The CGIAR Systemwide Program on Integrated Pest Management

The importance of non-plant biodiversity for crop pest management: Enabling conservation and access

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Acronyms and Abbreviations

ABS	Access and benefit sharing
AMF	arbuscular mycorrhizal fungi
CGIAR	Consultative Group on International Agricultural Research
CGM	cassava green mite
EPNs	entomopathogenic nematodes
HGT	horizontal gene transfer
IPCC	International Plant Protection Convention
IPM	Integrated Pest Management
IITA	International Institute of tropical Agriculture
NPV	nuclear polyhedrosis virus
TRIPS	Trade Related Aspects of Intellectual Property Rights
WTO	World Trade Organization

Introduction

This brief addresses the importance of biodiversity to agriculture from an angle often overlooked: that of the non-plant forms of life protecting crops in the field. The importance of these bacteria, insects, nematodes, fungi, spiders, mites, and viruses is often invisible, but it is being revealed in the devastating pest outbreaks that the world is seeing as balanced agro-ecosystems are disrupted.

The Rio Summit of 1992 focused the world's consciousness for the first time on two interlinked problems that – if they remain unresolved – would threaten the continuation of human civilization as we know it: global warming and the loss of biodiversity. Follow-up conferences, most recently in Copenhagen, Mexico City, and Durban, have brought new appeals and the first policy structures. But while the effects of global warming might be mitigated or, over centuries, reversed, lost biodiversity cannot be restored.

Parallel to this effort, and increasing since the publication of Rachel Carson's *Silent Spring* in 1962, has been an awareness of the importance of a healthy agricultural environment for feeding a growing world population. Fifty years later, we still do not know exactly which components of biodiversity sustain soil, water and plant growth. But we have no doubt that a rich food-web of interdependent, usually inconspicuous, and often unknown organisms of different functional groups needs to be preserved.

Most discussions on wild biodiversity have concerned showy species that are attractive targets for conservation in natural habitats or zoos and botanical gardens. Meanwhile, the fundamental role of biodiversity in agricultural systems is championed by a global network of gene banks. Collected crop diversity, particularly of the type that is held in trust by the Consultative Group on International Agricultural Research (CGIAR), is largely well characterized and ready to be deployed wherever new needs emerge.

Our knowledge and stewardship of agricultural biodiversity are sharply focused on those plant species that we know most intimately, and do not extend far into the vast array of animal and microorganism life forms that, to a large extent, shapes their development. This is a matter of what is most visible, and a matter of scale. In contrast to the 420,000 seed plant species that are estimated to exist in the world, there are thought to be some 4.9 million arthropod species, a million nematodes, and 5–30 million species of microbes.

Among other essential services provided by members of these taxa, researchers and farmers are continuing to discover new roles they play as biological control agents, eating, infecting, parasitizing, and out-competing pests. These can be used to advantage through three biological control strategies: classical (introducing agents from elsewhere to control an exotic pest); augmentative (mass-rearing and releasing many more of the existing natural enemies into a field); and natural (manipulating the environment to support natural enemies).

Agricultural intensification, land use management, globalization, and the wide distribution of crop germplasm are continuing to create new selection pressures on pest insects, nematodes, pathogens and weeds, as well as on their natural enemies. The result is a matrix of positive and negative pressures on food production systems. Climate change will bring additional selection pressures on pests and their control agents, altering environmental constraints and the geographic distribution of crops.

Conserving the biodiversity of these taxa – which is far greater than that of the crops they live on – is a challenge that we have only begun to take on. But in the face of changing climates, globe-trotting pests, strained farming systems, and eroding wild habitats, these genetic resources must be conserved and made available to researchers everywhere. The right organism may be there right at the margins of the field, or may only live in a country a world away, in the pest's original habitat. Either way, the biological control of pests is totally reliant on biological diversity, and so is the sustainability of agriculture in a complex world.

Taxa of biological control agents

Insects

Insect biodiversity is by far the most important source of biological control agents worldwide. Predatory insects simply feed on pests: parasitoids lay eggs in or on host insects which, upon hatching, kill the host. While most predators consume a wide range of prey, parasitoid insects are usually very specialized in the species they will attack, and so are particularly useful for targeted biological control of specific threats.

The importance of naturally occurring insect predators and parasitoids is easy to overlook. In a well functioning agro-ecosystem, diverse species keep pests under control without farmers even being aware of their services (Altieri, 1994). The role of biodiversity in regulating pest populations becomes evident only in the event of a disruption, such as the introduction of an invasive alien species, the creation of a large-scale crop monoculture, or heavy use of pesticide. In these circumstances, the natural enemies which would have kept pest populations under the damage threshold are not available any longer, and the pest can multiply and disperse without being affected by natural limiting factors.

When an invasive pest comes from a distant region, a classical biological control intervention begins with the correct identification of the pest and its area of origin. Reference collections of dried specimens are often used in this process. Studying insect biodiversity in the pest's original ecosystem can turn up efficient biological control agents which can be introduced into the invaded region. Ideally these should be highly host-specific parasitoids which will not threaten other forms of local diversity. Most of such successes in the last 120 years have been achieved with parasitoid species from a few families of wasps and beetles.

Mites and spiders

Beyond insects, predatory phytoseiid mites, that attack pest mites such as tetranychids, are of particular importance in many cropping systems, especially fruit trees. Spiders, a wholly carniverous order, are found in agroecosystems everywhere and play key roles in most sustainable cropping systems. They have been successfully used as biocontrol agents in orchards to suppress pest populations and decrease insect damage. This is usually achieved by a reduction in pesticide applications which increases the spider population. In rice farming, spiders are often introduced into paddies (Maloney et al., 2003).

Conserving arthropod diversity

Biological control programmes need a large pool of diversity to draw on when looking for the right control agents because this balance is seldom as simple as one species eating another. To avoid unintended consequences, researchers tend to seek out highly specialized predators and parasitoids that are least likely to have an impact on other species in the environment. These must also have life cycles that properly overlap with those of the pest species so they can keep pest populations low at all times. And given the adaptive abilities of pests and the changeability of environments, a certain amount of within-species genetic variation can help a control agent to adapt to the new environment (Phillips et al., 2008).

At present, there is no technology that allows us to collect and store arthropod species on a large scale outside their natural environments. There are no "gene banks" for insects, mites or spiders. Live populations can be kept ex situ, but their natural genetic diversity and fitness are reduced with each generation (van Lenteren, 2003). Although reference collections of dried specimens are an important tool for identifying pests, these are not a way to preserve living biodiversity. The only real storehouses of potential arthropod control agents are their home environments, including pesticide-free agro-ecosystems, regions where wild or early domesticated crop lines survive, and the nearby wild ecosystems.

Nematodes

The phylum Nematoda, one of the most diverse groups of animal life, comprises nematodes that are both plant and animal parasites, in addition to numerous free-living forms. Plant parasitic species of these tiny worms are a major constraint to crop production across the globe. They are particularly damaging to intensive vegetable production, and to crops in tropical and sub-tropical areas where life cycles are short and population build-up potentially rapid. As pests they have been a specific target for efforts in microbial biological control, but not all nematodes are harmful. Species that parasitize insects, known as entomopathogenic nematodes (EPNs), along with others that attack molluscs, hold their own promise for use in biocontrol. These are being increasingly exploited in augmentative biological control products, applied mostly to crops under controlled conditions or in commercial systems.

Unlike insects, many nematode species can be conserved *ex situ* in culture collections. Coming from such a diverse phylum, however, effective EPNs can often be highly host-specific and sensitive to climate and ecology. The most effective species for augmentative biological control are often those recovered from the local environment. In less developed countries, knowledge of indigenous nematode species is at best very limited, but even cursory surveys often turn up a wealth of new findings. As such, the potential of nematode pest control is largely unknown and potentially huge.

Fungi

Countless species of fungi play different roles in agriculture. They are the principal agents of decomposition; they form symbioses that make nutrients available to crop roots; they cause plant diseases by parasitizing plants or by infiltrating grain and producing toxins that make it unsafe to eat; and they can act as biological control agents.

Spores of some species are sprayed as biopesticides to attack insect pests, cause diseases on weeds, or inhibit the germination of parasitic weeds (Striga hermonthica, Orobanche cumana). Fungal agents are also used to control and out-compete related species, such as the atoxigenic strains of Aspergillus spp., which are applied to soils to edge out those wild strains that can contaminate crops with aflatoxin (Atehnkeng et al., 2008; Dorner, 2010).

Other fungi protect crops in less direct ways. Endophytes live harmlessly inside plant tissue, inducing their hosts to develop greater resistance to pests and diseases. This is referred to as bioprotection. Endophytic species called arbuscular mycorrhizal fungi (AMF) colonize the roots of plants, such as banana, and seem to protect them against nematode attacks (Jefwa et al., 2010).

Bacteria

Of the enormous diversity of bacteria that exist in the world, only a few species have been used widely as augmentative biological control agents or biopesticides. The most successful of these, however, including *Bacillus thuringiensis* and *Pseudomonas* spp., are used on a large commercial scale all over the world.

The most famous biopesticide is perhaps *B. thuringiensis*, which has been applied to crops since the 1920s. The insecticidal toxins it produces have also been applied to crops directly, and since the 1990s the sequence for producing these *Bt* toxins has been encoded in the genomes of transgenic crops. However *Bt* resistance is beginning to appear locally in some pests, and it is likely that researchers will have to delve deeper into the incredible diversity of bacterial life for future biopesticides.

Viruses

Augmentative biological control products based on viruses are the least common among microorganism-based solutions. So far these have drawn on a single family, the baculoviruses, and particularly the nuclear polyhedrosis virus (NPV). Baculoviruses, which attack moth and other insect larvae, are useful because of their extreme host specificity. More than 600 host species have been described, associated with specific strains of the viruses. This makes them safe and highly targeted biopesticides, but has presented challenges to their large-scale commercialization.

Conserving microorganism diversity

In biodiversity terms, the defining characteristic of microorganisms is their rapid rate of reproduction – as fast as a new generation every 20 minutes. They may reproduce sexually or asexually, and in addition to this, can exchange genetic material through horizontal gene transfer (HGT), a source of variability that can easily cross species boundaries. The full extent of HGT in bacteria and viruses has only begun to come to light, and recently evidence of this mechanism has even been identified in fungi, including the toxigenic Aspergillus species (Slot and Rokas, 2010).

Given their short generation times and the ability of individuals to modify themselves mid-generation through HGT, microorganisms have a capacity for rapid adaptation and diversification that far exceeds the pace of change in arthropods or the crops themselves. Thus, it may seem that the conservation of microorganism biodiversity is of little importance. When there are a billion bacteria to be found in every gram of soil, it is easy to imagine that microscopic biodiversity is flourishing everywhere.

This may be true, but the great specificity of many biological control agents to certain pests, certain plants and certain environments means that the microorganisms associated with each of these do need to be understood and conserved. Fortunately, most fungi, bacteria and viruses are amenable to ex-situ conservation in microorganism collections. These can be the focus of much-needed systematic efforts to characterize biodiversity.

What microorganism collections preserve are type strains: living references for worldwide research on taxonomy and function. This consolidation and cataloguing of knowledge on biodiversity is the true task of microorganism conservation, making sense and use of specially adapted organisms in the great sea of microscopic life.

Necessary conservation mechanisms, procedures, and responsibilities

Conservation of biodiversity in culture collections

Microorganism culture collections have a clear role to play in conserving, characterizing, and making microbial biodiversity available to the research world and, ultimately, to farmers. The World Data Centre for Micro-organisms lists nearly 600 collections in operation, most hosted by governments and universities. These hold some 1.79 million strains: nearly 800,000 of bacteria, 500,000 of fungi, and 32,000 of viruses (WDCM, 2012).

While these numbers may appear large, they are dwarfed by the tens of millions of unidentified microbial species that biologists believe to exist. And the collections are not all, or even mostly, useful to agriculture: they are a hodgepodge of genetic resources gathered for medical research, industrial processes, food science, microbiology, botany, veterinary science, and many other applications.

For microorganisms to be used as control agents in agriculture and horticulture, live populations are required that can be multiplied on request. This requires their preservation on artificial media, with routine tests to ensure that the traits for which they were originally chosen are not lost. When this does occur, the organisms may need to be re-introduced to their host. Biotrophic fungi must be either stored as spores in a vacuum under liquid nitrogen, or maintained on a host – both labour and cost-intensive options.

The world's microbial collections send out more than half a million samples to researchers every year through official requests, but the informal distribution of cultures through peer-to-peer exchanges is probably much more extensive. These informal systems are often a simpler way for associates to gain access to material, but in practice most of them operate as closed networks that may leave out researchers who are less well-connected. The majority of collections do not even produce catalogues of their holdings.

Uneven access is a particular problem because most collections are in developed, temperate countries – not the tropical and subtropical regions that form the greatest sources of microorganism biodiversity. Recently, investment is growing in some developing or transitional countries, such as Brazil which now ranks third in the number of strains held. But elsewhere, skilled systematic taxonomists are being lost, new members of staff are not being trained, and governments do not see the need to increase this capacity as a priority.

What is needed, in essence, is for collections to be interlinked and understood in functional terms. Such a system exists for crops themselves: the global genetic holdings of the CGIAR are held in international trust and well characterized by function, so researchers can have easy access to varieties suitable for particular situations.

Similar coordination in microorganism collections could help researchers to find the most likely biological control agents with much less difficulty. Major leaps in genomic, metagenomic, proteomic, and lipidomic techniques in recent years offer promising new tools for this programme, giving collectors new ways of interpreting the functions of organisms and whole communities of organisms.

Conservation in the field and the wild

For insects, spiders and mites, which cannot be stockpiled *ex situ*, natural biodiversity embedded in ecosystems and agro-ecosystems provides the only source of control agents. Organic or IPM farms are perhaps the most vital pools of diversity for pest control – especially those in the region of a crop's origin. These must persist, or we may wipe out future control agents with broad spectrum pesticides.

Life in the field is a relatively recent adaptation for any invertebrate, however; the real birthplace of a pest species and its enemies is in the wild. Much research still needs to be done on which natural ecosystems are likely to preserve potential control agents. But the search can lead biologists to unexpected places. For now, all conservation of land ecosystems is relevant to pest management.

Natural biological control using species already present in the system should always be considered first in any pest management attempt. A farmer can promote natural enemies by reducing insecticide use, or can attract them, as with the planting of nectar-rich flowers alongside fields (Gurr et al., 2010). Mobile predators such as coccinellids and lacewings move back and forth easily from this vegetation. Such strategies protect a field while also preserving the biodiversity that may save many others in the future.

Where naturally occurring control agents are not up to the task, augmentative biological control should be the next approach – especially when used to concentrate indigenous predators in the field. Because augmentation relies on generalist predators, indigenous agents are preferable even in response to exotic pests. There is real danger in introducing a new generalist that might further destabilize an ecosystem.

However, the growing numbers of exotic pests with no local enemies are increasing the importance of classical biological control efforts that bring predators and parasitoids thousands of miles from their home ranges. Local species have been known to adapt to control exotic pests, particularly generalist parasitoids; this occurs regularly with introduced leafminers. But with most serious exotic pests, it doesn't pay to wait and hope that local species will adapt to restore a balance.

In most of these situations classical biological control promises a more rapid and decisive solution. With highly specific parasitoids, such as Homoptera, finding and exploring the home range of the invading pest often leads to spectacular solutions within ten years. Such programs rely on good international collaboration among entomologists, taxonomists, quarantine authorities, and mass-rearing specialists, and, most importantly, on procedures being followed to avoid non-target effects. These are regulated by national laws, as well as the International Standards for Phytosanitary Measures No. 3 (IPPC, 2005).

The most important procedure is quarantine, where potential agents are identified and reared to make sure that they carry no diseases and are not themselves damaging to other control agents or non-target organisms such as bees or silkworms. Narrow host-specificity is the best guard against such effects. Specificity is especially the key if plant-eating insects, such as weevils, are imported to control exotic weeds.

Preserved reference collections

Biologists have described more species of arthropods than of any other type of life, but thousands more come to light every year. This biodiversity needs to be studied and characterized continually to understand ecological interactions and to allow the rapid identification of both pests and their enemies. Taxonomic mistakes have troubled the history of biological control, accounting for failed introductions of control agents and unforeseen impacts on non-target species. For reliable identification, reference collections of dried specimens are a vital tool.

Unfortunately, reference collections in the tropics, where most biodiversity is found, are few and under threat. A revitalization of the now almost defunct BioNET International program (www.bionet-intl.org), with links among insect museums and support for tropical biodiversity collections, could reverse this decline. Increasing the maintenance and accessibility of collections is becoming all the more necessary as new molecular tools allow researchers to use specimens in more powerful ways.

Developments in DNA analysis now allow identification based on dried specimens that are up to 15 years old. Genetic barcoding has lowered costs to around US$2.50 per sample, and sometimes it is possible to identify a species over the internet without cost. This presupposes, however, that the relevant insects have been identified by DNA analysis of a collection. Such data are still uneven; the first results of this effort are just now becoming available for East Africa, while West Africa is almost totally devoid of data.

Protecting rights, access, and benefits of biocontrol resources

Intellectual property issues

Since the establishment of the Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS) by the World Trade Organization (WTO) in 1994, the ramifications of intellectual property law for crops and plant breeding have been worked out in court cases and governmental policies all over the world. In contrast, the application of TRIPS to the regulation of biological control agents and other non-plant taxa relevant to agriculture remains less defined.

TRIPS states that WTO members may exclude plants and animals from patenting, but microorganisms must be subject to patent (WTO, 1994, Article 27(3)(b)), reflecting the importance of proprietary bacteria and viruses to the pharmaceutical industry. In reality, however, there is no single scientific definition of a microorganism (Adcock and Llewelyn, 2000), and some countries have used this deficiency in language to justify the patenting of all manner of microscopic biological materials, including cells and genes.

In the most common interpretation, arthropod and nematode control agents are not patentable in WTO member states, while bacteria, microscopic fungi and viruses may be patented if they constitute new inventions, as with specially bred or genetically engineered lines (Adcock and Llewelyn, 2000). Since biological control relies on relationships between species that have evolved within natural ecosystems, there has been little application for genetic improvement or engineering within this field, and thus intellectual property rights should not play a major role in the search for agents for biocontrol.

Access and benefit sharing (ABS)

Biocontrol agents are also covered by the 1993 UN Convention on Biological Diversity, and its supplementary Nagoya Protocol on Access & Benefit Sharing (UN, 2010), which has not yet come into force. Where the Convention recognized every country's right to control access to its genetic resources, the Nagoya Protocol will provide a transparent legal framework for sharing the benefits of these resources, including tracing the use of materials internationally and enforcing domestic ABS laws abroad.

In classical biological control, the benefits are almost exclusively public goods, as introduced agents spread freely and cannot be sold. For the mostly public institutions that carry out classical biological control, benefits are shared through joint research, joint publication and the exchange of materials. Augmentative biological control has a more commercial side in the mass production and sale of control agents, but low profit margins mean that benefit sharing has not yet become an issue.

So far, the greatest impacts of ABS measures on biocontrol have been the transaction costs faced by researchers attempting to move pests, predators, and parasitoids between countries. Researchers often need access to a large pool of candidates from multiple countries, and different regulations and bilateral agreements compound the difficulty and expense. Internationalization of procedures can simplify the process while also building trust in the equitable use of every country's heritage of biodiversity.

The Nagoya Protocol does recognize that it may be necessary to develop specialized ABS agreements to suit the needs of certain sectors. It also explicitly recognizes the importance of genetic resources for food security. Taken together, these two elements suggest a streamlined multilateral process of pooling, accessing, and sharing benefits associated with the use of biocontrol agents. The Protocol's governing body, once it comes into force, should consider working towards such a process (SGRP, 2010).

Case studies

Parasitoid control of the cassava mealybug

The most spectacular success in the classical biological control of an insect pest on a continental scale in recent years is without doubt that of the introduction of the exotic parasitoid Anagyrus lopezi against the invasive cassava mealybug. This pest was inadvertently introduced into Africa from South America in the 1970s, causing widespread devastation to cassava fields across the whole cassava belt.

After some years spent studying the biodiversity of mealybugs and related natural enemies in the pest's presumed area of origin, the parasitoid A. lopezi was discovered in 1981 and subsequently introduced to Africa by IITA. Within a few years of the first releases, the parasitoid had spread to match the entire area of the cassava mealybug's distribution in sub-Saharan Africa (Neuenschwander, 2001).

The impact of this parasitoid on cassava production was clearly visible and economically quantifiable. It has been estimated that this biological control project allowed savings in the order of 9 to 20 billion US$, with a cost–benefit ratio from 1:170 to 1:430, depending on the scenario used in simulations (Zeddies et al., 2001). As assured in pre-release host range studies, this highly specialized exotic parasitoid had no negative impact on non-target insect species.

The A. lopezi intervention is one of hundreds of cases of classical biological control that have been totally successful in suppressing a pest in a sustainable way. In contrast, there is no case in which a chemical pesticide has been 100% successful. With all chemical pesticides, resurgent outbreaks of secondary pests and growing resistance by primary pests eventually undermine effective control.

Nematode control of insects, slugs and snails

Nematodes are important biocontrol agents of insects, slugs, snails, fungal pathogens, and even other nematodes. Entomopathogenic nematodes (EPNs) in particular have proven their worth with demonstrated successes in numerous crops, where they are now used for insect pest control on a regular basis, sometimes entirely replacing pesticides. Slug-parasitic nematodes, since their relatively recent discovery, have also shown a high potential for efficient and economically viable pest control and are already being used commercially in Europe. A range of nematode products are available for management of an array of target pests, such as against citrus root weevils, black vine weevils, stem borers, white grubs, and slugs and snails, but these are mostly applied in the developed world. The untapped resource of nematodes as biocontrol agents remains potentially vast.

Predatory mite control of a mite pest

The cassava green mite (CGM) Mononychellus tanajoa Bondar (Acari: Tetranychidae) invaded Africa through Uganda in the early 1970s and spread throughout the African cassava belt. Its exotic nature prompted scientists and governments in sub-Saharan Africa as well as international donors to initiate a classical biological control program to complement ongoing efforts in resistance breeding and the development of cultural practices for controlling the pest. Starting in 1983, the program achieved worldwide recognition as a unique example of the successful classical biological control of a mite pest on a continental scale. Its success is largely attributed to the discovery, introduction, and impact of Typhlodromalus aripo De Leon, the most efficient among several predatory mite species introduced from Colombia and northeastern Brazil. This predator is now established in at least 20 countries in sub-Saharan Africa and has reduced CGM densities by up 60%, increasing cassava root yield up to 80% depending on location and cassava variety (Hanna and Toko, 2003; Yaninek and Hanna, 2003; Hanna et al., 2005). For three countries in West Africa where economic analyses of the benefits have been completed, CGM biological control with T. aripo has provided enormous economic benefits at no cost to the farmers: nearly $2.2 billion from 1983 to 2020 for Bénin, Ghana and Nigeria (Alene et al., 2005; Neuenschwander and Hanna, 2007). In the remaining countries where CGM biological control has been achieved, similar benefits continue to be generated.

Improving the effectiveness of fungal control agents as biopesticides

Fungal pathogens applied as biopesticides have been shown to be more efficient than their natural counterparts at controlling target pests. This is because they are applied in higher concentrations, and because the formulations and timing are calculated to best overcome environmental constraints to infection. For example, a biopesticide was developed for the control of desert locusts and grasshoppers under Sahelian conditions using an isolate of the fungus Metarhizium anisopliae (Lomer et al., 2001). Registered for commercial use as Green Muscle (Green Guard in Australia), this biopesticide overcomes environmental constraints through the suspension of spores in an oil formulation, which increases infectivity by providing the required humidity levels and protection against ultraviolet light. Green Muscle has supplanted the use of synthetic chemical insecticides in many areas, as it provides increased sustainable control efficacy of target pests without negative impacts on other species or the environment as a whole (Langewald et al., 2003).

Implications of climate change for pests and biological control agents

In many countries in the coming decades, climate change is likely to happen too quickly and drastically for crops to adapt. This will bring radical changes as farmers look for alternatives to previously suitable crops. The effects of climate change on pests and biological control agents are harder to predict, but are often the opposite of their effects on crops. Warmer temperatures and new crop introductions will allow pests of all types to expand their ranges. In general, drier conditions lead to attacks by insects and viruses while fungal and bacterial diseases flourish in wetter periods; climate change promises both of these for different regions.

Arthropods are reliant on appropriate temperatures throughout their life cycles, and higher biodiversity is generally found nearer the tropics. Rising temperatures are already causing insect pests to expand their ranges into higher latitudes. Increased survival of insects through warm winters can also worsen outbreaks from year to year. Of course, these same changes will also have an impact on predators and parasitoids, but only where they are present in the agro-ecosystem. Unfortunately, host-specific control agents are usually less flexible and more prone to disruption than the pests they control.

Climate change will also open up new ranges to microorganisms and their insect vectors. Highly adaptable microbes will not be threatened by changes, but their relationships with the rest of the ecosystem – including crops and pests – will shift in important ways. New crops will be introduced to regions as their climates come to resemble other parts of the world, and pests and diseases will follow close behind. The result will almost certainly be an increased demand for biological control agents from other countries. Climate change will happen on a global scale, and countries will depend more than ever on having access to the biodiversity of crops and their attendant non-plant species across national borders.

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