrospectively, with growing interest in environmental effects of biological control, some of these natural enemies, particularly more generalized predators, may not have been introduced. However, environmental impact assessments have shown that none of the species introduced have affected native insect species. Post-release research revealed why *E. lopezi* was superior to other species. This is typical of biological control introduction: our ecological understanding of biological control can contribute, through experimentation and modelling, to the selection of effective natural enemies, but most introduction programmes are under too much pressure from affected parties to undertake substantial pre-release research. Hence, much research is retrospective, but nonetheless accumulates as valuable knowledge for similar future problems.

With abundant donor funding, a regional programme engaged governments across Africa and implemented an extensive programme of production and release of *E. lopezi*, even modifying aircraft for this purpose. Surveys demonstrated that the parasitoid reduced mealybug populations in all infested areas, although this happened at different rates and with different endpoints influenced by cassava varieties and growing conditions. By 1992, the mealybug had been reduced to a minor pest across Africa.

This project, often heralded as the largest and one of the most expensive biological control programmes in history, was also shown to have been extremely cost effective (See Section 2.7.4). It highlighted the particular value of biological control in developing countries, where alien pests can direct affect food security by dramatically reducing production of staple food crops, and where there are few affordable pest control options. Another lasting result of this programme has been the extensive training of African scientists in biological control, and a series of subsequent successful programmes against invasive insect and weed pests, where newly empowered national biological control programmes have taken responsibility for implementation. At the same time, it must be said that donor interest in biological control projects, related perhaps to their rapid delivery and demonstrably high benefit to cost ratios, dominated investment in biological control in Africa for some time, to the exclusion of supporting capacity building in IPM and management of native pests. Nonetheless, Africa has today an impressive level of biological control expertise, as a proportion of its overall pest management capacity, which bodes well for the future.

2.6 Biological control in IPM systems

The classification of biological control into different approaches is arbitrary, and these different approaches are strongly inter-linked. For instance, augmentation and introduction approaches lie along a continuum of persistence of natural enemies in an agro-ecosystem. Introduction of a particular natural enemy may work in certain circumstances, while augmentation of the same species may be necessary in another, because its persistence may be reduced or only seasonal.

Further, once natural enemies are released in the environment, for augmentation or introduction, they become part of the local natural enemy community. Hence, natural enemy conservation is an important part of successful augmentation and introduction: there is little value to releasing natural enemies into a system that is using pesticides in a way that will kill them off. Augmentation measures are often deliberate elements of IPM systems. When local natural enemies do not provide sufficient pest control, augmentation may be an effective intervention that avoids the disruptive effect of chemical pesticides. Similarly, alien pests disrupt local pest control systems. Historically, pesticide use against new alien pests often causes resurgence of secondary, local pest species. Introduction of specific and effective natural enemies may suppress these pests, eliminate pesticide use and restore IPM systems. IPM in many tree crop systems (e.g. fruit, nuts, forestry) is underpinned by former introduction programmes against alien pests such as scale insects, aphids, mealybugs. In these systems, as with the cascade systems of protected cultivation (see Section 2.4), maintaining successful biological control is so important to production that new pest problems require non-chemical, usually biological solutions – hence introduction programmes may *drive* biological control into crop systems.

In IPM systems, biological control interacts with other control measures. Chemical pesticides have a history of antagonism with biological control, but in recent decades, implementation of threshold-based pesticide use of IPM and the development of more selective chemical products has greatly improved opportunities for integrating biological and chemical control. Further, biological control has a critical role to play in maintaining the availability of necessary pesticides in IPM systems. Pest resistance to pesticides is widespread, and evolves and spreads particularly rapidly when intensive pesticide use causes strong selection pressure on pest populations. Natural enemies, by reducing both pesticide use and pest populations, slow this evolutionary process. For instance, in the pesticide induced outbreak of rice brown planthopper, *Nilaparvata lugens*, illustrated in Section 2.3.1, high pest populations quickly overcame single gene resistance in rice varieties bred against planthopper. The introduction of IPM, based on natural enemy conservation not only reduced pest populations but restored the contribution of resistant plant varieties to pest suppression. In the rice IPM programme described in 2.3.1, establishment of IPM allowed planthopper resistant plant varieties, which had broken down under intensive pesticide-induced resurgence, to be re-deployed effectively (Gallagher *et al.* 1994).

Another key element of IPM, the breeding or engineering of plants resistant to pests, has strong potential compatibility with biological control. Ecological theory suggests that successful biological control requires natural enemies to have the efficiency and reproductive capacity to overcome pest population growth. Plant resistance reduces the growth rate of pest populations, and hence would facilitate the successful action of natural enemies. It is likely that the complementary nature of plant resistance and biological control operates in many crop systems. In practice, however, the deliberate efforts of plant breeders and biological control practitioners have usually each sought their own "single technology solutions" to pest problems and integration has been limited. Because there is so much "partial resistance" created in plant breeding which remains under-utilized, and so many biological control opportunities, through conservation or augmentation, that provide good but not complete or continuous control, the capacity to integrate partial plant resistance and biological control to provide complete control of pests is considerable (Thomas and Waage 1996).

2.7 What is the value of biological control?

The justification for conservation and use of biodiversity for biological control must rest on demonstrating the value of biological control to agriculture and society. To value biological control, we might measure its contribution to the level of production of food, fibre and other crop products and/or to the stability or security of that production. However, biological control may have indirect benefits as well, for instance its value in reducing environmental effects of excessive pesticide use and contributing generally to sustainable food production systems (Menzler-Hokkanen, 2006). Further, biological control approaches may have application beyond agriculture, for instance, in the control of alien weeds in national parks, or in the control of insect vectors of infectious human or animal diseases.

Efforts to place an economic value on biological control have been patchy. Studies are often either very narrow, focusing on one pest in one control programme, and therefore difficult to extrapolate, or very broad and based on many assumptions, hence speculative. Entirely different methods have been used to value conservation, augmentation and introduction approaches. For this reason, no attempt is made here to provide a consolidated valuation, rather valuation of each approach will be reviewed and these will then be integrated and compared.

2.7.1 Valuing biological control as an ecosystem service

A number of attempts have been made to value biological control as an ecosystem service. These calculations have been at such a general level that they may usually be considered to incorporate the value of all approaches to biological control, including conservation, augmentation and introduction of natural enemies. In most studies, a range of services from biodiversity are estimated, with biological control being just one of these. Studies of this kind often make very broad and challenging assumptions.

Costanza *et al.* (1997) estimate a total value of ecosystems services worldwide of $33 trillion annually and, without presenting detail on calculations, attribute $417b of this to biological control. However, most of the value of this service was attributed to natural ecosystems, mostly marine, only $34b was attributed to cropland itself. Naylor and Ehrlich (1997) derive a strictly agricultural value for biological control in the USA by combining the cost of pesticides and their subsidies, plant breeding for resistance and pest control externalities and postulating that biological control, if widely used, would offset much of this. From this they estimate the value of biological control to the US as between $54b and $1 trillion per annum. However, while pesticide use does sometimes only replace natural control with chemical control, it is not realistic to assume that biological control would completely replace chemical control and plant resistance, at no cost.

Pimentel *et al.* (1997) and Pimentel (1997) assumed that natural enemies provide about 60% of the non-pesticidal control of pests. In the USA, they estimate that this is worth $12b per annum (in contrast to $20b benefits from pesticidal control) and worldwide $100b. Losey *et al.* (2006) have used similar methods for estimating the value of *insect* natural enemies in the USA. They assumed that natural control (including natural enemies, crop resistance and environmental effects) suppresses 65% of the potential damage to crops in the USA from insect pests, and calculate that this saves $14b to agriculture annually, $4.5b of which is attributable to insect natural enemies.

2.7.2 Valuing conservation of natural enemies

Our understanding of the value of natural enemy conservation is based almost entirely on the comparison of agro-ecosystems with and without natural enemies. Three lines of evidence indicate that, without the self-renewing action of local natural enemies, many pest species, or potential pest species, would be more abundant, causing substantial losses:

– Pest resurgence, where pesticides are shown to eliminate local natural enemies while having limited effect on the target pest, leading to pest outbreaks and losses, as discussed in Section 2.3.
– Biological control introductions, which reverses this observation, demonstrating that addition of specific natural enemies to pests which have escaped natural control typically reduces their populations, often by two or more orders of magnitude (Beddington *et al.* 1978).
– Experimental field studies which physically or chemically exclude natural enemies from pest populations and record substantial pest population increases (Luck *et al.* 1988).

Putting an economic value on this reduction of pest burden has been achieved in some IPM programmes where reducing pesticide use has restored control by natural enemies. Van den Berg (2004) has reviewed 25 IPM programmes based on farmer field schools, all of which involved reduction of pesticide use and conservation of natural enemies. Across these programmes, based in Asia, Africa and Latin America, largely on rice, cotton, vegetables, there was a consistent and usually dramatic reduction in pesticide use in the year following training, and often an increase in yield. Economic benefits to farmers were widespread, but only one study related benefits to costs of training (van den Berg *et al.* 2003). This study, on rice IPM in Sri Lanka, revealed a seven-fold benefit of training within the first year, in terms of increased farmer income relative to training costs, and farmers continued to use IPM methods over the six year study period.

Thus there is some evidence that the benefits of conserving natural enemies, following their disruption by pesticide use, may outweigh the costs. It is far more difficult to obtain estimates of the value of other measures to conserve or enhance the action of local natural enemies. Many measures which might enhance biological control by local natural enemies will have other kinds of economic impacts as well. Hence, measures like inter-cropping or zero-tillage, which may enhance natural enemy action, will affect the economics of production in other ways, making it difficult to isolate the specific value of the biological control element.

2.7.3 Valuing augmentation of natural enemies

Worldwide, augmentation is practiced as a public sector and a private sector activity. It is difficult to place an economic value on public sector augmentation, but its distribution and trends give some indication of the context under which it is seen to bring benefits. Public sector augmentation has involved particularly mass production and application of natural enemies against pests in field crops, including viral, fungal and bacterial biopesticides and egg and larval parasitoids against insect pests in such crops as sugar cane, cotton, soybeans, vegetables and maize.

Historically, a strong political commitment to non-chemical pest control in the former Soviet Union and China led to use of the egg parasitoid, *Trichogramma* spp, on over 10m ha of agricultural land. With political change and access to a greater diversity of pest control products in these countries, this commitment to augmentation is decreasing. In tropical America, a similar strong political commitment to augmentative biological control continues in Cuba, where there are over 200 production facilities for microbial and macrobial biological control agents (Pretty 2002), while in other Latin American countries, there are at least 100 facilities for production of microbial and macrobial products in field crops (van Lenteren and Bueno 2003). There is a risk in public sector augmentation systems that success becomes synonymous with levels of production of natural enemies, rather than with demonstration of impact on pests and net benefits to crop production.

Much more is known about the economic value of strictly commercial production of microbial and macrobial agents, where figures for sales of products are available. Commercial supply of natural enemies for augmentation is undertaken by about 85 companies worldwide, about 25 in Europe, 20 in North America and the rest widely distributed in other continents. In recent years, estimates of global sales from these commercial companies flututate at around \$300m, most sales being generated by microbial products, a high proportion of these being Bacillus thuringiensis (Gelertner 2005; van Lenteren 2006). In the past decade, commercial sales of biological control agents have been growing by about 15-20% per annum.

Where it is well established, as in European glasshouse systems, commercial biological control is competitive with chemical control on price and enjoys a strong market advantage in situations where chemical control is undesirable.

For many years there has been an expectation that penetration of pesticide markets by biological products would be a measure of the success and value of biological over chemical control. Between 1980 and 2000, predictions of a major pest control market share for biological control products led to substantial venture capital investment. These grand expectations proved over-ambitious (Gelernter 2005). In fact, following this burst of venture capital investment, the commercial biological control business has returned to its previous pattern of supply into strong niche markets by small to medium sized companies. Expectation of displacing chemical pesticides from a large part of the marketplace have receded, and industry is focusing on growth in favourable niche markets, where there is much potential.

2.7.4 Valuing introduction of natural enemies

Introduction programmes have a high “up-front” cost to governments in terms of international exploration and safety testing of natural enemies. Historically, governments have been reluctant to start introduction programmes until introduced pests are already causing very substantial losses to crops and/or generating high costs of control. In calculating the economic value of introduction programmes, it is traditional to generate a benefit cost ratio by estimating these losses over time and treating them as equivalent to the benefits of successful biological control, and then dividing this by the cost of the introduction programme. There have been numerous studies of this kind for successful introduction programmes against insect and weed pests, which have been summarized in various publications (Huffaker *et al.* 1976, Tisdell 1990, Cullen and Whitten, 1995, Greathead 1995, Lubulwa & McMeninman 1998, Jetter *et al.* 1997). Benefits of successful programmes may range from about 2 to 1, to several thousand to one, and commonly fall in the range of the tens to low hundreds.

Of course, these studies record the benefits of successful control only, and the cost of failures is not incorporated into this calculation. At a national level, it may be possible to calculate the investment over time in introduction programmes and to set this against the benefits of successful programmes. For instance, Lubulwa and McMeniman (1998) have estimated the return on ten introduction programmes supported by the Australian Centre for Agricultural Research in the Pacific region from 1983 to 1996. While not all were successful, the aggregate value of about \$A25m exceeded the cost of about $A2m. Most countries active in introduction have rolling programmes which efficiently overlapping projects, allowing intermittent successes to generate the support needed to carry inevitable failures.

The cassava mealybug programme described in Section 2.5.1, which has benefited from detailed benefit:cost analysis. Norgaard (1988) caculated a benefit:cost ratio of 149:1, while a more thorough, later analysis by Zeddies *et al.* (2001) gives ratios from 170:1 to 430:1 under different scenarios of substituting lost food production. This was a major regional success on a staple food crop. One success of this kind can accommodate well over 100 failures at the same cost (in this case, $14-46m depending on the study) and still generate a positive benefit:cost ratio overall for biological control introductions. As success rates of introduction are usually estimated at above 10% it is likely that, even if failures were incorporated, the net benefits of introductions worldwide would be highly positive. Indirect effects of biological control programmes on the environment have not been included in benefit:cost calculations, but would be significantly positive where they replaced damaging pesticide use.

2.7.5 Valuing biological control: comparisons and conclusions

The very different approaches to biological control have attracted different forms of economic valuation. Valuation of biological control as an ecosystem service treats it as a free resource, without which, global agricultural production would bear greater losses than the estimated 30-50% of losses to attainable production which have historically been attributed to insect pests, diseases and weeds (Yudelman *et al.* 1998)). As we have seen, estimates of this "saved" production value are in the tens of billions of dollars for the USA and hundreds of billions worldwide. Pimentel *et al.* (1997), using data provided by Oerke *et al.* (1994) predict that natural enemies protect about 20% of world crop production. Overall, at this quite speculative level of estimation, the value of biological control appears considerable.

These analyses of ecosystem services also show that the value of biological control as an ecosystem service is actually a very small proportion of the overall value associated with biodiversity conservation. Hence, Pimentel *et al.* (1997) identify annual benefits from biodiversity of about $3000b to agriculture, recreation and waste management, only 5.5% of it relates to biological control, which is less than that associated with pollination (6.8%). Losey *et al.* make a similar calculation for insect biodiversity benefits in USA and conclude that only 7.5% relates to biological control, again far less than pollination. The implication is that conservation of natural enemies is most justifiable when it is associated with conservation of all aspects of related plant and animal biodiversity in agro-ecosystems and related habitats.

Analysis of specific approaches to biological control takes a more benefit to cost approach. Economic studies of IPM programmes and of introduction programmes effectively measure the economic value of "restoring" biological control relative to the costs. For both approaches, valuation is strongly affected by the timescale over which losses (= benefits restored) are estimated, but conclusions from limited studies are that these ratios are highly positive.

Much attention has been focused on the commercial markets for biological control as an indicator of its value to agriculture. This ignores that augmentation is only a small part of biological control, and commercial production only a part of augmentation. Nonetheless, sales of biological control agents into niche markets are strong and growing and indicate a continuing value of commercial biological control as a small but stable component of global commercial pest control.

Strictly economic estimates beg a comparison between biological control and other pest control methods, such as chemical pest control, with its recent global market fluctuating between $30b and $35b. Such comparisons ignore the very different contributions of chemical and biological control. In most crop systems, where pesticides are used, natural enemies are providing complementary levels of control, or are suppressing pests which are not targets of chemical control. IPM programmes address "market failures" in chemical control, as does augmentation, which has found its niche in crop systems where chemicals are difficult to use, ineffective or undesirable. Biological control introductions very often target similar crop systems where chemical control has a poor record (e.g. sucking insects in tree crops) and those systems which are too extensive for cost-effective chemical control (e.g. pastures, forestry, natural habitats) Hence, purely economic comparisons under-value biological control because its principle application is against pest problems which cannot be easily addressed by other methods. Biological control not only contributes across a broad range of crop systems, but without biological control for some pests and situations, sustainable pest management would not be possible.

Estimates of the value of biological control in this Section do not include indirect benefits, such as are associated in IPM with the reduction of environmental pollution or improvement of health as a result of pesticide reduction. Further, training in IPM, which has a strong basis in natural enemy conservation, has been shown to have very substantial benefits in terms of general improvements in crop management, a desire for continued learning and social and political skills (van den Berg 2004).

Finally, biological control is often applied in times of political emergency. Pest outbreaks, sometimes involving pesticide treadmills, or the appearance of new alien pests have, historically, been associated with crises in farmer livelihoods or consumer confidence, or even national food or trade security. Beyond its specific value to farmers and production, biological control has an additional political value in these situations, as a permanent and affordable solution for problems affecting confidence in agriculture at a national scale.

2.8 Future trends in biological control

What trends are likely in biological control over the next few decades? Conservation and augmentation of natural enemies will be considered separately from biological control introduction, because while all of these approaches will be affected by trends in pest management, changes in introduction will have an additional driver, namely trends in the occurrence of alien pest species.

2.8.1 Future of conservation and augmentation of natural enemies

Future pest management will have elements of natural enemy conservation, augmentation, pesticide use and other methods. The importance of conservation and augmentation in future will be strongly influenced by the future development of IPM, which treats these approaches as potentially important elements. It will also be influenced by the future of the chemical pest control. The emergence of genetically modified (GM) crop systems deserves consideration because it is spreading rapidly and replacing pesticide markets in the continued growth of the pest control industry.

In the past 50 years, IPM has been adopted as a national crop protection policy by an increasing number of countries. IPM has been interpreted differently by different countries and different approach have been taken, ranging from a commitment in USA to have 70% of crops under IPM, to actions by several European countries to reduce pesticide use by 50%. Critics have observed that commitments to IPM are not realized (Hamerschlag 2007) or that they focus on pesticide management and not natural enemy conservation (Ehler and Bottrell 2000). In a review of IPM, focused mainly on the USA, Kogan (1998) suggests that the great majority of IPM programmes simply use pest surveillance as a basis for managing pesticide applications, whilst incorporating natural enemy monitoring and methods such as augmentation, which characterize IPM as originally conceived, occurs in less than 10% of IPM programmes. IPM has provided an opportunity for the development of conservation methods and its spread will lead to a growth in conservation of natural enemies, but the rate of this growth will be very dependent on the extent to which IPM explicitly incorporates biological control elements.

Parallel to IPM trends in government policy, the food industry is playing a growing role in promoting elements of IPM. Largely driven by consumer concerns about pesticides, major food distributors and retailers are imposing IPM-like standards on their producers. This may take the form of certification schemes run by particular companies or by farmers associations. Organic production is growing and, while it continues to have a very small market share, it has considerable influence on public perspectives on pesticide use and sustainable agriculture. More widespread integrated production schemes make use of natural enemies in their promotion – ladybirds are a common icon of integrated production labels on food - if not substantially as yet in their schemes. These changes are being driven quickly and on a global scale, in part as a result of the consolidation of the food industry around fewer, larger multinational retailers and the growth of global sourcing of agricultural production for these demanding markets. As with national IPM initiatives, the effect of this on biological control will depend on how explicitly integrated production requirements identify active natural enemy conservation and augmentation, rather than simply minimal and safe pesticide use.

Within production systems, the future of augmentation is unclear. In the face of globalization of agriculture, direct government support to agricultural production, for traditional reasons of food security, may decline and with it government-subsidized biological control augmentation programmes. Further, public sector augmentative production may be lost, particularly in the developing world in the face of cheap, generic pesticide alternatives.

For commercial augmentation, however, we have seen that there is a stable, niche market in certain crop systems like high value horticulture, that this market is growing and that there is much room for growth. There is some evidence that the European glasshouse biocontrol market is saturated, and possibly even declining with competition from new specific pesticides (De Buck and Beerling 2006). However, only 5% of glass house production worldwide use biological control, so there is considerable scope for spread of this approach.

Guillon has estimated the 2003 global commercial market for augmentation at $425m (47% macrobial, 53% microbial), and the 2008 market at $573m, suggesting that slightly more of this 35% growth will be in microbials than macrobials (Guillon 2004). The principle constraint on the rate at which augmentation grows is presently the national regulatory systems that make difficult the registration of new projects, which is discussed further below.

The requirement and cost of pesticide registration and re-registration on minor crops is causing a dearth of effective pesticides in crop systems where augmentation and conservation have particular strength, which may prove a further stimulus to their growth. On the other hand, new chemical pesticides are being developed for a range of crop systems which are increasingly selective, in that they do not interfere with natural enemy action. While these products may complement natural enemy augmentation, they also have the potential to replace it, if more cost effective, as suggested above for European glasshouses.

The factors which influence the future of biological control conservation and augmentation are diverse and contrasting, making prediction difficult. On the basis of the spread of IPM and patterns of growth of commercial augmentation, it is reasonable to conclude that demand for biological control knowledge and technologies will grow steadily in future. This growth will be associated with the spread of IPM and augmentation in particular crop systems.

An increasing number of government and international agencies, farmer organizations and consumer groups are aware of IPM and its benefits, and it is likely that this will drive a conversion of systems to IPM and a preference for IPM in newly established crop systems.

However, it is important to observe that this trend towards IPM will also be punctuated, as in the past, by crisis and reaction. In a comprehensive review of pest management and IPM, Way and van Emden (2000) predict that broad spectrum pesticides will continue as a major component of pest management systems well into the 21st century. Where IPM is the preferred policy at the national or local level, this will necessitate active conservation of natural enemies.

However, in many countries and production systems, IPM is poorly understood, Here, chemical pesticide use and misuse is likely to continue to generate the patterns of pest resurgence which have emerged in the 20th century. There is a strong history of such pest management crises initiating national and even regional IPM initiatives with long-lasting effects. While avoidable new pest control crises are regrettable, their potential to drive IPM development should be recognized and used. Such crises may be particularly apparent in developing countries undergoing agricultural intensification, such as those in sub-Saharan Africa and South and East Asia, and in new crop systems, such as those for bioenergy crops, where there is little experience of pest control.

Finally, one of the least predictable drivers of future natural enemy conservation is the introduction of genetically modified (GM) crops. GM technologies have, so far, focused on reducing the impact of insect pests (Bt crops) and weeds (herbicide tolerant crops), with some limited activity in other areas, e.g. viral coat protein technologies to protect plants against viruses diseases. Resistance to more insects and viruses, and to fungal and bacterial diseases and nematodes are likely features of future transgenic crops.

All of these modifications potentially "compete" as pest management solutions with measures to conserve natural enemies of pests. They also compete with augmentation, particulary biopesticides, a particular example being the displacement of *Bacillus thuringiensis* from markets where Bt cotton has been adopted.

Will biotechnology, by producing more pest resistant crops, replace the need for biological control conservation and augmentation? It is difficult to see this occurring. Firstly, GM technologies will be targeted by companies and breeders against intractable pest problems on a crop that lack effective, alternative methods of control, as this is where future markets lie. Some areas where biological control is effective many not be easy targets for GM crop technologies. For instance, sucking insect pests (Hemiptera) have so far been particularly difficult to combat with GM technologies, whereas many of these are particularly amenable to biological control.

The lack of attention by industry and government to possible effects on natural enemies early in GM crop development generated very considerable concern about incompatibility with biological control and IPM. IOBC and other organizations have initiatied studies on non-target effects, and this has led to an international project to establish guidelines for the integration of GMOs with natural enemies and other components of IPM (Hilbeck and Andow 2004). While there are some specific areas of concern, the general impression so far is that GM crops do not pose the kinds of conflict with biological control that broad spectrum chemical pesticides did in their time (Romeis and Shelton 2006) and that reduction of broad spectrum pesticides on Bt crops allows natural enemy populations to grow. Recent studies in UK, where concern about the biodiversity impact of GM herbicide-resistant crops is particularly strong, have shown that in some GM crops increased herbicide use may decrease biodiversity, including presumably natural enemy diversity, although impact on biological control was not measured (Firbank et al. 1999).

Considerably more research is needed on the way in which GM crops and biological control can be better integrated for farmers. Yang *et al.* (2005), in an important experiment comparing conventional, IPM and Bt cotton production in China showed that farmers employing IPM generated better yields with Bt crops than those not doing so. The active conservation of natural enemies allowed reduction of pesticide use on minor pests, and thereby proved important to realizing the full benefits of using GM crop technology.

Independent of any direct interaction, there is a real risk that a sector-wide pre-occupation with new GM crop solutions may simply displace public and private investment in biological control. At worst, we could see a repeat of the history of chemical control, where the domination of pest control technology by multi-national companies, with their powerful political influence, resulted in under-investment in non-chemical approaches to pest management, which ended only when the dominant technology began to break down. For instance, the likely demise of *Bacillus thuringiensis* as a biopesticide in cotton systems employing Bt cotton may be the logical result of market forces, but will such changes affect the way in which government research funds, which are still so important to both biopesticide and GM crop research, are invested in future? To avoid this myopic, "silver bullet" approach to pest control repeating itself, there is a need for GM technology to be seen, with biological control, *as a component of IPM systems* (Waage, 1996; Way and van Emden 2000). If this occurs, GM crop development may be biological control-neutral in future.

2.8.2. Future of biological control introduction

The future of biological control introduction rests very much on the future of alien pest problems themselves. It is the nature of such problems to accumulate in countries, such that their economic burden mounts. A number of countries, particularly in the developing world, have an "introduction backlog", where alien pest problems exist which have been controlled successfully elsewhere, but lack of resources has prevented local action.

Another factor which will influence future introduction is the growing interest in alien invasive species affecting the natural environment. This problem, highlighted in the Convention on Biological Diversity (CBD) in the early 1990s, has led to many new introduction programmes against alien "environmental" pests, particularly weeds. With a large "backlog" of alien environmental pest problems in many countries, we can expect introduction programmes to grow and diversify in decades to come, simply on the basis of current pest problems.

However, the other factor affecting the future will be the rate of arrival of new pest problems. Today there is a broad consensus that dramatic growth in international trade, travel and transport is not simply continuing the introduction of new alien pests, but dramatically accelerating it. Studies of annual interceptions of non-native arthropod species at US ports from 1990 to 1999 suggest an increasing trend (National Research Council 2002). In UK new agricultural pest and disease outbreaks fluctuated around 150 from 1993 to 2000 and then jumped to 350 in 2002 (National Audit Office 2003).

Interpreting interception records is complicated by the fact that reporting will increase with growing inspection effort (Work *et al*. 2005) and, of course, that interception rate may not be related to establishment rate of new pests. There is in fact very little information on changing rates of alien invasive pest establishments. Evidence for US agricultural insect pests and crop diseases, suggests that introduction rates are unchanged over recent decades (US Congress 1993, Sailer 1983). Whatever the evidence for accelerating alien invasive pest problems, the perception that bio-invasion is a price we will pay for globalization is widespread. Climate change, by making some habitats more amenable to invasion by pests and diseases, is likely to contribute to an increase in alien pest problems in some regions.

Putting together existing opportunities for biological control introduction, new demand from environmental conservation, the possible acceleration of new alien pest problems due to globalization and climate change, This leads to the conclusion that there will be a growing demand for biological control introduction. It is important to note that this growth will engage many new stakeholders in biological control introductions, which will require considerable education and possibly modification and extension of research and regulatory systems that underpin this approach.

2.8.3 The future of biological control - conclusions

Across the breadth of biological control, including conservation, augmentation and introduction, likely future trends suggest an increase in demand. Key drivers will be the spread of IPM and augmentation in established crop systems, new IPM initiatives associated with anticipated problems of intensification, and the acceleration of alien species problems and resulting demand for introduction programmes. Meeting this growing demand and opportunity for biological control will fall firmly on the public sector, particularly government, because it is governments that will continue to drive enabling IPM policy and research, and to drive enabling regulatory systems for augmentation and introduction. Furthermore, public sector research will continue to underpin biological control development, because conservation and introduction deliver public goods. Even for augmentation, which will grow gradually more commercial, we know that public sector research provides critical R&D support to the SMEs, and will probably continue to do so.

In conclusion, biological control has considerable value (Section 2.7) and this value to society will increase in future (this Section), providing that governments can take the steps necessary to enable its growth. Many of these enabling steps will be national by nature, particularly with IPM, but some may be international. The international context of biological control and its future will be considered in the next Section.

3. MAPPING THE INTERNATIONAL ENVIRONMENT

International activities in support of biological control have developed by inter-governmental initiatives, by professional organizations and by industry. In this Section, some general developments will be reviewed, highlighting particular international and inter-governmental issues associated with natural enemy conservation, augmentation and introduction. Observations will also be made on the distribution of biological control activity between countries, and where gaps occur in capacity.

International activity in biological control has been characterized over the last few decades by both inter-governmental and non-governmental activities. A major inter-governmental step in fostering political support for biological control was Agenda 21. Launched by the UN at the Rio Earth Summit in 1992 and reaffirmed a decade later in Johannesburg, Agenda 21 is a comprehensive plan of action for sustainable development. Under its section on sustainable agriculture, it stated that "Integrated pest management, which combines biological control, host plant resistance and appropriate farming practices and minimizes the use of pesticides, is the best option for the future, as it guarantees yields, reduces costs, is environmentally friendly and contributes to the sustainability of agriculture". http://www.un.org/esa/sustdev/ documents/ agenda21/english/agenda21toc.htm). Agenda 21 called for national research and development of IPM and for action by UN at the international level to stimulate IPM networks and research on biological and other controls.

Reference has already been made to the activity of FAO and CAB International, as inter-governmental organizations, in providing technical support to biological control worldwide. Similar work is undertaken by other, regional inter-governmental institutions like the Tropical Agricultural Research and Higher Education Centre (CATIE) in Costa Rica, and advanced research institutes like the International Centre for Insect Physiology and Ecology (ICIPE) and the Centres of the CGIAR. The Global IPM Facility was established in 1997, sponsored by FAO, the World Bank, UNDP and UNEP (http://ww.fao.org/ag/ AGP/AGPP/IPM/gipmf). It has used FAO's considerable experience in biological control and in rice IPM to extend IPM activities, including farmer training in natural enemy conservation, to other crops and regions, often fostering regional programmes.

The international conventions in which biological control has most relevance are the IPPC and the CBD. The IPPC has developed international guidelines for biological control introduction (see Section 3.3.1). In the CBD, biological control is identified in the Interim Guiding Principles for the Prevention, Introduction and Mitigation of Impacts of Alien Species., which states that "in some instances, biological control may give long-term suppression of an alien invasive species without recurrent costs, but should always be implemented in line with existing national regulations, international codes and principle 10 above" (http://www.biodiv.org/decisions/default.asp?dec=V/8) . Principle 10 relates to deliberate introduction of organisms and its control. The CBD also identifies biological control in its Agrobiodiversity Work Programme, requesting that Parties undertake studies on "the role of natural enemies and other organisms in … pest and disease control … at field and landscape levels" (http://www.biodiv.org/ programmes/areas/agro/default.asp).

With respect to non-governmental activities, outside of the inter-governmental sector, the International Organization of Biological Control (IOBC) was established in 1955 as a global voluntary professional organization affiliated to the International Council of Scientific Unions (ICSU) (http://www.unipa.it/ iobc/view.ph). It promotes environmentally safe methods of pest and disease control, including natural enemy conservation, augmentation and introduction. Its members include biological control specialists from around the world, organized in six regional sections. Through these sections and specific working groups, IOBC has produced IPM guidelines for a range of crops, guidelines for quality control in augmentation, and (with FAO) guidelines on safety of biological control introductions (see Section 3.3.1).

Private sector, international activities in biological control have been limited. International associations created by pest control industry have directed little attention to biological control, which simply reflects that this is a very minor part of their business. But in the case of augmentation, the International Biopesticides Manufacturers Association (IBMA) has been very successful in creating links between these smaller companies as described in Section 3.2.

3.1 Conservation of natural enemies

The importance of natural enemy conservation is embodied today in national policies supporting integrated pest management. As we have seen, IPM policy does not always explicitly recognize the role of natural enemies and the importance of supporting biological control research and systems. IPM has developed independently in many parts of the developed and developing world. Its distribution has therefore been reasonably equitable between developed and developing countries. Developing country activities have been strongly supported by development assistance programmes and international agricultural institutions, such as the FAO, which has, for instance, organized with other international organizations and donors, regional IPM programmes in Asia in rice, vegetables and cotton. For these reasons, awareness of natural enemy conservation, as a foundation for IPM, is well distributed globally, with models in most crop systems and regions, and in both developed and developing countries.

Independent capacity for IPM, however, remains limited in countries which cannot undertake research in the taxonomic, biological and ecological areas which underpin natural enemy conservation. A number of institutions, besides FAO, provide information and support to developing country national programmes in IPM and its biological control elements. These include CABI International, the International Agricultural Research Centres of the CGIAR, the IOBC and a range of national programmes in developed countries through bilateral development initiatives.

3.2 Augmentation of natural enemies

Augmentation worldwide is characterized by many small production units or companies which supply natural enemies for biological control. Both developed and developing countries have long experience in augmentation, although strictly commercial production has progressed further in developed countries.

Augmentation generally supports local, at most national markets. There are only a very few exceptions to this. The biopesticide, *Bacillus thuringiensis*, has found a global market, in contrast to most microbials, and in Europe some glasshouse biological control industries, which themselves grew from local farm-scale product units, now service growers on a regional scale, and very rarely beyond this. As discussed earlier, while the future growth of augmentation is highly promising, we are unlikely to see development of multinational biological control businesses or of biological control products marketed by multinational crop protection companies.

Like IPM, augmentation will remain a local activity, and international opportunities will involve sharing knowledge and building capacity for augmentation in different countries and crop production systems. IOBC has played a particular leadership role in this area, through international working groups on arthropod mass reading and quality control, and on *Trichogramma* and other egg parasitoids, the most widely augmented insect natural enemies. These groups have greatly facilitated the exchange of material and information to improve local augmentation efforts.

Another important service is provided by the International Biocontrol Manufacturers Association (IBMA), which was created in 1995 to represent the views of biological control producers, who are mostly small companies with limited resources (http://www.ibma.ch). Its membership is, so far, largely North American and European, but it is growing in Asia, Africa and Latin America. IBMA is particularly and it is active in sharing information and lobbying for regulatory changes to facilitate biological control development (see below).

There are two areas where inter-governmental cooperation will be very important to the future of augmentation. The first involves cooperation of governments in overcoming regulatory barriers to development of biological control products, and the second involves the international movement of natural enemies for augmentation.

Historically, the use of natural enemies in pest control was not regulated, as they were living organisms just like crops and pollinators. However, with the development of natural enemies as commercial crop protection products, and particularly of biopesticides as formulated products, there has been a trend in governments towards registering them just as is done with chemical pesticides.

While biological control products are generally characterized by their specificity and safety, and hence pose substantially less risks than some conventional pesticides, there are good arguments for ensuring their quality and safety through standard tests and registration procedures for new biological products. Unfortunately, this has usually involved application of existing pesticide registration procedures to biological products. Biological and chemical products are not easily comparable with respect to measuring safety and efficacy (Section 2.4), and this has interfered with the efficient registration of biological products.

However, the greatest barrier to registration is created by its cost. Successful chemical pesticides have had, historically, very large markets and an increasingly small group of multinational companies are able to spend hundreds of millions of dollars on product development and registration. Registration costs imposed by governments are high, reflecting these large markets and industry’s ability to pay. By contrast, most augmentative products, because they are specific and/or local, have very small markets. In Europe, this means that the cost of registration for a biological product may be prohibitively expensive despite a market and demand. Expensive requirements for extensive safety, field and other testing, developed to suit chemical pesticide registration, may be inappropriate for biological control products.

This problem is even more severe in development countries. Here, there is less capacity to operate registration systems, and data from developed countries are usually accepted for registration. This will exist for pesticides, but not for new local biological control products. Without local government procedures and capacity, it will be difficult for any biological control products to reach the market (Tripp and Gisselquist 1996).

A number of countries, recognizing the importance of providing alternatives to chemical pest control, have sought to facilitate registration of biological control products. In the USA, a fast tracking process for biological control agents has dramatically reduced the cost of bringing a product to market, making it possible for small companies to develop, register and sell specialized products. Fast-tracking is also under discussion in Europe, where IBMA has proposed a registration procedure quite separate from that for chemical pesticides (IBMA 2005). In Africa, several countries with a long experience in biological control are taking steps to create a favourable regulatory environment for biological control products (Anon 2005).

At an international level, there exists now an opportunity to harmonize regulations of biological control. The OECD has a longstanding project to harmonize registration procedures in its countries for macrobial (OECD 2004) and microbial (OECD 2003) products. Harmonization *does not* in itself mean facilitation of biological control, and it may often mean the opposite. International effort should make facilitation a deliberate part of its objective, in support of national and international commitments to IPM

The other issue of international significance for augmentation relates to the fact that natural enemies for augmentation are often moved internationally. This may happen in two ways. An existing biological control product may be sold and shipped from one country to another, or natural enemies may be collected in one country to be developed into biological control products in another. The first issue is generally dealt with by the regulation of commercial biological control products (see above). The second involves programmes that resemble biological control introduction.

In the European glasshouse system, for instance, alien pest mites, leafminers, thrips and whiteflies have been effectively controlled for decades with mass-produced, alien natural enemies. The constant arrival of new alien pests into these systems, and the desire by producers to obtain more effective agents for existing alien pests, has encouraged international exploration for natural enemies for augmentation.

For microbial agents, there is a longstanding tradition of collecting pathogen isolates from many localities for screening and selection of the most promising species or strains. It is not always the case, with more generalized microbial and macrobial agents for augmentation, that the best species or strain will come from the target pest in its area of origin. Thus, it was through such an international exploratory activity for strains of *Bacillus thuringiensis* that a strain effect against fly larvae, *B. t. israelensis*, was discovered in soil in the Israeli desert (Goldberg *et al.* 1977) , which has subsequently come to underpin control campaigns for insect vectors of human disease worldwide . For this reason, biopesticide formulations may often be, technically, alien species as well.

For many years it as been presumed that augmented natural enemies do not disperse widely from where they are applied. Therefore, even if they are alien species, they would pose no potential threat to local agricultural or natural habitats, in contrast to natural enemies in introduction programmes. However, this is no longer assumed, and a number of recent European programmes have examined the environmental risk posed by augmentation of both native and alien natural enemies and how this is measured (Hokkanen *et al.* 2003, van Lenteren *et al.* 2003). In developing guidelines for biological control introductions, FAO extended coverage to include natural enemies exported or imported for augmentation, as discussed in the next Section.

Thus, augmented natural enemies may be subject to regulations as products and as alien species. International cooperation in both areas is required to facilitate access and use of such organisms.

3.3 Introduction of natural enemies

Introduction programmes are inherently international, as they involve the movement of natural enemies between countries. Hence, over the past 150 years, countries have depended on other countries for access for exploration and local knowledge of pests and natural enemies. A global level of expertise, and a tradition of international cooperation and reciprocity has grown from this, as has an international system to ensure the safety of biological control introduction.

Historically, some governments have been extremely active in introduction, due to both their agricultural research sophistication, and their “settler culture” status, which means that they introduced much of their agriculture and hence have substantial alien agricultural pest problems. These include the USA, Canada, Australia, New Zealand and South Africa.

However, introduction programmes have a long and successful history in the developing world as well, associated initially with colonial agriculture, and subsequently with the interest of international development agencies. In 1926, the UK government established an international institute for the purpose of introducing biological control agents against alien pests and weeds in colonial agricultural systems. This grew into the Commonwealth, and then International Institute of Biological Control, which continues to facilitate introduction programmes for developing countries through a network of laboratories in tropical America, Africa, Asia and Europe. The French government also developed during the 20th century a development-focused programme in biological control introduction. In the 1980s, the international agricultural research centres of the Consultative Group on International Agricultural Research (CGIAR), being, like IIBC, an internationally distributed network of laboratories with expertise in pests and natural enemies, also became very active in introduction programmes for developing countries.

Many of the developing country problems addressed by these projects involved alien pests of staple food crops or export commodities, which threatened food or economic security, and for which alternative control methods, particularly chemical control was simply unaffordable by the affected communities. Such projects readily attract funding from multilateral and bilateral donor agencies, particularly because they can deliver dramatic benefits delivered to poor farmers over short time scales. Hence, introduction programmes have often been “quick and easy wins” relative to most rural development programmes. Further, affected governments will often consider these problems “emergencies” and ask for international assistance. The FAO Technical Cooperation Program has often responded to such requests, as have national desks of bilateral donors.

A good perspective on the distribution of benefits of biological control introductions can be gained by analysis of introduction programmes. Altieri (1991) estimated that, up to 1981, 353 species of natural enemies were introduced to developed countries from developing countries, while 263 went the other way. A study by CABI (1994) comes up with a similar pattern: biological control agents for insects and weeds have come from 98 different countries, 57% of which were developing countries, while of the 121 countries which have undertaken at least one introduction programme, about half were developing. An indication of the distribution of actual benefits of introduction can be gained from an analysis by Christopherson (1995), based on data from Julien (1998) and Greathead and Greathead (1992). The table below gives the total number of introductions of natural enemy species made against insects and weeds which were attributed with a level of success, and distributes these, for countries in each economic class, between species donated by those countries to others, and species received. Note that this is not a measure of North-South or South-North flow, as developed countries may donate species to other developed countries, etc. Rather, it represents, for countries in different economic classes, the status of their "introduction budget".

National economic status (from (World Bank statistics, 1994)	Successful introductions benefiting the countries	Successful introductions arising from the countries and benefiting others
High income	451	306
Upper middle income	163	242
Lower middle income	159	109
Lower income	90	206
Total	863	863

The table shows that all categories of countries have both donated and benefited from successful biological control, often to about the same degree – a strikingly equitable level of benefit sharing. Note, however, that "successful introductions" may different greatly in their real economic value, hence this is not an economic measure of benefit sharing. Secondly, it is clear that high income countries have been more active in *both* "receiving" and "donating" agents, as we might expect, while the poorest countries have given more than they have received. This latter observation may be due to less effort being made by or on behalf of the poorest countries, or simply that they have less alien pest problems, due to greater isolation from world trade.

The movement of natural enemies between countries for biological control has safety implications which have attracted international attention and action. Originally, concern focused on the risk that biological control agents might themselves become agricultural pests. This was of particular concern with respect to weed biological control, as the plant feeding insects used often belonged to taxa that included major crop pests.

During the 20th century, a system of testing the host specificity of agents was developed and refined by the major countries and institutions undertaking introduction programmes. For weeds this involved both tests of a wide range of species related to the target weed, to establish host specificity of the natural enemy, and tests of crops and wild plants of significance in the intended region of introduction. For natural enemies of insect pests, tests were usually made against economic insects (e.g. bees, cochineal) and sometimes native wild insect species of particular interest.

By the late 1900s, an international dialogue amongst biological control practitioners had ensured a high level of consistency in safety testing procedures amongst the handful of countries regularly involved in biological control, but not all countries had access to this knowledge. In 1989, a project was started to develop guidelines for all countries on the safe introduction of biological control agents, leading ultimately to new IPPC phytosanitary standard, ISPM3. This is described in the case study in Section 3.3.1 below.

The ISPM3 Guidelines identified the importance of environmental impact assessment for intended biological control introductions. In the 1980s, environmentalists and ecologists began to express concern about the possible impact of introduced natural enemies on non-target species in natural ecosystems. A number of cases were identified where an introduced natural enemy had reduced populations of rare native insect or plant species (Howarth 2000, Fowlett and Duan 2000).

These kinds of non-target environmental effects had not been a priority for consideration when many of these programmes had been developed. For instance, the biological control in Australia of the alien prickle pear cactus, *Opuntia* spp., by the Argentine moth *Cactoblastis cactorum* was so successful that this programme was repeated against this cactus in many other countries where it was invasive, including a number of Caribbean islands. Subsequently, the moth spread into the United States, where it attacked an indigenous cactus, and is now spreading towards Mexico, a unique area of cactus biodiversity (Zimmermann *et al.* 2000). Were such a biological control programme contemplated today, non-target effects would be given much greater priority in safety testing, and it is quite likely that introductions would not proceed so close to an area of cactus diversity.

Non-target and environmental effects of introduced natural enemies have now received considerable attention by biological control specialists (Wajnberg *et al.* 2000; Bigler *et al.* 2006), and this is leading to new approaches to measure environmental risk and to provide a better benefit/risk profile for introduction programmes for decision makers (Sheppard *et al.* 2003).

As part of the current study, an informal survey was made of biological control specialists involved in introduction programmes in CABI, USA and Australia. They were asked them whether environmental concerns about introduction programmes had reduced activity in this area of biological control. They all replied that environmental concerns had certainly increased the length of biological control programmes, because of the additional testing involved, but not the level of demand or activity. Indeed, paradoxically, much demand for biological control introduction today comes for invasive pests affecting natural ecosystems. This now constitutes a substantial proportion, often the majority, of ongoing projects and its recent growth underpins the healthy state of biological control introduction activity today.

To conclude, there are now strong, international agricultural and environmental agendas on biological control introductions. While the environmental community remain concerned about the risks of biological control introduction, they also accept it as a valuable strategy in combating invasive species. This mixture of caution and acceptance is implicit in Decision VIII/27 made by the CBD at its eight Conference of Parties in 2006, which urged "Parties, other Governments and relevant organizations to evaluate and take appropriate measures (e.g., develop guidance or codes of practice regarding the trade and use of biological control agents) at national, regional and global levels to address the potential risks of biological control agents as invasive alien species, taking into account the work of relevant international bodies and agreements such as the International Plant Protection Convention, as well as the experience of countries at national level".

3.3.1 Case study: development of international guidelines for the safe movement of natural enemies

Guidelines to ensure the safety of biological control introductions were first developed as an International Standard for Phytosanitary Measures (ISPM 3) and approved in 1997 (Greathead 1997). They were subsequently revised and releases in 2005 as Guidelines for the Export, Shipment, Import and Release of Biological Control Agents and other Beneficial Organisms, and can be found under ISPMs on the IPPC website (https://www.ippc.int). These guidelines relate specifically to the safety of moving natural enemies between countries, and do not address the issue of benefit sharing.

The original Code of Conduct was aimed at ensuring the safe importation of alien (=exotic) biological control agents capable of self-replication. Hence, it included both species for introduction and augmentation, as well as for research. The Code was intended to ensure that all countries had guidelines for biological control, as well as to encourage harmonization amongst existing guidelines in different countries.

The Code listed the different responsibilities of government authorities, of exporters and of importers. Responsibilities covered include the preparation of dossiers on the pests to be controlled, including its identity, biology and an analysis of the risks which it poses. For natural enemies, a dossier should be prepared which provides information on how the natural enemy is to be identified, its biology and ecology, including its host range and specificity, any possible non-target effects and any contamination which may occur in its cultures and how this can be recognized and removed.

The revision of the Code into Guidelines in 2005 extended its cover to include not just natural enemies but other beneficial species, such as pollinators, and to place emphasis not on the fact that species to be introduced are exotic, but on the properties that might pose risks (Quinlan *et al.* 2003, 2006). It also makes more explicit mention of the need for imported natural enemies to be safe with respect to non-target species in natural environments.

The original intention was that the Code would be accompanied by specific guidelines on proven and effect methods for achieving the requirements of the Code. For instance they would include methods for pest risk analysis, natural enemy host range testing, measurement of non-target environmental effects, etc. The continuing lack of such practical guidelines is a profound shortcoming of the documentation.

Kairo *et al.* (2003) have made an assessment of the use of ISPM3 since 1995. They conducted a survey of national programmes in 42 countries, which included 104 introductions of 43 natural enemy species against 28 insect pests. Of these 104 introductions, 70 were accompanies by dossiers prepared as per ISPM3 guidelines. Most of these dossiers were prepared by developing countries, where the guidelines clearly had the greatest benefit. For some of the other introductions, countries used similar, existing national guidelines. The availability of ISPM3 was also found to have other beneficial effects, including the facilitation of cooperation between adjacent countries in mounting regional biological control programmes, raising awareness of potential environmental effects, which were not high priorities in some developing countries, and increasing donor confidence.

3.4 Biological control: where is international action needed?

The future development of biological control will depend largely on activity at the national level, undertaken particularly by the public sector, but also by a growing commercial augmentation sector. However, there are a number of issues at an international level which will be important to the future development of biological control which will be considered in this Section.

Fortunately, the substantial involvement over recent decades of FAO and other organizations in biological control and IPM in development countries, supported by a wide range of development assistance agencies, has ensured that globally, biological control experience and expertise is well distributed across developing and developed countries. This will greatly facilitate international collaboration and cooperation in future.

At an inter-governmental there are three actions of particular importance to facilitation of biological control and IPM development. Firstly, governments can cooperation to share and exchange knowledge and skills in biological control conservation, augmentation and introduction and in IPM implementation and policy. This could be coordinated by international organizations, like FAO, with its strong track record in regional projects, international exchanges and training in biological control, but it should also make use of professional associations, particularly IOBC, and industrial associations, like IBMA as a source of networks and expertise.

Secondly, there is a need for international cooperation in making registration requirements and procedures for commercial biological control products efficient and harmonious. Governments should work together to develop a common "fast tracking" approach to product registration which supports development of local biological control industry and products.

Finally, there is a need for international cooperation in biological control introduction. An excellent basis for this has been created with guidelines on the safety of biological control introductions (see Section 3.3.1). However, this process now needs to be extended beyond safety considerations to other aspects of international cooperation, and beyond agriculture to other sectors with a growing stake in biological control. Cooperation on access to biological control agents for introduction and augmentation is a particular issue that will be discussed in the next Section.

4. CHALLENGES TO THE USE AND CONSERVATION OF BIODIVERSITY FOR BIOLOGICAL CONTROL

In previous Sections, we established that biological control is valuable, and that this value will most likely grow in future. We have identified that much biological control addresses issues of public good, and depends today and in future on public sector investment and particularly governmental commitment. We have established that some of this commitment needs to be made at the international level in order to secure the global benefits of biological control. This justifies a consideration of international approaches to conservation and use of genetic resources for biological control.

In this Section, the international challenges facing conservation and use of natural enemies are considered. To do this, comparison will first be made with the conservation of plant genetic resources, and its international dimensions.

Crop varieties are the products of centuries of artificial selection by farmers. The International Treaty on Plant Genetic Resources for Food and Agriculture (ITPRG, FAO 2001) has the objectives of "conservation and sustainable use of plant genetic resources for food and agriculture and the fair and equitable sharing of the benefits arising from this use". It requires of its parties that they conserve these resources, through inventory, characterization and *in situ* and *ex situ* collections, so as to minimize or eliminate threats to these resources. The principle threat is that crop varieties will be lost with changes in agricultural systems, and with them traits and genes of potential value for future plant breeding and agriculture (Engels and Wood 1999).

The Treaty also calls on parties to use plant genetic resources sustainably, broadening the genetic base of crops and carrying out research that supports sustainable agriculture, including research into diversification of crops and farming systems. It establishes a multilateral system of access and benefit sharing under which parties allow open, international access to germplasm from a specified range of crop species, facilitating as well access to information and technology, within a provision for sharing any benefits derived from this transfer.

This treaty is compatible with the Convention on Biological Diversity and its Bonn Convention (Convention on Biological Diversity 2002) which supports a transparent framework for access and benefit sharing for genetic resources, and gives particular emphasis to facilitating taxonomic research. Generally, the CBD has placed more emphasis on bilateral mechanisms for equitable sharing of benefits, which may be particularly appropriate to the exploitation of plants as sources for particular chemistry or genes. The ITPGR is more focused on a well known and threatened resource, namely the food crop diversity of the world, whose value is closely related to our capacity to mix it up through exchange and breeding. Hence, a multilateral approach is more appropriate (Stannard *et al.* 2004).

Thus, for plant genetic resources, we have an international system which recognizes the global value of plant genetic resources arising in different countries from centuries of domestication and breeding, and takes measures to ensure that it is not lost permanently, and that international access to it is maintained.

How does this situation compare with the conservation and use of genetic resources for biological control? To answer this, we must first ask whether it is possible that natural enemy biodiversity could be lost.

4.1 Could we lose biodiversity for biological control?

Crop varieties are of value because of their intra-specific diversity, generated by breeding, which may be lost with agricultural change. Valuable genetic resources for biological control, with a very few exceptions, constitute wild biodiversity of value at the inter-specific level. Biodiversity loss in these terms would therefore mean local or global extinction of species.

The loss of species or intra-specific variation in natural enemies would be most likely to result from dramatic changes in agro-ecosystems, associated with intensification or crop replacement, or from degradation or loss of natural habitats where pests or their close relatives persist as wild species.

Communities of natural enemy species can be suppressed for long periods by agricultural practices, particularly pesticides. This can lead to the “effective loss” of natural enemies as a resource to farmers until good management practices, such as IPM, are applied. This loss is real in economic terms, but it is probably rarely permanent. There is little evidence for local or global natural enemy extinction in agro-ecosystems. Natural enemies appear capable of persistence and rapid recovery when conditions permit – indeed it is this property which has facilitated IPM implementation under conditions of pesticide-induced pest resurgence.

Obryki *et al.* (2002) have suggested that transgenic crops may have a similar effect on removing specific natural enemies of pests controlled by those crops. Again, it is likely that this would be a local and temporary effect. Strategies for resistance management, which maintain non-transgenic crops in the agro-ecosystem would also maintain natural enemies.

The greatest risk of permanent loss of natural enemies to conservation biological control would arise where natural enemy strains have “evolved with their agro-ecosystem”, such that agro-ecosystem change would threaten their existence, in much the same way that local land races of crops are threatened by changes in crops and cropping systems. There is very little evidence that natural enemies adapt to particular agro-ecosystems in this manner. One example is the evolution of pesticide resistance in some natural enemies. This has occurred fortuitously, for instance, in the predatory mites which attacks the apple pest, *Typhlodromus pyri* (Way and van Emden 2000) in Europe. Naturally-acquired pesticide resistance in these predators facilitates integration of biological and chemical methods in IPM in orchard systems and has underpinned IPM for many decades. However, there is no basis to believe that these pesticide-resistant predatory mites are under threat of extinction in this ecosystem. Indeed, subsequently, creation of pesticide resistance predator populations has been achieved through artificial selection and applied successfully in the field (Hoy 2006).

With respect to genetic resources for augmentation, appropriate natural enemies are often not highly host specific and hence their desirable properties are more “substitutable” with other species or strains from other regions. The risk that desirable microbial species and genes will not be easily rediscovered after agro-ecosystem change is offset by the capacity for maintaining living collections (see Section 4.2).

For introduction programmes, the principle threat is the loss of future, highly specific biological control agents for future alien pests. These agents and pests may reside in agro-ecosystems or natural habitats and they will often be rare, sometimes unknown to science, as we have seen for cassava mealybug and its natural enemies (Section 2.5.1). In their native habitats, they are vulnerable to habitat destruction and changes in land management. For instance, in Eastern Europe, changes in chemical weed management along roads have decreased populations of a number of native plants which are invasive alien weeds in North America. This has made it more difficult to find and collect populations of natural enemies from these plants for testing in biological control programmes (CAB International, pers. comm.). A particularly valuable smut fungus of the widespread tropical weed, *Ageratina riparia* was found on a very isolated population in Mexico and no where else, which suggests that some valuable natural enemies may be lost with the loss of just a few local habitats (Barretto and Evans, 1988).

An informal survey of experts in biological control exploration, taken for this study, failed to turn up specific examples of the local extinction or loss of sources of natural enemies of value to introduction programmes. However, experts did observe that, even without extinction, habitat change may make natural enemies or their hosts very difficult to discover during exploratory studies. Exploratory programmes are necessarily limited in time and funds, and often large areas must be explored when the exact area of origin of the pest is unknown. For example, exploration for the natural enemies of the alien cypress aphid, which had appeared as a pest in East Africa in the late 1980s, were complicated by the wide distribution of the aphid on alien conifers in the Northern Hemisphere and considerable taxonomic confusion (Watson *et al.* 1997, Day *et al.* 2004). Exploration over five years covered North American, Europe and Asia, and it was only towards the end of this that the likely true area of origin of the pest was found in Syria. In such a situation, it is quite likely that, with fewer resources for exploration, the true area of origin of the alien pest may not have been found, particularly if it was restricted due to habitat change or other human activities.

What habitats would we conserve in order to optimize future introduction programmes? Clearly, without knowing the pests which will emerge, this is difficult. However, areas of origin of important crops and their pests would be priorities for conservation, just as they already are for crop germplasm. Certain ecosystems have provided complexes of pests to new countries, often through the movement of peoples and agriculture in historic times. Thus, Central Asia is a likely source of many western European insect and weed pests, while Western Europe is, for reasons of colonial history, a source for many alien pests of North America, Australia and New Zealand. The river systems of Amazonia have been the source of a range of several waterweeds which have been highly damaging invaders throughout the Old World, including water hyacinth, *Eichhornia crassipes* (Julien *et al.* 1999).

It would be possible, for any local agricultural or natural ecosystem, to identify major alien pest species that may have their origin in that ecosystem. In this way, a biodiversity conservation project may be encouraged to include, specifically, measures to identify and conserve organisms of potential value to biological control introduction or augmentation. In the 1990s, the World Resources Institute published a journal advertisement for its Tropical Forest Project which illustrated how rainforests preserve valuable species. One example used was the beetle, *Agasicles hydrophila*, from Amazonia, which is used in the USA for biological control of the alien water weed, *Alternathera phylloxeroides*.

4.2 *In situ* and *ex situ* conservation

Plant genetic resource conservation has focused on two strategies. *In situ* conservation involves the conservation domesticated or cultivated plants in the agricultural and natural surroundings where they have developed their distinctive properties. *Ex situ* conservation involves conservation of crops outside their natural habitat, and usually refers to seed collections, of which there are many at the national and international level. Generally, *in situ* conservation is preferred, and has the advantage of engaging farmers in the conservation and further development of these resources (Brush 1999, Crucible Group II 2000). However, it requires protection of agro-ecosystems which may involve legislation and incentives, while *ex situ* conservation may be easier when it involves the collection and storage of seeds from different areas. The very large collections of seeds held by the international agricultural research centres of the CGIAR, are a distinctive feature of the *ex situ* conservation strategy under the ITPGR.

In the context of genetic resources for biological control, there are a number of factors which strongly favour an *in situ* approach. First and foremost, there is little risk of loss of biodiversity for biological control that would justify *ex situ* collection. Further, biological control in crops will involve the action of a community of many natural enemy species. Hence *ex situ* conservation of an effective local biological control activity would involve the culture of many species, some of which would be very difficult or expensive to maintain. Experience with biological control introductions and augmentation have shown that arthropod natural enemies may undergo genetic changes in culture which may affect their effectiveness upon release in the field (Bouletreau 1986, Hopper *et al.* 1993). Further, the critical features of biology and ecology of these natural enemies that would underpin their value in particular crops at particular times will only be visible *in situ*.

Does *ex situ* conservation of living natural enemies have any conservation value for genetic resources for biological control? Some natural enemies have become particularly important in augmentation, and maintenance of these well-characterized species of proven effectiveness is valuable, particularly when their original isolation from field populations is now in the distant past. In this context, the ongoing production of natural enemies for distribution and sale generates itself a self-sustaining collection of natural enemies. While these are commercial products, access to these species involved is not difficult. None of the approximately 150 species of natural enemies currently sold for augmentation are restricted by intellectual property rights, where such rights exist they protect production or application methods, not access to the species themselves. Hence, augmentation programmes, public and private, maintain a valuable, global e*x situ* resource for biological control.

There is a long history of collection and maintenance of cultures of micro-organisms from agricultural and natural ecosystems, including natural enemies of pests. It is relatively easy to maintain cultures of certain pathogens of pests on agar and other media. For some, long term storage of living specimens can be achieved with freeze-drying or freezing in liquid nitrogen, which reduces deterioration of quality.

Microbial culture collections have been built over recent decades for a number of reasons, including biological control. They provide germplasm for exploitation of microbes in industry and agriculture, as sources of metabolites for such applications. Hence, they are, in effect, an ex situ repository of biological control agents.

There exist many natural collections and several collections of global significance, including the USDA Agriculture Research Service Culture Collection (http://nrrl.ncaur.usda.gov/) and the CABI Genetic Resources Collection (http://www.cabi.org/datapage.asp?iDocID=206), which provide microbial cultures freely to researchers. There are also important specialist collections for biological control, including parts of the CABI collection and the USDA ARS Entomopathogenic Fungi Collection, with its over 6000 isolates of more than 400 fungal taxa from about 1000 host species (http://arsef.fpsnl. cornell.edu/mycology/ARSEF_Culture_Collection.html). The World Federation of Culture Collections (http://www.wfcc.info/), part of the International Union of Biological Sciences, promotes the establishment of culture collections and develops common standards for maintenance and access to cultures. Industry has undertaken extensive collection and screening of micro-organisms for secondary metabolites or, very occasionally, for use in biological control. These private collections, while extensive are usually made for specific projects, and not characterized and maintained as a resource for continued use.

Living, *ex situ* microbial collections are of enormous value in supporting research and taxonomy of natural enemies, in the same way that collections of dead insect material aids with identification of natural enemies for new biological control programmes. The also serve as reference collections for natural enemies used in biological control programmes. Their use and value as a source of biological control agents for new programmes is probably secondary to this taxonomic use – most new research biological control research will involve new exploration for organisms with particular qualities. However, culture collections will be important to understanding the identity of any new organisms discovered, and these may then be added to these collections as future taxonomic resources themselves.

In conclusion, *in situ* conservation of natural enemies is the best approach to conserving genetic resources for biological control. *Ex situ* collections probably have little value in preventing loss of genetic resources, but have considerable value in supporting taxonomy and research on natural enemies for biological control.

4.3 What might limit access to biodiversity for biological control?

The second issue arising from the model of plant genetic resource conservation is access to genetic resources for biological control. There are two important aspects of access: access to resources themselves, that is, to living natural enemies, and access to information and expertise necessary for the use of these resources.

Access to local, living natural enemies is not limited for those who know what they are seeking. However, introduction programmes, and sometimes augmentation programmes, involve access to natural enemies from other countries. Here, national and international regulations on the movement of living organisms between countries apply. In Section 3.3, issues relating to the safety of such international movement were discussed, including internationally agreed guidelines, under the IPPC, on the movement of biological control agents for introduction and augmentation. However there are no international instruments which relate specifically to access to biological control resources.

Introduction programmes usually involve international exploration, during which natural enemies, often new to science, are collected, studied and moved to the country of intended introduction. While many countries and institutions now have capacity in most steps of an introduction programme, historically, only a few have experience in the exploratory component. This reflects the high level of specialized biological expertise, taxonomic, quarantine and financial resources needed for introduction programmes. Much of this expertise resides in national agricultural research programmes in the USA, Canada, France, UK, South Africa, Australia and New Zealand, in the international organization CAB International (which incorporates the former Commonwealth and, later, International Institute of Biological Control) and in some research centres of the CGIAR . The use of introduction by so many countries worldwide (see Section 3.3) reflects that many national programmes have been assisted in exploration by these institutions. FAO, CABI and other advanced international research institutions have been particularly active in providing exploratory assistance to development country introduction programmes.

Over the decades, exploratory programmes have taken the general approach of engaging with national agricultural research institutions in the country of exploration. Exploration is a joint activity between that institution and the external institution. This has been shown to have several advantages:

Exploratory programmes are more effective and efficient when they use local expertise. Local institutions benefit from exploration in several ways. Training may be provided, as well as capacity building and operational funds. The natural enemies collected often require identification by experts outside their country of origin, and this enhanced taxonomic knowledge of local biodiversity returns, along with voucher specimens to the national institutions. Often, local partners in exploration are the national biological control research units themselves. They may in future participate in future international programmes of exploration and introduction against their own alien pest problems, in cooperation with the same external partners. Thus, cooperation in exploration helps to build international professional links and the spirit of cooperation and reciprocity that has characterized biological control introduction as an activity.

The export of local natural enemies to other countries is subject to regulations in the country of origin about release of such biological material. For this study, an informal survey of experts on biological control exploration was taken to gather an impression on how national programmes addressed this issue of access.

In exploratory programmes for biological control introduction, permission to export natural enemies is usually sought with the assistance of the cooperating national institution. There is a great deal of variation between countries in the actions required to gain this permission. Sometimes, problems are encountered in gaining permission to export natural enemies. A common problem is that the national institution requesting permission to export is usually agricultural, while responsibility for export of genetic resources rests in an environmental ministry, where there is little understanding of biological control. In some cases, there is no mechanism for obtaining permission to export. In others, permission to collect and export materials, even for research may be denied on principle or may attract substantial fees. Countries that have more formal and complex procedures for natural enemy export are usually those which regulate more strongly access to biodiversity in general.

The Convention on Biological Diversity (CBD) has had a major effect on how governments view and regulate external access to local biodiversity. Parties have agreed in Article 1.5 to the "fair and equitable sharing of the benefits arising out of the utilization of genetic resources, including by appropriate access to genetic resources and by appropriate transfer of relevant technologies, taking into account all rights over those resources and to technologies, and by appropriate funding". Other parts of the Convention augment this with commitments to share information and foster technical and scientific cooperation. The CBD has produced guidance on access and benefit sharing, its Bonn Guidelines (Convention on Biological Diversity 2002) emphasize the need for prior informed consent in collecting and exporting biodiversity, and the importance of engagement of national stakeholders in research as a key element of benefit-sharing. The guidelines also recommend, quite explicitly, that the provision of material internationally for taxonomic research should not be restricted.

There has been a continuing dialogue in the CBD process on access and benefit sharing, much of which has been directed at identify best models for benefit sharing. Most recently, an expert panel has been tasked to explore “the form, intent and functioning of an internationally recognised certificate of origin/source/legal provenance and analyse its practicality, feasibility, costs and benefits" with a view to achieving benefit sharing objectives. While the Convention encourages international access to genetic resources, there has been much concern about unfair exploitation of the knowledge of indigenous peoples and irresponsible "bio-prospecting" by large multinational corporations. Understandably, this has led to greater caution in some governments about request for exploration and export of local organisms.

Has exploration for biological control agents been affected over recent decades by an increase in national restrictions on exporting local biodiversity? The experts surveyed indicated that there was a small but clear trend in this direction in some countries, but not others. New regulations in some countries in Asia and Latin America in particular had placed restrictions on export of local natural enemies or slowed that process. One consequence of national restrictions is that exploratory programmes for natural enemies, which would logically cover an eco-region comprising many countries, may chose to develop programmes with those countries with a history or mechanism for cooperation in biological control and exchange of natural enemies.

From a practical perspective, as noted earlier, delays in access to natural enemies can have the same effect as lack of access, because time and resources for exploration are often limited. While there is no perception that there is a dramatic change in access or an immediate threat to the future of biological control introductions, there is concern amongst biological control practitioners that access may become more limited if trends continue. They believe that national institutions responsible for export permits, often associated with environment departments need to be better engaged and informed about biological control, its processes and benefits.

The growing demand for biological control solutions for alien invasive species affecting native biodiversity may provide an opportunity for such engagement. In a series of regional workshops (Barnard and Waage 2004), the Global Invasive Species Programme (GISP) has brought together national government agricultural and environment departments in the Baltic/Nordic Region (2001), Meso-America (2001), South America (2001), West Africa (2004), East Africa (1999), Southern Africa (2002), South and Southeast Asia (2002), the Indian Ocean (2003)and the Austro-Pacific Region (2002) to address invasive species problems, including the use of biological control (See GISP website, http://www.gisp.org/publications/workshops/index.asp, for proceedings of specific workshops). In many cases, this was the first time that national agricultural and environment staff responsible for alien pest problems in their respective sectors had ever met.

International access to natural enemies for augmentation faces the same challenges as access for introduction, except that, increasingly, exploring for new natural enemies is shifting from being a research cooperation between government research organizations or universities to being part of the R&D programme of commercial companies seeking new or better natural enemy products. Commercial producers are often interested in finding natural enemies of well known, globally distributed pests which have better properties for mass production and use in specific conditions. Hence, they will be interested in collection of a variety of species and strains from agro-ecosystems in many countries. Unlike introduction programmes, this might not need to involve partnerships with specific national programmes, capacity building or other benefits, but such partnerships may facilitate access and export of natural enemies for augmentation.

4.4 Knowledge and biological control

As indicated in Section 2 the great diversity of natural enemies means that their effective use requires access to considerable taxonomic, biological and ecological knowledge. It is useful to contrast the role of knowledge in use of genetic resources for biological control with that required for plant genetic resources. In the table below, properties of *species level* genetic resources for plant breeding, pharmaceutical "bio-prospecting" and biological control are compared.

USE OF GENETIC RESOURCE	crop breeding	pharmaceutical bio-prospecting	Biological control
PROPERTIES			
Diversity of genetic resources	low	high	high
Current knowledge of diversity	high	high/low*	low
Knowledge required for use	high	Low	high

* some source species, like plants may be well known while others, like micro-organisms, may not.

Conservation of plant genetic resources for crop breeding draws upon considerable existing knowledge of a relative small variety of genetic types – in this case, largely intra-specific variants. Conservation of genetic resources for pharmaceutical bio-prospecting and for biological control draws upon a very limited current knowledge of a very larger number of genetic types which are almost always wild species. For bio-prospecting, little knowledge is required of these species for their effective use, they are simply sources of chemical products or genes. This profile may be typical also for some microbial natural enemies which may be mass-screened as isolates from extensive exploration. However, substantial knowledge (taxonomic, biological and ecological) is required for effective conservation, introduction and augmentation of natural enemies. This means that, relative to the conservation of other genetic resources, particularly plants, effective conservation of genetic resources for biological control requires more commitment to the conservation and exchange of the knowledge essential to their exploitation. Further, while much knowledge about plant breeding is "stacked" behind the specific identify of a crop variety, knowledge about biological control is much more "horizontal", requiring for each target pest species, information on a wide range of natural enemies, their biology and ecology.

In a real sense, lack of access to this knowledge about natural enemies is equivalent to the lack of access to the living resource itself. Of particular importance is the capacity to identify natural enemies species, thereby unlocking information on their biology and use. As Hawksworth and Mound (1990) put it, "named reference collections are the basic tool for communicating information about biodiversity between different workers in time and space". There is considerable concern that decline in investment in national and international taxonomic capacity and services will make it more difficult in future to provide this knowledge.

Conservation-based initiatives to characterize and catalogue the world's biodiversity, such as the Global Taxonomy Initiative (www.biodiv.org/programmes/cross-cutting/taxonomy), and database projects like Species 2000 (www.sp2000.org) and the Global Biodiversity Information Facility (www.gbif.org) will be of much value to biological control, given the very large proportion of poorly known species which are, in fact, natural enemies. However, without deliberate focus, such efforts may not be of direct benefit to biological control.

Taxonomic initiatives directed at biological control are usually associated with specialist groups in museums and universities. Some of these provide taxonomic services nationally, and even internationally. However, international taxonomic services of particular importance to developing countries have been in decline. A novel approach to the fragmentation and decline of taxonomic capability has been the BioNET International (www.bionet-intl.org) initiative. BioNET is a global network for taxonomy which has focused particularly on insects and micro-organisms, the two groups of greatest significance in biological control. It comprises a series of local partnerships amongst taxonomists and organizations, organized as regional "loops", presently nine in the developing world, which develops and shared taxonomic expertise and tools. BioNET International has a strong training and capacity building element, and its global structure facilitates links between regions in the developing world and large collections in the developed world. Regional taxonomic tools and keys are an important output of such concerted efforts, but these will need much more support to build the taxonomic knowledge necessary for biological control worldwide. Another interesting model for global taxonomic support is the Global Plant Clinic (www.globalplantclinic.org) currently a donor funding project, which draws together taxonomic services in developed countries to support diagnostic needs for pests and natural enemies in designated developing countries.

As mentioned in Section 3,2, networks of microbial culture collections have a critical role to play in maintaining living materials for taxonomic purposes. They also act as portals to other information. Thus, the USDA Germplasm Resources Information Network (www.ars-grin.gov) documents and distributes germplasm and information on organisms of agricultural importance, while the WFCC-MIRCEN World Data Centre for Micro-organisms (http://wdcm.nig.ac.jp) provides a directory of culture collections and databases on microbes.

The internet has provided a unique new resource for biological control knowledge, because of is capacity to gather and provide access to very large amounts of written and visual information on natural enemies. IOBC has been innovative in creating an internet textbook for biological control (van Lenteren 2005) and in providing assistance to scientists in developing countries in writing research papers. CABI's Biocontrol News and Information provides regular biological control news and reviews, as well as a compilation of published abstracts. Another important innovation has been the publication on line of the regular International Symposia on Biological Control of Arthropods (see Hoddle 2005) and on Biological Control of Weeds (see Spencer 2000). giving instant global access to these important proceedings. Many websites have been established which provide biological control information relevant to particular methods, crops or regions – two of many examples include the Ecological Database of the World's Insect Pathogens (http://cricket.inhs.uiuc.edu/edwipweb) and the USDA Release of Beneficial Organisms Database (www.ars-grin.gov/nigrp/robo.html). However, it is often the case that databases are established with short-term project funding and have difficulty in continuing maintenance, hence they may become increasingly historical, restricted and therefore progressively less useful. Nonetheless, the potential for local web-based information sources for biological control is considerable.

An interesting interface between IT, taxonomy and information are recent initiatives to characterize species by their DNA sequences, such as the GenBank initiative (www.ncbi.nlm.nih.gov/taxonomy). These initiatives also have promise to improve our knowledge base of natural enemy diversity, but a sequence, like a specimen, still needs to be associated with taxonomic resources. For instance, while as of 2004, about 16% of known fungi are now at least partially sequenced in this databank, but there is concern that a significant proportion of them may not be properly identified (Hawksworth 2004).

The other key aspect of knowledge on natural enemies is research. It is impossible to survey global or developing country research capacity in this area, but a number of general observations can be made. Research on biological control of pests is still profoundly a public sector activity. In most countries, it is undertaken in universities and government research institutes. These programmes have a disturbing tendency for self-perpetuation without application. The sheer diversity of natural enemies and the complexity of their biology can provide decades of interesting scientific investigation on particular groups without progress towards their better conservation or use under field conditions. Further, many natural enemies, particularly micro-organisms, show considerable biological control potential in the laboratory which is not shown when they are subsequently tested in the field as biological control agents. Researchers in public institutions are often poorly skilled in taking biological control systems into practical or commercial application. Hence, we find many developed and developing countries today experiencing an unfulfilled demand for biological control, despite their having research capacity in this area, because they lack effective mechanisms or incentives which turns research into practical methods or useful products.

Clearly, research that underpins commercial augmentative biological control is an exception, as this is an area which has grown rapidly through focused R&D to develop each new natural enemy product. It is noteworthy that this industry remains highly dependent on public sector research. Indeed, Gelernter (2005) suggests that the failure of the venture capital investment in biological control technologies in the 1990s to lead to a step-change in that industry was due to the failure of investors to appreciate the very substantial R&D costs required, which were "hidden" in public sector research. Models from this successful industry might be useful in helping much public sector biological control research find useful application.

Some of the most useful research in biological control, relevant to all approaches and critical to its uptake, relates to field methods for assessing the action and efficacy of biological control. These methods, which include exclusion methods to examine pest populations in the absence and presence of natural enemies, direct observation and population analyses are extremely versatile, and can be adapted for sophisticated academic research purposes, or for farmer field schools (Luck *et al.* 1988; van den Berg *et al.* 1997).

Given the anticipated growth in demand for biological control indicated in from Section 2.8.3, we might ask whether we are seeing a parallel growth in research. The present answer is probably “no”. This may be partly due to the failure of much past research to find application, referred to above, or competition from other areas of agricultural research. In recent years, research on biotechnology has captured much interest as an alternative to chemical control, and possibly some of the investment that might otherwise have gone to biological control. Indeed, in 1988, the US National Academy of Sciences issued a new definition of biological control that leaned heavily towards crop genetic manipulation, which drew a challenge from biological control researchers (Garcia *et al.* 1988) that this would lead to reduced emphasis on the full range of biological control approaches, and particularly its ecological aspects.

Kairo (2006) has recently evaluated agricultural research publications to determine trends in research on different approaches to biological control. Between 1980 and 2004, publications on biological control have fluctuated between 3500 and 4500 per year, with no clear upward trends. The pattern is best described as stagnant, and contrasts greatly with the rise in publications on agricultural biotechnology. There are no strong trends in biological control publications from different regions, or in publications on biological control introduction or augmentation. However, there has been as steady rise in publications on IPM. This analysis points to a potential future gap between demand for biological control and research capacity, indicating a need to strengthen biological control research.

5. SYNTHESIS AND RECOMMENDATIONS

This review has identified biological control as an important and valuable component of crop protection, and that its value will continue, and probably grow in future. How then should principles of biodiversity conservation and use be applied to protect the natural enemy diversity that delivers this biological control? Clear differences have emerged between biodiversity for biological control and that for plant breeding. Most importantly, the natural enemies that deliver biological control in agricultural systems are extraordinarily diverse and most are poorly characterized and known. Hence, while it may be desirable to conserve and utilize a substantial proportion of our natural enemy biodiversity, as we do our crop germplasm today, in reality this is quite impossible.

Most natural enemies cannot easily be maintained in *ex situ* conditions, even if this were desirable. *In situ,* we are confronted with many species whose identity, value, biology and conservation is poorly understood. The considerable specificity of natural enemies means that the benefits of conserving them, quite unlike crop germplasm, may be extremely local (e.g. for one pest on one crop in one region). Further, we suspect that there may be redundancy in natural enemy complexes, such that we may not need all local species for effective biological control, but to identify the critical subset for conservation would take considerable research. Finally, and most challenging, we can be sure that in future we will need new, yet unknown natural enemies for introduction and augmentation against yet unknown, alien pests.

Thus, there is no simple approach to conservation of biodiversity for biological control. In generating the recommendations below, the following procedure for identifying priorities for conservation and use has been used:

- identify the most valuable biodiversity for biological control
- make an informed judgement on how that may change in future
- identify whether and how access to that biodiversity may be lost
- prioritise conservation as a product of the value of natural enemies and the probability of their loss or under-use.

From Section 2.7, and above, it is clear that the value of biodiversity for biological control resides in conserving and using a great variety of species in many different contexts – conservation, augmentation and introduction. From an economic perspective, we can draw three conclusions about the value of this biodiversity:

- its greatest contribution, through conservation, is in suppressing pests that would otherwise cause damage, that is, it is hidden
- this value is not substitutable by other pest control measures, such as pesticides or GM crops in a sustainable or cost effective manner
- where biological control is a deliberate intervention, e.g. in augmentation or introduction, it can be competitive with or superior to alternative measures in particular circumstances

Thus, although our attention is naturally focused on biological control intervention like augmentation and introduction, the most valuable biodiversity is that which is present and acting in agro-ecosystems already. This is not likely to change in future. In future, we can anticipate that local disruption of biological control will occur, as it has in the past with pesticide misuse, and will lead as before to pest outbreaks and then new, restorative IPM and biological control programmes. Improvements in IPM, use of less toxic pesticides and GM crop technology will tend to reduce the frequency of disruption events. However, IPM methods are not as yet widespread, and many are focused on changing pesticide use and not natural enemy conservation. We can anticipate continued pest outbreaks and the need for restorative IPM and biological control programmes well into the future, particularly in developing countries which are undergoing agricultural diversification and intensification in order to become food secure and competitive in international trade.

Both introduction and augmentation have clear areas of agricultural production where they are superior to alternative pest control measures. These will remain relatively limited – it is not likely that augmentation will displace more than a small fraction of global chemical or GM-based pest control, and introduction will be naturally limited to the control of new alien pests. However, the economic value and “market share” for both measures will increase in coming years. Augmentation of macrobials will spread globally in its existing niches and microbial products have the potential to fill gaps left by reduced use of chemical pesticides. Demand for introduction will grow as a result of accumulation, and possibly acceleration, of alien pest introductions.

The biodiversity required for both augmentation and introduction in agriculture is found in the local biodiversity in agro-ecosystems and associated habitats. Hence, conservation of local natural enemies also contributes to maintaining the biological resource for future augmentation and introduction.

The conservation of biodiversity in local agro-ecosystems is an activity for farming communities and national governments. However, it has considerable international significance, for three reasons. Firstly, countries which fail to prevent or manage pest outbreaks may fail to maintain food security and to participate effectively in international trade, becoming a burden on other countries. Secondly, uncontrolled pest problems will spread rapidly to other countries. Finally, because many of our pests today are alien, one country will hold natural enemy resources of potential future value to other countries. This last point will be considered in more detail below. Therefore, it is appropriate and necessary to establish a degree of international cooperation in conservation and use of local biodiversity for biological control.

Is local biodiversity for biological control at likely to be lost? While it is clear that intensified agriculture, particularly the use of chemical pesticides, can suppress and displace local natural enemy populations, often resulting in pest resurgence, experience suggests that natural enemies can survive such events, probably by exploiting natural habitats and other crops in the local area, and recover when conditions improve. While they may not persist in crops at levels which maximize their contribution to pest control, the probability of extinction, even local extinction, appears to be low.

The greatest threat to local natural enemy biodiversity, therefore, is not its loss but the failure to use it to greatest effect. This failure could lead to agricultural practices, including pesticide use, which causes pest outbreaks with national and international implications, as above. Effective use of local natural enemies relies on an understanding of their biology and ecology. We have seen that this understanding is limited by a lack of information on natural enemies and a specific lack of taxonomic services to assist in their identification. These two needs are linked, as correct identification is the key that unlocks information resources on particular species or functional groups. Further, we have seen that this understanding is limited by a lack of research, particularly practical research, on natural enemy conservation and use. Much of this research today, and in future, will require support of the public sector. This is even true for that research destined for commercial exploitation in augmentation, as much of this will be undertaken by small, local businesses with insufficient R&D funds.

Pulling these arguments together, the greatest value from biodiversity for biological control will be gained by conserving local natural enemies. Although the probability of local loss of biodiversity is low, the probability of its under-use is high, leading to a priority for national commitment to policies that support local natural enemy conservation and the research and education that maximizes its use.

Recommendation 1. The conservation of natural enemies for biological control in crops should be an explicit objective in international standards on good agricultural practice and in national and international policy for integrated pest management.

Recommendation 2. National and international measures should be taken to improve taxonomic research, collections and services in support of biological control, and to support public sector research to improve understanding and use of natural enemies.

While conservation by each country of natural enemies in their local agro-ecosystems will ensure a resource for future introduction and augmentation in other parts of the world, national programmes may not be fully aware of this international benefit, and the national responsibility this creates. Alien pest species are often poorly known in their area of origin. They are often not pests there, and conservation of their natural enemies therefore becomes a part of more general, national biodiversity conservation policy. This policy is often developed and implemented by environmental, rather than agricultural departments, and there may be little appreciation by responsible authorities of the value and biological control significance of conserving otherwise insignificant, invertebrate and microbial species.

While there may be a benefit to raising awareness of this valuable biodiversity, we must ask as we did for natural enemy conservation, whether this biodiversity is at risk of being lost or under-used? Unlike local natural enemy biodiversity, where biological control involves very many species, diverse functional groups and some redundancy, introduction programmes involve particular species, often only a few, selected for reasons of specificity, climatic adaptation, effectiveness and safety. Clearly, there is a greater probability of losing these few species through local or total extinction, than of losing local biological control function arising from the action of many species. As we have seen, natural enemies for augmentation against alien or native pests may not need to be as specific as those for introduction. Hence the probability of loss of alien species for future augmentation may be less that that for introduction.

We have also seen that local or total extinction is not necessary to prevent effective introduction programmes. An alien natural enemy and its host need only become sufficiently rare to be missed in exploratory programmes to be effectively “lost”. These programmes run on very limited budgets, they may be brief, and they and may be constrained geographically (see below). They must often cover vast areas because the target pest is of unknown origin. Reduction in local abundance and distribution of hosts and natural enemies may mean failure of an introduction programme, even without extinction.

There is, therefore, a probability that biodiversity for introduction and augmentation programmes against alien pests may be lost. How is this likely to occur? Loss may arise through agricultural practices in the area of origin of hosts and natural enemies, such as pesticide use. However, considering the resilience of natural enemies in agro-ecosystems, biodiversity loss may be more likely through the process most responsible for general biodiversity loss, namely habitat loss. As we have seen, there is so far only limited, and largely anecdotal, evidence that potential natural enemies for introduction may be lost through extinction, but all of these anecdotes relate to habitat loss.

Using the approach described above, we can surmise that the overall value of introduction and augmentation may be less than that of conservation, but it is growing, and the probability of loss of biodiversity is considerable higher. This makes the conservation and use of biodiversity for introduction and augmentation against alien pests a second priority. This will involve countries taking action to conserve local natural enemies that may be of future value in control of alien pests in other countries. Because these species are unknown at present, this action needs to be general. National programmes may need to link environmental and agricultural programmes, and international advice and support will be important. In particular, concerted effort can be made by inter-governmental bodies, like the CBD, IPPC and FAO to incorporate natural enemy conservation into the agenda of national biodiversity and agro-biodiversity conservation plans. The growing importance of biological control introduction for the management of alien invasive species affecting conservation should facilitate collaboration on biological control between environmental and agricultural sectors.

Recommendation 3. The conservation of habitats of natural enemy species for biological control of future alien pest problems in other countries should be an explicit element of national and international measures to conserve biodiversity in agro-ecosystems and natural ecosystems.

We have established in this review that utilizing biodiversity for introduction and augmentation is threatened not only by direct loss of that biodiversity, but by loss of access to it. The international movement of natural enemies for biological control has experienced a of success. However, it has encountered problems with safety, first with respect to risks to agriculture, and more recently with respect to potential environmental impacts. This has attracted considerable research, the development of national standards, and the development by IPPC of an international standard, ISPM3. There is an need for continuing work on improving ISPM3 in the area of environmental risk assessment, but there is now a clear, international mechanism for addressing safety issues in biological control.

However, there is no similar international mechanism for facilitating access and benefit-sharing to natural enemies for biological control. The process of international movement remains today quite *ad hoc*, varying between programmes and between countries, strongly based on precedent and implicit reciprocity. In the face of increasingly formal approaches to the movement of biodiversity so as to ensure access and the fair and equitable sharing of benefits, there is an opportunity, and perhaps a need, to give the international movement of natural enemies for biological control a more formal context.

Before considering the nature of this more formal context, let us review the present situation. As we have seen, international movement of natural enemies for biological control has been carried out largely as a public sector activity. For various reasons, introduction programmes are carried out by governments in the public interest. Augmentation for alien pests has its origin in introduction programmes where natural enemy establishment is difficult, and hence mass production and release is required. In a proportion of cases, this has become commercialized. Here, the companies involved are generally small to medium scale and serve local markets.

Introduction programmes often arise under crisis situations, where alien pests have caused outbreaks which threaten production of important cash or food crops and, in the case of some developing country programmes, food security. Rapid action is often required, and alternatives to biological control, particularly use of pesticides, may be prohibitively expensive to sustain, undesirable on environmental or health grounds, or both. Hence, introduction or augmentation of alien natural enemies addresses a need that often cannot be met by local means or alternative measures like pesticides.

Over the past , all countries have experienced alien pest problems. Governments already cooperate internationally to reduce the risk of introduction of alien pests, through multilateral agreements embodied in international conventions including IPPC and CBD, and more recently the trade mechanisms of the WTO.

Because alien pest problems are ubiquitous, it is also a fact that virtually all countries have benefited from the international movement of natural enemies for introduction and augmentation. The analysis of introduction programmes presented in this review indicates that the benefits of this movement have been shared by all countries. There has been less use in very poor countries, but it is not clear whether this is a result of less access or fewer alien pest problems there. In any case, there is a strong tradition of international development assistance that has allowed developing countries to participate extensively in introduction programmes on a national and regional basis. The returns on this investment are so great that this is likely to continue as risks from alien pests increases in coming years.

There is also an growing trend today for regional approaches to introduction programmes, where it is in the interest of one country to assist another in the same region with the control of an alien pest problems which threatens all countries.

The actual practice of moving natural enemies internationally has involved, in most cases, direct involvement of national agricultural research institutions in the countries of origin through cooperative research with institutions from the country affected by the alien pest. This relationship has often involved cooperative taxonomic and biological research. Where the country of origin is a developing country, benefits of this cooperation have often involved training, strengthening of taxonomic capacity and research collaboration.

A distinctive feature of introduction programmes is that benefits from the selected biological control agents to the country of their origin are usually negligible, because they are already present, and hence the target pest is not a pest there. In the case of augmentation, where for instance a biopesticide product may result from international exploration, the same situation may apply. Where it does not, as in the case of the development of a biopesticide for locusts (Section 2.4.1), where the country of origin of the selected strain, Niger, has a need to control these pests, mechanisms for sharing benefits have been piloted. In this case, they involved training and research collaboration as well as an agreed fund to receive a share of profits from product sales to be invested in further biological control work in the region.

While the process of international movement of natural enemies for introduction and augmentation has, to date, been largely a bilateral action supported in most cases by international organizations, the observations above create an argument for a multilateral approach. Biological control has a strong global public good character. All countries benefit from access to natural enemies, and at the national level, all farmers benefit from biological control introductions, rich and poor. Addressing problems quickly in one country reduces their rate of spread to other countries and accelerates solution of the problem for all, as born out in many past regional programmes.

Multilateral agreements already exist to prevent alien invasive species problems and to ensure the safety of biological control introductions. A multilateral approach on access to natural enemies for biological control and benefit-sharing will complement and strengthen these. There exists already for many years a strong precedent in introduction programmes for benefit sharing arrangement, particularly support and collaboration in taxonomic and biological control research. A multilateral instrument will encourage countries to develop national capacity in biological control and introduction methods, which will benefit all countries.

Recommendation 4. Governments should consider establishment of a multilateral system of exchange of natural enemies for biological control on a complementary and mutually-reinforcing basis, which ensures fair and equitable sharing of the benefits of biological control worldwide.

It should be clear from this review that the commercial dimension of augmentation arises from a need for a continuous supply of natural enemies for release in some agro-ecosystems, and not from opportunistic exploitation of otherwise “free” biological control. The development of augmentative methods still requires considerable public sector research support and faces barriers to registration of new biological products created by regulatory systems developed for chemical pesticides. Augmentation will continue to be provided by relatively small, locally-focused companies which cannot bear the current costs of product development which have been set for much larger, more wealthy, multi-national agrochemical companies. There is a need to create appropriate regulatory systems for biological products at that national level which encourages rather than blocks development of safe and effective biological control products. At the international level there is a need for harmonization of regulatory procedures which will facilitate this, including sharing of information on fast-track registration methods and knowledge on successful development of local augmentation businesses.

Recommendation 5. Governments should develop appropriate national regulatory systems for biological control products which encourage and support the development of augmentative methods, and should harmonize these regulatory requirements and share knowledge at an international level to facilitate development of effective augmentation systems and businesses.

Finally, biological control is only one service provided by crop-associated biodiversity, and many species in agro-ecosystems, besides those specific natural enemy species which we might conserve and use, contribute indirectly to pest suppression. As we have seen, factors which disrupt biological control in crops may often disrupt other valuable processes, such as the maintenance of soil fertility or pollination. Finally, these other processes, like biological control, are dependent on improvement of taxonomic services, public sector research and measures to facilitate commercial development.

Hence, there is a compelling argument for taking a holistic approach to the conservation of crop-associated biodiversity, where biological control may be a component service in a broader agreement on conservation and use of non-crop genetic resources. This approach may best serve the specific objective of protecting genetic resources for biological control, ensuring their use as part of good agricultural practice.

Recommendation 6. In considering future measures for conservation and use of genetic resources for agriculture, governments should consider a broad approach to the conservation and sustainable use to crop-associated biodiversity, including access to knowledge and capacity building, a component of which will be important to biological control of pests.

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