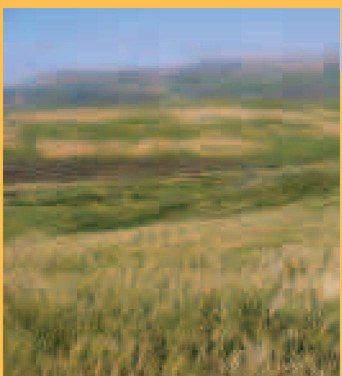
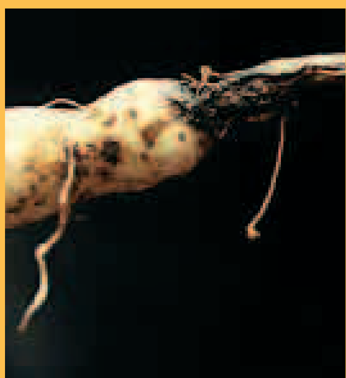
IPM Research Brief No. 2

The Systemwide Program on Integrated Pest Management

Soil Biota and Sustainable Agriculture: Challenges and Opportunities







About the SP-IPM

When delegates to the Earth Summit met in Rio de Janeiro in 1992, they recognized a looming crisis in international development. Attempts to raise living standards through conventional development approaches were not only having a woefully limited impact on poverty and other indicators of underdevelopment, they were also 'costing the earth'. In effect, inappropriate development strategies were destroying the planet's ecological life support systems.

In the field of agriculture, undue reliance on pesticides and fertilizers to raise production was undermining the sustainability of that production. In the Agenda 21 action plan that emerged from the Summit, integrated pest management (IPM) was explicitly recognized as a key part of the solution to this problem. It would allow more food to be produced with less negative impact on agricultural and natural ecosystems. In 1996, as part of its response to Agenda 21, the Consultative Group on International Agricultural Research (CGIAR) launched its Systemwide Program on Integrated Pest Management (SP-IPM).

The SP-IPM is a global partnership whose task is to draw together the IPM efforts of the international agricultural research centers and their partners, and to focus these efforts more clearly on the needs of poor farmers in developing countries. The program tackles those areas where research promises solutions to pressing problems of sustainable agriculture but where impact has so far been limited. The SP-IPM expects to achieve rapid progress by alleviating constraints such as fragmentation of R&D efforts and weak links between researchers and farmers. It is already breaking down barriers to information exchange, filling research gaps where necessary, and developing effective models of partnerships among researchers, extensionists, and farmers. Specifically, the SP-IPM promotes:

- Inter-institutional partnerships for increased effectiveness of IPM research
- Holistic and ecological approaches and methodologies for IPM technology development
- Effective communication among stakeholders for informed IPM decision-making
- Farmer uptake of IPM technologies for larger, healthier harvests
- Public awareness of IPM and its impact on sustainable agriculture.

The program's stakeholder groups are as follows: international research institutions that include IPM as a major part of their agenda; specialized agencies and networks promoting and supporting IPM; nongovernmental organizations (NGOs) and farmer support groups; and the plant protection industry. The R&D organizations and farmers who are our principal clients benefit from the program through access to technical resources and expertise, information, advice, collaborative field activities, and capacity-building activities. All these services aid their efforts to manage pests, achieve greater food security, and raise their incomes within a healthier environment.

Core donor partners are the Governments of Norway, Switzerland, and Italy. Donors supporting special projects have included funding agencies in Australia, Denmark, New Zealand, the United Kingdom, and the United States, as well as the Global IPM Facility and the World Bank (through the CGIAR).

For more information write to:
Coordinator, SP-IPM
International Institute of Tropical Agriculture
08 Tri Postal 0932, Cotonou, Republic of Benin
E-mail: ipm-center@cgiar.org
Website: www.spipm.cgiar.org

About this Brief

The IPM Research Brief series is part of the SP-IPM's strategy for promoting information exchange among stakeholders. Its purpose is to build public awareness and understanding of the benefits of integrated pest management and to encourage the full integration of this approach into mainstream agriculture.

The main targets of these briefs are agricultural research managers, policy makers, and the development partners with whom governments plan IPM inputs into agricultural and rural development activities. The briefs analyze the biological and ecological bases of IPM-related food insecurity issues of common concern across different agroecosystems and regions. They also synthesize research results and advise on opportunities for scaling up the benefits achieved in pilot studies.

This brief addresses the challenges and opportunities presented by the great diversity of species that make up the living component of the soil—the so-called soil biota. Until relatively recently, much of the research on soil organisms concentrated on pest species, including weeds, plant pathogens, and various soil-dwelling vertebrates and invertebrates. While such species are clearly important, the roles played by other members of the soil community have been somewhat neglected.

Current research suggests that the soil biota is an important resource whose potential value in increasing the sustainability of agricultural systems is not yet fully appreciated. The aim of this brief is to increase public awareness of the principal groups of soil-dwelling organisms, their roles in agroecosystems, and how they can best be managed by farmers in the developing world. In addition to summarizing the current state of knowledge, the brief also outlines research needs and policy objectives that will help reinforce and support the advances already made.

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Soil Biota and Sustainable Agriculture: Challenges and Opportunities

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Soil: a Dynamic Living Resource under Threat

Soil is a complex mix of organic and inorganic matter that includes thousands of different species, the vast majority of which are still undescribed. Some of the organisms are pests which cause significant crop losses while others perform 'environmental services' such as biological control of pests, aeration, drainage, and nutrient and water cycling. As a dynamic living resource, soil is the basis of sustainable agriculture, as well as the physical support for most other human activities.

In many areas of the world, soil fertility is declining and erosion is getting worse. Marginal lands are especially susceptible. Worldwide, an estimated 2 billion hectares of land are considered degraded, that is, less productive due to deterioration of essential soil processes. The deterioration usually results from interactions among three types of processes: physical, such as erosion, crusting, and sealing; chemical, such as nutrient depletion, acidification, and pollution; and biological, such as organic matter depletion and loss of soil flora and fauna.

Asia, Africa, and Latin America together account for an estimated 75% of the global area of degraded land, with 750, 490 and 240 million hectares, respectively. North America, Europe, and Australia each have an estimated 100–200 million hectares of degraded land. Loss of soil structure and fertility, together with the increasing incidence of pests, weeds, and diseases, are often responsible for the migration of small-scale farmers practicing shifting or semishifting cultivation, as in the forest and savanna areas of Africa, South America, and Asia.

Attempts to reverse this global trend by means of more sustainable agricultural practices depend on a thorough understanding of soil structure and function. However, while the physical and chemical characteristics of soils have been extensively studied, the great diversity of soil organisms and the complex interactions among them remain poorly documented and understood. It is only comparatively recently that the importance of the soil biota in maintaining soil quality, plant health, and soil resilience (the ability to recover from natural or anthropogenic disturbance) has been recognized. Despite growing interest in developing more sustainable agricultural systems, soil biota management remains a largely neglected area of agricultural research-for-development.

Soil erosion in Ntcheu, Malawi. To combat land degradation scientists need a thorough understanding of not only the physical and chemical aspects of soils, but also their biological components.

Soil Health and Plant Health

Soil ecosystems are among the most complex of all terrestrial communities, and the role of the soil biota in maintaining plant health is not fully understood. The composition of the soil biota is strongly influenced not only by the nature of the underlying organic matter and mineral components, but also by environmental variables such as temperature, pH, and moisture. Numbers and types of soil organisms thus vary widely both in time and space, and are greatly influenced by agricultural activities such as tillage and cropping practices.

There is a strong relationship between soil fertility and plant health, in the sense of the plant's ability to resist pests and diseases. Poor land management and declining soil fertility often result in a negative feedback cycle characterized in part by an increase in soil-borne pests and diseases. Agricultural practices such as adding lime, inorganic fertilizers, and pesticides can change the physical and chemical nature of the soil environment, thereby altering the number of organisms and the ratio of different groups of organisms. Since plant health is intimately linked to soil health, managing the soil in ways that conserve and enhance the soil biota can improve crop yields and quality. A diverse soil community will not only help prevent losses due to soil-borne pests and diseases but also speed up decomposition of organic matter and toxic compounds, and improve nutrient cycling and soil structure. Colonization of roots by mycorrhizae or other endophytic fungi, for example, can confer resistance to root-feeding insects. Conversely, a plant's ability to compensate for root damage can be compromised by nutrient deficiency if soil fertility is low.

Elusive Targets: Soil-borne Pests and Diseases

From a crop management perspective, soil pests and diseases pose special problems. They are hidden from view and hard to detect until the sudden appearance of damage creates an urgent need for rapid, curative treatments. Even then, damage due to soil pests and pathogens may be misdiagnosed and ascribed to other causes, such as nutrient deficiencies. In general, farmers are less aware of soil-borne pests and diseases (and less able to recognize them) than those attacking the above-ground parts of the plant. In the case of some insect pests, for example, farmers may fail to make the connection between the damaging, soil-based larval stage of the insect and its above-ground adult stage during which little or no damage occurs.

At the research level, the complexity and diversity of subterranean ecosystems pose unique challenges to those seeking to quantify the effects of individual taxa or species assemblages. This work is made even more difficult by the complex nature of many tropical cropping systems. Population densities of soil organisms can vary widely within a few meters, with their distribution being greatly influenced by the physical, chemical, and biological characteristics of the soil. Furthermore, different types of soil organisms require different methods for their extraction, identification, and quantification, and for the estimation of crop losses caused. The diversity of available techniques may make it difficult to compare results from different research groups.

Principal Soil Organisms

Scientists have devised various schemes for characterizing and classifying soil organisms in order to be able to cope with their great diversity. Apart from the conventional taxonomic approach, there are classification schemes based on body size, function (decomposition, etc.), and the role of organisms from an anthropocentric point of view. The last-mentioned of these systems recognizes 'productive' biota (such as crop plants), 'destructive' biota (pests, pathogens, and weeds) and 'resource' biota (species that contribute to soil processes such as decomposition but that do not produce a harvestable product). Under body size, there are three main groups: the microbiota (<100 µm diameter), the mesobiota (100 µm to 2 mm diameter), and the macrobiota (>2 mm diameter). The main taxonomic groups included in these various systems are listed in Annex 1.

North African cereal crops afflicted with dryland root rots. These soil-borne diseases cause the plant's spikelets to dry out. Seed may be shriveled up or entirely absent. Photo: ICARDA

Microorganisms are the most abundant members of the soil biota. They include species responsible for nutrient mineralization and cycling, antagonists (biological control agents against plant pests and diseases), species that produce substances capable of modifying plant growth, and species that form mutually beneficial (symbiotic) relationships with plant roots. This last group includes mycorrhizal fungi, various actinomycetes, and some bacteria.

Within the soil biota, the most important groups of both destructive and resource organisms are the bacteria, fungi, nematodes, arthropods (such as mites and insects), earthworms (mostly beneficial), and weeds.

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Crop Losses from Soil Organisms

In the tropics, soil-borne pests and diseases are recognized as major causes of reduced crop yields and therefore of economic losses to farmers. Plants grown on marginal land with low soil fertility often lack vigor and are particularly susceptible to the ill effects of these organisms. Soil-borne pests, for example, can undermine the development of healthy root systems.

The damage caused by soil organisms appears to be on the rise in the tropics, in part due to the pressures on the land from continually expanding human populations and associated changes in cropping patterns. Nevertheless, these agricultural losses and their economic significance are often poorly quantified. Here are three examples of the significant damage caused by soil organisms.

- In Central and South America, white grubs (*Holotrichia* spp.) cause major losses in maize, sorghum, bean, potato, and rice production, at times exceeding 50% of the total yield. Similarly, white grubs have been reported to seriously damage bean and groundnut crops in Africa.
- Sweet potato weevils of the genus *Cylas* are considered the world's most destructive pest of sweet potato, with crop losses of up to 73% reported from Uganda. In the highlands of Peru, farmers ranked the Andean potato weevil (*Premnotrypes* spp.) as the most important pest of that tuber crop, with losses in single fields of up to 75%.
- In recent years, burrower bugs (*Cyrtomenus bergi* and other soil-borne hemipterans) have gravely damaged a range of crops in Central and South America (see box, Development of a New Pest). When burrower bugs feed on cassava roots, they can introduce soil-borne pathogens such as *Aspergillus*, *Diplodia*, *Fusarium*, *Phytophthora*, and *Pythium*. The resulting lesions can reduce root starch content by more than 50%, and may wipe out a crop's entire commercial value.

Bacteria

The most abundant members of the vast community of soil organisms are bacteria. Per gram of soil, they can reach densities of one billion (one thousand million) individuals—and an estimated 20 000 to 40 000 species. The magnitude of bacterial biodiversity has only recently been revealed through molecular techniques that can differentiate between hard-to-culture taxa.

Bacteria play important roles in many soil processes, including the cycling of nitrogen, carbon, and phosphorus, and

*Adult Andean potato weevil (*Premnotrypes* spp.) and the damage to potatoes caused by larvae. Photo: Jürgen Kroschel, CIP.*

the degradation of pesticides and other potential pollutants. They can multiply rapidly under favorable conditions, although very high growth rates are generally limited by the availability of nutrients. Bacterial populations are typically greater and more diverse close to plant roots. It has been estimated that 5 to 10% of root surfaces may be occupied by bacteria.

Various endophytic bacteria (e.g., species of *Azotobacter*, *Acetobacter*, and *Azospirillium*) not only fix nitrogen but also stimulate the production of root hairs. This increases the host plant's capacity to take up water and nutrients and compensate to some extent for grazing by root-feeding pests. Various bacteria that colonize seed coats and plant roots produce compounds capable of affecting plant growth. These growth-promoting rhizobacteria (including species of *Pseudomonas*, *Bacillus*, *Serratia* and *Arthrobacter*) can also increase plant resistance to pests and diseases through a variety of mechanisms, including the production of structural materials that strengthen root tissues and antibiotic metabolites that directly affect other elements of the soil biota. In some cases, these beneficial bacteria displace potential pathogens by competing for nutrients. Or, they may stimulate increased synthesis of defensive compounds by the plant itself, resulting in so-called induced resistance or systemic acquired resistance. *Rhizobium etli*, for example, induces systemic resistance in potato roots to the potato cyst nematode (*Globodera pallida*). Some rhizobacteria are able to suppress weed growth while leaving crops unaffected.

The relationship between bacterial endophytes and their host plants is a subject of increasing interest to those seeking better ways to manage the soil biota. Plant roots themselves produce a number of compounds that affect microbial populations in their vicinity (the so-called rhizosphere). These compounds may act as attractants, repellents, biocides, or biostats (compounds that inhibit microbial growth), and as such offer new possibilities for the manipulation of both pathogens and beneficial species.

Soil Biota

Fungi

Fungus fruiting body from the forest floor in Ibadan, Nigeria. Three stages of decomposition are shown.

As with the bacteria, the great diversity of fungi remains poorly documented. It has been estimated that only about 5% of fungi have so far been described. Fungi play as important a role in soil processes as do bacteria, but tend to be more abundant in slightly acid soils. They vary widely in size, preferred habitat, and mode of life.

Fungal plant pathogens (e.g., some species of *Fusarium* and *Verticillium*) can cause diseases such as root rots and vascular wilts that are significant problems in many parts of the world. In the early 1990s, for example, the increasing prevalence of fungal root rots severely restricted the viability of bean crops in parts of Kenya. Many soil-borne fungal pathogens (e.g., *Rhizoctonia solani* and *Pythium* spp.) are capable of infecting a range of plant genera. Furthermore, plants infected with fungal diseases may be more vulnerable to attack by soil-dwelling insects. In Malawi, for example, it was found that groundnuts were more vulnerable to attack by termites if they were infected by fungal pathogens such as *F. solani*.

However, some fungi form symbiotic relationships with plant roots, enhancing the plant's ability to take up nutrients. (See box on Mycorrhizal Fungi.) There is some evidence that such relationships can help less competitive plants to become established in pasture systems.

Harnessing beneficial fungi: These five-week-old soybean plants are infected with Meloidogyne *nematodes, which damage roots and increase the plants' susceptibility to bacterial and fungal infections. No treatment has been given to the four plants in the middle. Left, a broad-spectrum insecticide, carbofuran, has been used to control the nematodes. Right, plants have been inoculated with a mycorrhizal fungus, which enhances plant nutrition, and a fungus of the genus* Trichoderma*, which confers a measure of disease resistance on the plants.*

Many species of soil fungi are saprophytic (i.e., grow on dead organic matter), while others are parasitic on animals or plants. Some are important antagonists or biological control agents of soil-borne pests or diseases (e.g., species of *Dactylaria* and *Arthobotrys* for nematodes, *Beauveria* and *Metarhizium* for insect pests, and *Trichoderma* and *Coniothyrium* for plant-pathogenic fungi).

Nematodes

Nematodes (roundworms or eelworms) are the most abundant microfauna in the soil and are particularly numerous in the top 5 cm. In the top 2 cm of soil, their numbers may exceed two billion per hectare. The number of nematode species worldwide has been estimated at 80 000 to 100 000 species.

The majority of soil-dwelling nematodes feed on bacteria and fungi, but many prey on other nematodes, protozoa and rotifers, and some species are parasitic on insect pests. More than 2000 species are parasites of higher plants. These include cyst and root-knot nematodes, such as certain species of *Heterodera*, *Globodera*, *Cactodera*, and *Meloidogyne*), and 'migratory' species such as *Pratylenchus* spp., *Ditylenchus destructor*, and *Scutellonema bradys*. Their feeding lowers crop yields by disrupting water and nutrient uptake or by decreasing fruit or tuber quality or size; it can also allow fungal and bacterial pathogens to gain access to damaged roots, causing secondary infections. The presence of root-knot nematodes, for example, is known to increase the incidence of root rots and fusarium wilts in a wide range of crops.

Mycorrhizal Fungi

A wide range of soil-borne fungi can invade the roots of higher plants to form mutually beneficial relationships called mycorrhizae. The best known of these associations are arbuscular mycorrhizae which are especially important in acid soils, where phosphorus is often the limiting nutrient. The hyphae (threads of mycelium) enhance the uptake and translocation of nutrients (particularly phosphorus) into the host plant, and the fungus in turn receives carbohydrates from the plant. Mycorrhizal fungi can also increase the drought tolerance of their plant partners and enhance their resistance to plant pathogens, nematodes, and toxicity caused by heavy metals.

Mycorrhizal fungi can be found in the roots of grasses, some trees and shrubs, and most agricultural crops. In mature roots, the proportion of root weight attributable to a mycorrhizal fungus can vary from about 3% in sorghum to about 16% in soybean.

The mycelium of a mycorrhizal fungus, which can extend several centimeters around the plant root, enhances the formation of soil aggregates, a particularly valuable trait in coarse, sandy soils. In addition, the mycelium is an important resource for fungus-grazing insects (e.g., some *Collembola*) and conducts root exudates further out into the soil, enhancing the carbon supply for other members of the soil biota. Dense populations of bacteria have been found in this part of the rhizosphere, and synergistic interactions between arbuscular mycorrhizal fungi and other beneficial members of the soil microbial community (such as *Trichoderma* spp.) have been observed.

Both maize roots are infected with Pratylenchus sefaensis *nematodes. However, the healthier one, left, comes from a potted plant that was first treated with* Glomus mosseae, *an arbuscular mycorrhizal fungus that shows promise as a way to manage nematodes.*

Agricultural practices can have major impacts on mycorrhizal fungi, both positive and negative. On the one hand, conventional tillage disrupts the networks of fungal hyphae in the soil, delaying colonization of crop plants and reducing their phosphorus uptake. As a result, crop yields are lower than those obtained in zero-tillage systems. The absence of suitable host plants (over winter, for example), long-term fallowing, or continuous monoculture can all cause severe declines in soil fungal populations. On the other hand, well planned crop rotations, mixed cropping, and the use of cover crops can all conserve or enhance this important resource.

Some crops are more dependent on mycorrhizal relationships than others. Faba beans and maize, for example, depend more heavily on mycorrhizae than do wheat and potatoes, while brassicas and beets do not support mycorrhizal relationships at all. Including the latter in crop rotations can therefore reduce or delay root colonization in the crops that follow.

Plant parasitic nematodes tend to be more damaging pests in the tropics than in temperate zones. This is because their population growth rate is favored by warm, humid climates and the longer growing seasons in these regions, which allows for more reproductive cycles per year. Nematode pests are associated with almost all crops grown in the tropics and cause losses of millions of dollars each year. It has been estimated that, worldwide, plant-parasitic nematodes annually reduce agricultural production by about 12%. Losses are particularly severe in developing countries due to insufficient expertise for species identification, inadequate quantification of the pest problem, and a limited range of management options.

Small attackers, big victims. Damage from microscopic nematodes topples plantain plants.

Worldwide, root-knot and cyst nematodes are especially important pests and infestations by them continue to undermine national efforts to improve food security and alleviate poverty. Losses to individual crops often go unnoticed or are attributed to other causes. This is because most symptoms of nematode damage such as chlorosis (yellowing), patchy growth,

Root-knot nematode on sweet potato.
Photo: J. Bridge, CAB International

stunting, and wilting in hot weather, are easily confused with nutrient deficiencies or sometimes with bacterial or fungal diseases.

Compared with the plant-parasitic nematodes, much less is known of the biology and ecology of other nematodes. This is particularly true of the bacteria-feeding nematodes, which are generally considered to be beneficial or harmless. These species, often concentrated in the root zone of higher plants, play an important role in soil nutrient cycling and can help distribute bacteria that promote plant growth.

Although nematodes are not capable of widespread dispersal on their own, in agricultural systems they may be spread via contaminated machinery, land levelling, irrigation, and soil erosion.

Mites

Although these are among the most common soil-dwelling mesofauna, they tend to be restricted to the leaf litter and surface layers. They are more diverse than any other single group of soil arthropods (including the insects), and this diversity is reflected in their feeding habits and life history. In general, they are more important in their role as resource biota than as destructive biota. Some species feed on fungal spores, while numerous predatory species attack nematodes, other mites, insect eggs, and larvae. Other species feed on plant debris, dung, or carrion and are important members of the decomposer community. Although some mite species feed on living plants and others are parasitic on livestock, in general these potential pests are only a minor component of the mite fauna.

Insects

The number of taxa of soil-dwelling insects is relatively small compared with the diversity that marks other major groups of soil organisms. With many species, only part of the life cycle (egg, larva and/or pupa) is spent in the soil, although some taxa are associated with specific soil types.

Root-feeding species can reduce crop yields by reducing a plant's ability to absorb water and nutrients and may cause further losses by facilitating the entry of soil-borne pathogens. In contrast, predatory and parasitic insects can contribute to the biological control of both invertebrate pests and plant pathogens. Some *Collembola*, for example, show a marked preference for feeding on the spores of fungal pathogens, including *Rhizoctonia solani* and *Fusarium oxysporum*. Species that feed on organic matter (detritivores) may be important members of the decomposer community. Some insects have ambivalent roles. For example, although termites are usually viewed as pests, in arid tropical soils with low earthworm populations the burrowing activities of termites can also help decompose organic matter and improve soil structure and porosity.

Stictococcus vayssierei*, a subterranean scale insect, is an emerging pest of cassava in Central Africa.*
Photo: SP-IPM

Termites and ants are usually the dominant components of the soil insect biomass. As such, they are probably more important than all other insects in their effects on soil structure. They can also be significant pests. In parts of Malawi, for example, it has been estimated that the two most destructive termites (*Pseudacathotermes militaris* and *Macrotermes michaelseni*) damage crops on 72% and 49% of all smallholdings, respectively. In Africa as a whole, the subfamily *Macrotermitinae* is considered the most damaging group, affecting a wide range of crops, including tree and pasture species. Their success as pests has been attributed to their ability to survive cultivation, feed on both living and dead plant material, and cultivate saprophytic fungi that serve as food in the dry season.

Other important root-feeding insects include the 'white grub' larvae of various scarab beetles (*Scarabeidae*), weevils (*Curculionidae*), wireworms (*Elateridae*), and false wireworms (*Tenebrionidae*). Some *Hemiptera*, *Orthoptera*, and larval *Lepidoptera* (e.g., cutworms) are likewise important in parts of the world. The significance of different species as pests is related to their host range. Those capable of feeding on a wide variety of plants, so-called polyphagous species, are generally the most difficult to control. The distribution and damage potential of many soil-dwelling insects is also strongly influenced by soil moisture and rainfall patterns, with the more successful species being able to survive periodic drought.

White grub. Illustration: SP-IPM

As noted earlier, damage by root-feeding insects can result in secondary infections by plant pathogens. Root crops are particularly susceptible to this type of damage, since the harvested part of the plant is directly affected. Potatoes, for example, soon become infected with bacteria and fungi if damaged by larvae of the potato tuber moth (*Phthorimaea operculella*), resulting in the rapid rotting of the tuber. The same is true of sweet potato tubers damaged by larvae of the sweet potato weevil (*Cylas formicarius*). In groundnuts, the level of aflatoxin (caused by the fungus *Aspergillus flavus*) can increase if the pods are damaged by termites, since the latter can transmit fungal spores.

Earthworms

The Greek philosopher Aristotle referred to earthworms as the "intestines of the earth". The description is apt not only because these invertebrates physically resemble digestive organs but also because they perform something of a digestive function when they break down plant residues in the soil and recycle nutrients. Experiments with maize, for example, have shown that plant residues can degrade 30% faster in surface soil containing earthworms than in soil without them.

Earthworms perform a variety of other ecosystem services as well. For instance, they enhance soil porosity thereby reducing rainwater runoff and allowing for infiltration of moisture to plant roots. They also play a vital role in water purification, agrochemical detoxification, and maintenance of soil stability.

When it comes to sheer biomass, earthworms usually account for the bulk of invertebrates that make their home in the soil. Along with ants and termites, they have a special distinction as 'ecological engineers'. This is due to their ability to excavate remarkably large amounts of soil and to create organo-mineral structures through their casts (excrement).

To date about 3700 species of earthworms have been scientifically described. However, the actual number is estimated to be at least twice that, with the overall knowledge gap being significantly greater for tropical earthworm species than species in temperate zones. Although many aspects of earthworms' soil engineering role have been documented, interactions with other members of the soil biota, and how those affect plant growth and health, positively or negatively, are much less well understood.

Weeds

In the tropics, crop losses due to competition with weeds are on the order of 25%, with weed removal often the most labor-intensive task in smallholder systems. In most areas, the weed population centers on about 20 particularly troublesome species. The individual taxa may be indigenous or introduced, but they usually share a few key traits, especially rapid vegetative

In the tropics, competition from the soil biota's most visible component—weeds—typically results in crop losses of around 25%.

growth, high fecundity, and persistence in the soil seed bank. Weed species that resemble the crop in their early stages (e.g., grass weeds in cereal systems) are particularly difficult to deal with when hand weeding is the main control technique.

Besides competing with the crop for water and nutrients, weeds can also act as alternative hosts for pest nematodes and plant pathogens. And by boosting the humidity around the base of crop plants, weeds also increase the likelihood of infections by pathogens such as *R. solani* and *Sclerotium rolfsii*. Some weed species are parasitic on certain staple food crops, in some cases causing total crop failure. (See IPM Research Brief No. 1, 2003, Tackling the Scourge of Parasitic Weeds in Africa.)

The role of weeds in relation to soil-dwelling insect pests has not received a lot of scientific attention, although in some cases weeds are known to act as alternative hosts, maintaining the insect pest between crop cycles. Wild *Ipomoea* species, for example, can support the sweet potato weevil (*Cylas formicarius*) between crops, and in Zimbabwe, the groundnut plant hopper (*Hilda patruelis*) can survive the dry season on a variety of different weeds, allowing it to invade groundnuts as soon as they emerge. But weeds may also play a constructive role by supporting higher numbers of soil-dwelling predators that serve as pest control agents.

Managing the Soil Biota

In natural ecosystems, outbreaks of pests and diseases, including those mediated by soil, are comparatively rare. In this respect, it is generally accepted that biological diversity contributes to the relative stability of natural systems. This is probably as true for subterranean communities as it is for those above ground. Agroecosystems, in contrast, are typically much less diverse than natural ecosystems, and are subject to frequent anthropogenic disturbances. They have much simpler food webs and more open nutrient cycles, which makes the maintenance of soil biodiversity—and ecosystem stability—much more difficult. However, there are many direct and indirect means of influencing the soil biota to improve plant health in the short term and to increase soil quality and productivity in the long term.

Direct Methods

These fall into two broad categories: temporary reduction of pest populations and longer-term enhancement of beneficial species.

Reduction: biofumigation and solarization

Synthetic soil fumigants like methyl bromide have sometimes been used to control soil-borne plant pathogens and nematodes, particularly for high-value cash crops. However, environmental concerns have stimulated considerable interest in the search for less hazardous alternatives. Biofumigation is one such option. It involves the use of plants (or other organic materials) which, as they decompose, produce toxins in concentrations high enough to suppress soil pests and diseases. The decomposition of various brassica species, for example, results in the release of toxic levels of isothiocyanates. A considerable amount of research has been conducted on how best to exploit this effect. Appropriate brassica species are generally selected on the basis of their suitability to local conditions and the type and quantity of isothiocyanates they produce. The plants are usually incorporated into the soil just before flowering, when levels of glucosinolates (isothiocyanate precursors) are generally at their peak.

Another approach, for high-value crops, is solarization. Moist soil is covered with a plastic film so that temperatures beneath the film reach levels lethal to soil-borne pathogens. This technique has been used in Malawi for control of club-root disease of brassicas, and has reduced field populations of plant-parasitic nematodes (including species of *Meloidogyne*, *Pratylenchus*, and *Tylenchus*) by up to 97% at depths of 20 centimeters. It has also been used successfully for managing weeds.

In some cases, a higher degree of control has been obtained by combining biofumigation with solarization. Combining poultry manure applications with solarization, for example, was found to be more effective at controlling plant pathogens than either approach alone. In effect, higher temperatures associated with solarization enhanced the release of toxic levels of

Plastic sheeting has been laid out to solarize the soil as a way to manage Plasmodiophora brassicae*, the cause of cabbage clubroot disease.*

ammonia from the manure. However, while techniques such as these may be useful in the short term, they inevitably lead to negative effects on the beneficial components of the soil biota.

Collection and destruction of soil-borne pests by hand also constitute a direct control method. In India, farmers have reduced adult populations of *Holotrichia* spp. (*Scarabeidae*) in this way. When adult beetles congregate in trees before mating and laying eggs, farmers shake the trees and kill the fallen beetles on the ground. Fires and lamps have also been used to lure and kill adults at night. However, collective action across a large area is needed to achieve a significant reduction in damage by larvae. Overall, high labor requirements limit the usefulness of manual collection methods.

Enhancing beneficial organisms

Over the years many efforts have gone into culturing and releasing beneficial members of the soil biota such as mycorrhizal fungi, plant growth-promoting rhizobacteria, and biological control agents. Various biological control agents for all groups of soil pests occur naturally, and attempts have been made to isolate these natural enemies (mainly fungi, bacteria, nematodes, and insects), increase their numbers artificially, and then release them back into the field at relatively high densities. Large-scale use of this approach depends on low-cost production techniques, delivery at the right time and in the right quantities, and, in the case of commercial production, meeting local registration requirements. Such an approach is perhaps better suited to growers of high-value crops in developed countries than to small-scale farmers in developing countries.

Nevertheless, recent research has generated promising results, particularly in the area of seed dressings. Mixtures of the mycorrhizal fungus *Glomus mosseae*, the nitrogen-fixing bacterium *Bradyrhizobium japonicum*, and the antagonistic fungus *Trichoderma pseudokoningii* have been shown to improve soybean growth and reduce damage due to nematodes (*Meloidogyne* spp.). Treating seeds with species of *Streptomyces* and *Bacillus* has provided some control of dry root rot (caused by *Macrophomina phaseolina*) in chickpea, and of fusarium wilt in pigeonpea. Similarly, cultures of *Rhizobia* have been used to inoculate legumes, and mycorrhizal preparations enhance the establishment of newly planted trees. In each case, the use of organisms as seed dressings rather than as more diffuse soil treatments makes maximum use of microbial resources.

One highly sophisticated approach to the manipulation of soil fungal communities involves efforts to replace toxigenic strains of *Aspergillus flavus* with more competitive atoxigenic strains of the fungus, thereby reducing the incidence of aflatoxin contamination of crops such as maize.

Indirect Methods

Indirect methods involve manipulating the factors that influence biotic activity (such as microhabitat structure, microclimate, and nutrient availability) rather than the organisms themselves. A number of techniques have the potential to increase soil biodiversity, in turn reducing the incidence of soil-borne pests and pathogens. Such methods involve the adoption or modification of agronomic practices to conserve and enhance naturally occurring populations of beneficial taxa, or reduce populations of injurious species.

Opportunities for modifying existing cropping systems with these aims in mind occur at all points of the crop cycle. They include adding organic matter to the soil (through mulches, green manures, or animal waste), reducing tillage, and adopting more diverse cropping systems. In some cases, only minor modifications of existing practices are required, making such methods more readily applicable to the needs of poor farmers than are the more resource-intensive direct methods. However, applying such techniques in the most effective manner requires a thorough understanding of below-ground food webs. Many of these techniques are currently under-utilized in tropical small-scale agriculture because they have yet to be critically evaluated in such situations.

Supplying organic matter

Organic matter can help modify soil structure and is of fundamental importance to many soil functions, including carbon cycling and sequestration and nutrient storage. Incorporation of rich and varied sources of organic matter not only supplies plant nutrients, but also helps to increase below-ground biodiversity by providing an array of substrates capable of supporting diverse soil organisms. Increased biodiversity in turn contributes to the ability of the soil to suppress plant pests and diseases. In Tanzania, for example, application of manure to bean fields resulted in a reduction in root damage by larvae of bean leaf beetles (*Ootheca* spp.), either because of higher levels of predators, parasites, or pathogens in such fields, or because the plants' own defences were stimulated in some way.

The interactions responsible for the observed beneficial effects of organic amendments on plant health can be both subtle and complex. For example, it has been shown that briefly exposing the eggs of two pest nematodes (*Meloidogyne incognita* and *Heterodera schachtii*) to aqueous extracts of various organic amendments (including poultry manure and composted tree bark) significantly increased their susceptibility to the fungal pathogen *Verticillium chlamydosporium*, presumably by degrading the egg membrane in some way. There is also evidence to suggest that soils with a high level of organic matter tend to have higher populations of beneficial nematodes and lower populations of plant-parasitic species, as well as a greater proportion of bacterial isolates capable of suppressing the growth of certain weeds. Thus, growth of the weed *Chenopodium album* was reduced by 75% in soils receiving annual inputs of green manure, composted plant residues, and cattle manure, compared with populations in non-amended soils.

Suitable sources of organic matter include animal wastes, green manures, crop residues, and composted vegetation. It is important to note, however, that the effects of organic amendments can vary not only with the nature of the material added, but also with soil pH. Thus, at pH 5 microsclerotia (resistant dormant stages) of the pathogenic fungus *Verticillium dahliae* were killed in direct proportion to the concentration of pig slurry incorporated into the soil, but no such effect was observed in soils of pH 6.5. Similarly, research on bean root rots caused by *Fusarium solani* has shown that while a green manure of *Calliandra* sp. reduced populations of the pathogen (and subsequent disease severity), additions of farmyard manure increased the severity of the disease.

In the case of *V. dahliae*, the toxicity effects of organic amendments have been attributed to various volatile fatty acids (including acetic, propionic, butyric, isobutyric, and valeric acids); manures that contained all of these compounds killed the microsclerotia, whereas those that contained only acetic acid and small amounts of a few other acids did not. Thus, the effects of organic amendments can depend not only on the characteristics of the organic matter (particularly the ratio of carbon to nitrogen), but also on the nature of the existing soil microbiota, and how individual taxa react to the addition of different organic amendments. For example, while *V. dahliae* populations were reduced by the application of pig slurry, populations of antagonistic *Trichoderma* spp. increased, further helping to suppress populations of the pathogen.

In so-called 'disease-suppressive' soils, the microflora is usually dominated by species that produce large amounts of antibiotics (e.g., various species within the fungal genera *Trichoderma*, *Penicillium*, and *Aspergillus,* and the actinomycete genus *Streptomyces*). Such soils typically have good physical structure, and even if very fresh, high-nitrogen organic matter is applied, the production of putrescent (poorly oxidized) products is very low. In contrast, most of the world's agricultural soils have a much higher proportion of pathogenic microorganisms, and the application of fresh organic material can result in the production of relatively high concentrations of poorly oxidized and malodorous compounds that can be toxic to crops. Addition of organic amendments to such soils stimulates microbial activity in general and increases the baseline populations of beneficial soil fungi, although different species may be more prevalent in some soils than others. The increase in disease suppression observed following regular additions of organic matter may be due to a variety of mechanisms. For example, the plant's own defences may be stimulated by the activities of microorganisms, or pathogenic species may be suppressed by more competitive species, or inhibited by species that produce toxic secondary metabolites or extracellular enzymes. Developing disease-suppressive soils through the use of organic amendments takes time. Over the years, though, benefits are enjoyed in the form of better plant health and soil structure.

Increasing plant diversity

As noted previously, the observation that 'diversity promotes stability' has been made in relation to both natural and managed ecosystems. In an agricultural context, intensive cropping—particularly in monoculture—tends to be associated with 'instability' in the form of short-term increases in the populations of soil-borne pathogens, invertebrate pests, and weeds, occasionally resulting in 'outbreak' situations. Increasing plant diversity can help reduce the frequency of such events and can be tackled at various levels:

- Taxonomic or species diversity (mixed cropping of various kinds)
- Genetic diversity within species (planting different varieties of the same species)
- Vertical diversity (planting crops of different heights)
- Horizontal diversity (arrangement of plants in space)
- Temporal diversity (e.g., seasonal differences in plant cover and diversity of growth stages achieved through staggered planting or sowing).

Different crops exploit soil resources in different ways. Maximizing the diversity of cropping systems in both time and space (by rotations, intercropping, and so on) creates a mosaic of soil resources and niches which in turn enhances below-ground biodiversity and improves the resilience of the system as a whole. Certain cropping sequences, for example, favor the build-up of various beneficial bacteria that promote plant growth, while the availability of the host crop is known to be the biggest single factor influencing the number and diversity of plant parasitic nematodes in the soil. Differences in root morphology and biomass, and in patterns of root exudation and carbon allocation, can all influence the population density and activity of other members of the soil biota. Furthermore, maintaining some kind of continuous plant cover through the use of living crops or mulches moderates fluctuations in soil temperature and moisture, and further enhances stability.

Cropping patterns thus have a profound effect on soil pests and beneficial species. The cropping sequence over time, for example, can greatly affect populations of soil organisms that are relatively host-specific (both pests and beneficial organisms). Thus, natural populations of arbuscular mycorrhizae can be increased by growing a suitable host prior to planting the main crop, while populations of host-specific pests or pathogens can be decreased by planting non-host plants as part of the rotation. However, while the benefits of crop rotation are often well understood by farmers, their land holdings may be too small to allow them to practice it, and continuous cultivation may then lead to a gradual increase in soil-borne pests and diseases.

Mixed cropping (in various forms) is widely practiced by small-scale farmers in many parts of the world, with intercropping being the most widespread cropping system in the tropics. These systems have many advantages over monocultures. The presence of non-host plants, for example, can interfere with the host-finding and establishment of mobile pests, and there is also the possibility of yield compensation by the intercrop if one species is damaged. Intercropping also helps to maximize food production from small areas of land and to minimize the risk of catastrophic crop failures.

Considerable research has been conducted on the reduction of above-ground pests and diseases through intercropping and attention is now turning to its effects on below-ground problems. However, the results obtained so far have been rather variable. In Malawi, for example, intercropped maize plots suffered less damage from termites than did monoculture plots; but, in India, intercropping groundnut with sunn hemp (*Crotolaria juncea*) had no effect on either termite abundance or crop damage. In Peru, infestations of potato tuber moth larvae (*P. operculella*) were reduced by intercropping potato with beans, onions, tomatoes, or maize, and in Colombia, intercropping cassava with *Crotolaria* sp. has been found to significantly reduce damage caused by the subterranean burrowing bug (*Cyrtomenus bergi*).

Intercropping can also reduce disease and weed problems. In Burundi, intercropping potato with maize reduced the incidence of bacterial potato wilt caused by *Pseudomonas solanacearum*, while *Striga* spp. can be suppressed by intercropping maize with legumes such as *Desmodium uncinatum*. Interplanting young plantations of tree crops such as cocoa, coffee, and oil palm with annual food crops is a useful weed-suppression strategy for the first few years, not only because of the shading effect of the latter, but also because, on smallholder farms, the food staples are more likely to be weeded, with incidental benefit to the tree crop.

It is difficult to generalize about the effects of intercropping. The outcome is likely to vary not only with the pest and crop species concerned, but also with agronomic factors such as planting date and the frequency and timing of cultivation. The choice of crops will also affect the quality and quantity of plant residues left on or in the soil, which in turn can influence the

Left, the adult banana weevil, Cosmopolites sordidus. *Above, damage to a banana corm caused by tunneling larvae. Photos: Cliff Gold, IITA.*

Sustainable Management of Banana Weevil

The banana weevil (*Cosmopolites sordidus*) is a major pan-tropical pest of banana and plantain (*Musa* spp.). Adults lay their eggs in the plant's pseudostem close to ground and the larvae bore into the rhizome, causing tissue at the edge of their tunnels to turn brown and rot. The plant is weakened and its ability to take up nutrients is reduced. If the infestation is heavy, the plant is small, or the variety particularly susceptible, the plant can die. Yield loss can thus be due to the death of the plant, reduced bunch size, failure to produce new suckers, and/or shortened plantation life. At present, there is no standard protocol for sampling the weevil, and assessment of larval populations involves destruction of the plant.

Nevertheless, a number of management techniques have been developed and adopted, and new approaches are being considered. Several resistant varieties of banana have been produced and released, providing a sound basis for an integrated management strategy that also includes cultural and biological controls. Banana weevils can reproduce in crop debris (including cut stumps); indeed, in some cultivars, weevil survival seems to be higher in crop residues than in growing plants. Hence, sanitation (removing and destroying crop debris immediately after harvest) is an obvious approach to cultural control. Research in Uganda has shown that such sanitation practices can significantly reduce populations of weevils and lead to yield increases of up to 70%. Since both banana weevils and nematodes can be transferred to new fields through infested planting material, simple cleaning strategies such as corm paring prior to planting have also been introduced and adopted by farmers in parts of Kenya and Tanzania.

Biological control agents are also under investigation. Research conducted at the International Institute of Tropical Agriculture (IITA) in Nigeria, for example, has resulted in the identification of a promising hymenopteran egg parasitoid and some dipteran larval parasitoids from Sumatra that might form the basis of a classical biological control program. There is also interest in exploiting the potential of native ants. Ants are generalist predators, and in Cuba some species have been reported to be effective predators of the banana weevil. Surveys in Tanzania and Uganda have recorded a diverse array of ants in banana plantations, with the number of species on individual farms ranging from 19 to 34, generally with *Pheidole* species predominating. Nests of these species occur in the soil, in crop debris, and in standing plants, and if their populations can be manipulated, they may be a useful addition to an integrated control strategy. Microbial control with the entomopathogenic fungus *Beauvaria bassiana* is another option currently under investigation.

Other approaches include attempting to identify and utilize various species of endophytic fungi that are known to colonize banana tissues. Certain strains of these fungi—which penetrate the host plant and grow internally for at least part of their life cycle—can increase host plant growth and/or confer a degree of resistance to weevil damage. Research with Ugandan isolates of some of these species has shown that they can be successfully inoculated into tissue-cultured banana plants, which themselves can form part of an integrated control strategy by ensuring that new plantations are pest- and disease-free at establishment. Various other fungi associated with the banana rhizosphere are also being assessed for their ability to control *Radopholus similis*, the burrowing nematode.

growth, survival, and reproduction of both pest species and their antagonists.

Mulching

A mulch has been defined as any form of covering applied to the soil surface. By this broad definition, it includes crop residues, weeds, green manures, and other plant material cut and carried in from elsewhere, as well as artificial materials such as paper and plastic. The organic mulches, which are more relevant to resource-poor farmers in developing countries, are quite common in the traditional farming systems of the humid tropics. Besides reducing soil erosion and improving nutrient cycling, mulching can also help suppress weeds, pests, and diseases. Herbicide use or time spent weeding by hand may be significantly reduced by mulching, and notable successes have been achieved by using mulches to suppress soil-borne plant pathogens. In Kenya, for example, black rot of cabbage caused by the bacterium *Xanthamonas campestris* was controlled by a grass mulch applied immediately after transplanting. In such cases, it is thought that the effect of the mulch is due to a combination of its role as a physical barrier (reducing rain splash of the pathogen onto the crop), together with its ability to change the microclimate at the soil surface and enhance the activity of beneficial soil microorganisms capable of suppressing pathogens.

Mulching has also been used to divert termites from crops, and in various parts of Africa, mulching with the weed *Tithonia diversifolia* has been shown to reduce nematode damage and improve crop growth. In Uganda, mulching of banana plantations appeared to reduce numbers of the nematode *Radopholus similis*, possibly because the mulch reduced soil temperatures, thereby slowing nematode feeding and reproduction. Conversely, the presence of crop residues on the soil surface may enhance the biological control of insect pests by entomopathogenic nematodes. It has been shown, for example, that such residues increase the persistence of *Steinernema carpocapsae*, probably by protecting it from desiccation or ultraviolet light.

Mulching nevertheless requires careful management: if crop residues are only partially decomposed by the time the next crop is planted, the incidence of some seedling diseases (such as those caused by *Rhizoctonia solani*, *Sclerotium rolfsii*, and *Macrophomina phaseolina*) can increase. While burial of crop residues increases the rate of decomposition and can help to improve soil structure, these benefits must be weighed against the generally adverse effects of tillage on the soil biota.

Host plant resistance

Genetically based host plant resistance to pests or pathogens may be constitutive (continually expressed) or induced (expressed only in response to damage). This so-called intrinsic resistance can be one of the most economical and sustainable options for the integrated control of many plant pathogens and some invertebrate pests, particularly nematodes. Recent research at the International Center for Agricultural Research in the Dry Areas (ICARDA) has resulted, for example, in the identification of several lentil lines resistant to vascular wilt caused by *Fusarium oxysporum*, while new varieties of beans resistant to root rots have been widely adopted by farmers in western Kenya.

However, there are a number of obstacles to the development and use of resistant cultivars. First, in situations where different strains or pathotypes of a pathogen or pest occur, the resistance may be of variable value. Second, selection for resistance-breaking biotypes can be rapid if resistant varieties are not deployed with care. Third, developing resistant germplasm is often a slow and costly process and the resulting seeds of improved varieties may either be too expensive for the majority of smallholders, or supplies may be inadequate to meet demand. Where this is the case, it is sometimes possible to obtain an acceptable reduction in soil-borne pathogens or nematodes by interplanting resistant varieties with local landraces. In some instances, new varieties may not be adopted because of differences in taste or other characteristics that render them unacceptable to farmers or consumers. Such

Under pressure from Rodpholus similis *nematodes, mulching can make a big difference for the health and production of plantain. The background portion of this West African stand has been mulched; the foreground has not.*

difficulties can be avoided by involving both farmers and consumers in breeding programs.

When new cultivars resistant to pests and diseases are being developed, their effects on weeds should also be considered. This is particularly true for varieties targeted on smallholder systems, in which weeding may account for up to 60% of all preharvest labor. Failure to take into account the effects of new varieties on weeds can create additional problems. For example, attempts to replace traditional tall varieties of rice with high-yielding semidwarf cultivars with erect (rather than drooping) leaves resulted in increased weed problems in some areas. On the other hand, cassava cultivars that spread and establish a complete ground cover in about 12 weeks require less weeding than do nonbranching forms. Some success has also been achieved in breeding crop varieties resistant to the parasitic witchweeds (*Alectra* and *Striga* species).

Reduced tillage

Conventional tillage immediately changes the structure of the soil microbial community, even if total microbial biomass is little affected. Under conventional tillage regimes, bacteria-based food webs predominate, and flushes of mineralization related to cultivation can lead to increased losses of nutrients and organic matter from the soil. In this way, tillage can increase the potential both for nitrate leaching and the emission of greenhouse gases such as carbon dioxide and nitrous oxide. In the long term, it can have deleterious effects on soil structure and biodiversity. Conventional tillage practices are generally unfavourable to soil mesofauna, macrofauna, and various fungi. Indeed, many of these organisms are extremely sensitive to perturbations of the soil. If tillage is minimized and crop residues are left on the surface, natural populations of many species in these groups can be enhanced and the spatial and temporal diversity of the subterranean food web increased. In zero-till or minimal tillage systems, fungus-based soil food webs predominate and nutrient leaching is reduced because nitrate levels tend to be lower. The choice of tillage system also has the potential to alter the level of fungal pathogens and the population density and diversity of nematode species. Conventional tillage, for example, can lead to soil compaction and a consequent increase in plant-parasitic nematodes at the expense of beneficial bacteria-feeding species.

Reduced tillage also has the notable benefit of cutting labor costs. Nevertheless, conversion of a conventional system to reduced or zero tillage may result in short-term increases in plant pathogens, invertebrate pests, and/or weeds. Thus, careful management is required in the first few years until the balance is tipped in favor of beneficial species.

Planting for Pest Management

The repellent or biocidal effects of particular plants can sometimes be exploited for the control of soil-borne pests and diseases. For example, the inclusion of some species of marigold (*Tagetes* spp.) in crop rotations has been shown to be a promising means of controlling some nematode species (e.g., *Meloidogyne* spp. and *Pratylenchus penetrans*).

In Uganda, a toxic plant is the basis of a novel means of managing East African mole rat or root rat (*Tachyoryctes splendens*). This mammal lives in subterranean burrows and causes considerable yield losses in many crops, especially cassava and sweet potato, by feeding on the roots and lower stems. Attempts to control the rats by traps, snares, and digging are only partially effective. A promising new approach involves planting *Tephrosia vogellii*, an indigenous leguminous shrub, around field margins and as scattered individuals throughout the field. The leaves and roots of *T. vogellii* contain rotenone, a natural insecticide that is also toxic to fish—and root rats. The shrub is easily established from seed. In fields heavily infested with root rats, it should be planted at 3 × 3 m spacings, with additional plantings at 1 m intervals around the field boundary. Other crops may be grown in the same field. After one year, the field should be clear of root rats, and the within-field *T. vogellii* plants can be removed. However, because *T. vogellii* is known to host some damaging species of root-knot nematodes, crops tolerant of these pests, such as maize, should be planted immediately afterwards.

Weeds, too, can be affected by the plant species growing around them. Allelopathy, the adverse effect of one species on another, may be mediated by the production of germination inhibitors or other root exudates. Such interactions can be exploited for low-input weed control. For example, interplanting of Kenyan maize fields with *Desmodium uncinatum* or *Calliandra calothyrsus* inhibits germination and growth of *Striga* spp.

Sanitation
Destruction of crop residues after harvest (to reduce pathogen inoculum or harborage areas for invertebrate pests) is a relatively simple technique for growers to adopt. However, in some cases, unexpected results have been obtained. For example, in one study, mechanical or chemical destruction of melon roots after harvest resulted in increased reproduction of the root-infecting fungus *Monosporascus* sp. compared with untreated controls. Again, however, such results may be the result of a relatively impoverished soil biota, with few antagonistic species.

Ridging and terracing
Growing crops on ridges or in raised beds can improve plants' ability to resist diseases exacerbated by compacted soils, such as fusarium root rot of beans. Such practices also reduce the incidence of diseases associated with wet soils, such as the seedling diseases and root rots caused by species of *Rhizoctonia* and *Pythium*. In the highlands of Africa, terracing has been shown to enhance the populations of some mycorrhizal fungi such as *Glomus callosum* and *G. occultum*, with consequent beneficial effects on crop growth.

Irrigation
Where irrigation is possible, it can help reduce damage by soil pests, both because some pests will be killed outright, and because well watered crops are better able to resist (or compensate for) damage to their roots.

Effects of Other Agricultural Practices
Development of a truly integrated approach to the management of soil biota will depend not only on adopting techniques for enhancing beneficial species, but also on techniques that mitigate or minimize the adverse effects of other agricultural practices.

Seed saving
Subsistence farmers generally retain their own seed for planting, a practice that has the advantage of preserving local cultivars adapted to the prevailing environmental conditions. While farmer-saved seed is often of good quality, problems can arise if it is contaminated with pathogens. If the seed germinates, it may produce seedlings of low vigor which are then predisposed to other soil-borne infections. Farmers should therefore be encouraged to save their best seed for planting, and perhaps to improve seed quality by careful management of the mother plants.

Growing tomatoes in Tanzania. Well watered crops are better able to resist root damage from soil pests and pathogens. But the presence of these organisms may increase farmers' workload by requiring them to irrigate more frequently than they normally would.

Pesticide use
Synthetic pesticides are rarely used by smallholder farmers, since they are normally prohibitively expensive except when subsidized by the State. In some cases, too, shortage of water is a constraint on their use. Where they are used, herbicides and foliar insecticides rarely reach the soil in sufficient concentration to directly affect most of the soil biota, although nitrifying bacteria are occasionally affected.

It has been reported that the decomposition of plant material treated with certain herbicides can trigger short-term increases in some plant pathogens. Fungicides and soil fumigants are the most damaging compounds, but again are rarely used except for some high-value crops. Seed dressings are the most economical means of deploying pesticides against soil pests. However, with the withdrawal of the persistent organochlorines (e.g., DDT and aldrin) in the 1980s, even seed dressings have become too expensive for most smallholders. Thus, interest in nonchemical methods of control has been revived. In recent years this interest has been further stimulated by the impending ban on methyl bromide. Under the Montreal Protocol, use of this pesticide, which is also a powerful ozone depleter, is to be eliminated in industrial countries by 2005, with some exemptions recently negotiated, and by 2015 in developing countries.

Application of inorganic fertilizers

Most fertilizers can inhibit local microbial activity, especially when they are applied in high concentrations. Some nitrogenous fertilizers can produce biocidal levels of ammonia. Furthermore, high levels of inorganic fertilizer, particularly in tropical soils, tend to reduce populations of mycorrhizal fungi. Some species may even disappear under such circumstances.

Clear cutting

Clear cutting forests or scrub can affect the soil biota for many years, with the severity of the impact being determined by soil characteristics, climate, and the nature of the subsequent plant cover. In general, the diversity of microbial species is little affected, but their relative abundance alters. Increases in the populations of some members of the microbiota may persist for 5 to 10 years after clear cutting, often accompanied by sizeable losses of soil nitrogen and other nutrients.

In termite-infested areas, clearing of woodland removes food and nesting sites. The species whose numbers increase after clearing are normally those with deeper subterranean nests (e.g., *Microtermes* spp.) or those that construct large mounds (e.g., *Macrotermes* spp.). *Microtermes* species, for example, have been known to increase from a mean density of 500 individuals per m^2 in woodland to 4000 in fields cultivated for eight years or more.

Burning

In contrast to the situation following clear cutting, the number of soil microorganisms generally declines after burning, mainly because soil organic matter is destroyed. However, although there is a perception that soil-borne pests and diseases are reduced by burning, this is seldom the case for plant pathogens. Temperatures are not usually high enough to kill all resistant (dormant) stages in the upper layers of the soil. The microbiota usually recovers rapidly following plant growth and litter accumulation, with the microflora probably re-establishing itself from the deeper layers of the soil and the microfauna from small patches of litter that escape burning. Some soil-borne plant diseases (e.g., vascular wilts caused by *Verticillium dahliae*) can thus occur even in newly cleared land, while root rots caused by fungi such as *Armillaria mellea* and *Rosellinia necatrix* can be a problem immediately after forest clearance but may quickly decline after a few cropping seasons. Furthermore, it has recently been found that viable bacteria and fungal spores can be transported considerable distances in the smoke from burning plant material, with the concomitant risk of spreading diseases to distant fields.

The weed flora also changes after bush clearance, with broad-leaved species predominating in the first few years and grass weeds gradually becoming more common thereafter.

Development of a New Pest: the Subterranean Burrower Bug

In the early 1980s, a new pest, the subterranean burrower bug (*Cyrtomenus bergi* Froeschner), was found on cassava roots in parts of Colombia and Panama. The bulk of the population is found in the top 20 cm of the soil. Feeding by both adults and immature burrower bugs allows soil-borne pathogens to enter the root tissue, resulting in the development of brown-black lesions and a considerable reduction in yield.

Since its discovery, the bug has spread to other parts of South and Central America. It attacks a wide range of crops, including potato, groundnut, sorghum, coffee, onion, asparagus, maize, and sugarcane.

The rapid rise of *C. bergi* to pest status is thought to be related to the reduction in plant diversity and simplification of agroecosystems that resulted from the intensification of local cropping patterns in its center of origin. Current research on the management of the bug focuses on intercropping, identifying sources of resistance, and the use of pathogens and parasites of insects, including fungi and *Heterorhabditis* nematodes. Research in Costa Rica has also shown that populations of the bug are consistently lower in zero-till maize plots than in conventionally plowed fields, presumably because plowing makes it easier for the insect to move through the soil.

The Way Ahead

Research Priorities and Approaches

In 2001, the Food and Agriculture Organization of the United Nations (FAO) informally surveyed the global community of soil biodiversity experts. It concluded that while a considerable amount of relevant research was being conducted on both natural and agricultural systems in various parts of the world, subtropical and arid regions were under-represented. Furthermore, while inputs of organic matter were the focus of considerable research effort, much less attention was being given to other important areas such as the biology of fungal root pathogens and the effects on the soil biota of tillage, agricultural chemicals, pH adjustments, and so on. The ecological effects of agricultural biotechnology and the relationship between soil biodiversity and the biological control of pests were also identified as areas that would benefit from more concerted interdisciplinary work. Some concern was also expressed over the general lack of expertise in natural resource management and development issues among those currently doing soil biota work.

These concerns should be addressed as a matter of urgency, since maintaining or enhancing soil biodiversity produces significant benefits both at the farm level, by improving returns on labor and other inputs, and at the national level, by preventing land degradation and by improving water quality. A rich and varied soil biota reduces the need for synthetic pesticides through the suppressive effects of naturally occurring biological control agents, helps prevent pollution by rapid detoxification of agricultural chemicals, and stems land degradation by improving soil structure. Furthermore, by improving nutrient cycling and reducing losses through leaching, a healthy and diverse soil biota can reduce fertilizer requirements.

To fully capitalize on the services provided by the soil biota, scientists and farmers in various ecological zones need to collaborate on the development of robust diagnostic tools and key principles for managing soil organisms. Standard protocols are needed for sampling each of the major groups of soil organisms, and also for determining their spatial and temporal variability. In the future, geographic information systems may contribute much to the documentation of different soil types and land-use histories. However, better understanding of the interactions between crops, soil fertility, and the soil biota will still be needed.

The following five research themes have been identified as being particularly important in this regard:

- The influence of the physical and chemical characteristics of soils on the distribution and abundance of soil pests, pathogens, and their natural enemies
- Techniques for reducing crop losses to pests through better management of soil fertility and plant health (including cultural practices and the effects of organic amendments)
- The effects of agrochemicals (including inorganic fertilizers) on key members of the soil biota
- Techniques for restoring soil fertility, with emphasis on methods suitable for resource-poor farmers in marginal areas
- The value of fungi, bacteria, and other organisms as indicators of soil health and fertility.

The research methods employed are also important since they directly influence the relevance of solutions to farmers, the foremost stewards of agricultural soils. Innovations that minimize pest and disease problems while maximizing the beneficial elements of the soil biota must take into account farmers' socioeconomic environment as well as their current understanding of biophysical constraints on production. Even if farmers typically lack advanced training in biology and soil science, they are usually highly observant, and many have considerable knowledge of the pests, weeds, and diseases that occur on their holdings. Participatory approaches to research for development offer practical means of maximizing farmer contributions to problem analysis and the design of solutions. This increases the chances of adoption, in part through an increased sense of local ownership of technology, and provides valuable feedback to scientists collaborating with farmers. Farmer organizations provide a practical venue for such joint learning.

The SP-IPM Response

The SP-IPM's Soil Biota Thematic Group is formulating a global project on soils that will promote sustainable and productive agriculture in Asia, Africa, and tropical America. Titled 'Better Lives from Healthy Soils: Integrated Pest Management in Soil

Agroecoststems', the research project will enhance the food security and livelihoods of poor farmers through soil ecosystem management for soil and plant health. It involves 11 international agricultural research centers and the national agricultural research systems (NARS) of 40 to 50 countries in the developing world. The participants will integrate research across centers, disciplines, crops, and ecological regions through a holistic approach.

The context of soil-borne pests is highly complex, with interactions among beneficial and harmful organisms, abiotic factors, cropping practices, and multiple crops within different geographic regions. This calls for a multidiciplinary approach that can be applied to different ecologies. The global project will take such an approach, creating a large pool of scientists who together will be able to achieve what no individual organization can. The involvement of a range of international centers and advanced institutions together with NARS and smallholder farmers of many countries will establish an interinstitutional network for the study of soil biota that will lead to the sustainable management of soil-borne crop pests. Field work will be done with the full participation of farmers and communities, thus ensuring a demand-driven process of innovation linked to strategic research.

A wide range of methodologies is currently being used in research on soil organisms. This poses a serious obstacle to scientific progress in the management of soil-borne pests. One of the objectives of the global project will be to standardize methodologies, thus increasing the value and comparability of the data generated. The development of databases and networks will speed up knowledge sharing and help participating scientists to make more efficient use of the data generated.

Supporting Public Policy

In many countries, legislation designed to protect the soil has lagged far behind measures intended to protect other natural resources such as air and water. Laws and policies to maintain or improve soil quality are urgently needed in many parts of the world. Population growth, land scarcity, and inappropriate land management techniques have all been identified as factors contributing to land degradation and hence to the need for policy intervention. However, if higher priority is to be given to the conservation and management of the soil and its associated biota, then policy makers need a better understanding of soil-based ecosystem services and of their monetary value. Developing a suitable policy framework for sustainable land management will require input from specialists in a variety of disciplines, as well as constructive dialogue between stakeholders at both local and national levels. Research institutions can contribute to the policy-making process by ensuring that adequate information is available, although the ultimate success of any legislative reforms will depend on the level of community and political support. Strengthening farmer knowledge and improving institutional linkages to promote information exchange should therefore be considered priorities.

In most cases, policy reform will involve harmonizing agricultural and environmental legislation to reconcile the apparently conflicting goals of high agricultural productivity and environmental protection, including biodiversity conservation. The overall aim should be to create a duty of care with regard to soil conservation and land use that has the broad support of the majority of stakeholders. Ideally, national policies should incorporate mechanisms for constant monitoring and modification, so that they can be adjusted to suit local conditions and so achieve truly sustainable development. Issues such as agricultural intensification must be handled with care in order to avoid potential conflicts. Although reduction in biodiversity is often seen as an automatic consequence of intensification, this need not be the case if the process is carefully managed. Indeed, landscapes composed of a mosaic of different levels of intensification can sustain very high levels of diversity, both above and below ground.

Recent initiatives aimed at developing a global policy framework for land use and soil conservation could be of tremendous benefit and should be encouraged. The aim should be to develop a set of guidelines encompassing the essential principles of sustainable soil management that will help individual countries develop suitable national strategies. Such an instrument would be invaluable in promoting the protection of soil resources and in helping to identify gaps in existing international legislation. The fundamental importance of the soil and its associated biota must be recognized at all levels if this valuable but often neglected resource is to be preserved and managed in the most appropriate way.

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Annexes

1. Classification Schemes for Soil Biota

Sized-based classification
This is probably the simplest and most widely used system for classifying soil organisms. It does have the disadvantage, however, that not all of the species in a particular taxonomic group will fall within the same size class.

Macrobiota. Organisms >2 mm in diameter and hence visible to the naked eye. This includes the various vertebrates that seek shelter or food in the soil (e.g., moles, badgers, mice), the invertebrates that live in or on the soil or surface litter (e.g., ants, termites, millipedes, centipedes, earthworms, spiders). Plant roots are sometimes also included in this group.

Mesobiota. Organisms ranging in size from 0.1 to 2 mm in diameter. Mainly small arthropods such as mites, springtails, proturans, diplurans, and symphylans. These taxa generally have limited burrowing abilities and tend to occupy soil pores, feeding on other invertebrates, organic matter, and microorganisms.

Microbiota. Organisms <0.1 mm in diameter. An extremely diverse and abundant group which includes fungi, bacteria, algae, cyanobacteria, actinomycetes, protozoans, rotifers, turbellarians, tardigrades, and nematodes.

Functional groups
Various classification schemes based on functional groups have been proposed. As yet, there is no general agreement on either the number of groups or their definition. The groups below are suggested as a general guide only.

Ecosystem engineers. Organisms that have a major impact on the physical structure of the soil through soil perturbation, formation of soil aggregates, and pores. These engineers (e.g., earthworms and termites) also influence soil organic matter, nutrient cycling, and biological activity.

Decomposers/litter transformers. Organisms involved in the breakdown of organic matter and hence nutrient cycling. These include various species of litter-feeding invertebrates (detritivores) and saprophytic fungi, bacteria, actinomycetes, and other microorganisms.

Microsymbionts. Microorganisms associated with plant roots that can enhance nutrient uptake or otherwise stimulate plant growth (e.g., mycorrhizal fungi and various rhizobacteria).

Soil-borne pests and pathogens. Invertebrate pests and pathogenic bacteria, fungi, and viruses.

Predators and parasites. This includes biological control agents (invertebrate predators and microorganisms) for all groups of soil-borne pests and pathogens.

Microbial transformers. Microorganisms involved in the transformation of carbon or other elements (e.g., nitrogen, sulphur, phosphorus), or the degradation of pollutants.

2. Selected Activities of Members of the SP-IPM Soil Biota Thematic Group

1. The Africa Rice Center (WARDA)
Integrated management of termites in upland rice production systems. Characterization of the extent, distribution, and severity of termite-related problems in West Africa, including interactions between termite damage and soil fungi.

2. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
Research on the major soil-inhabiting insect pests in the semi-arid tropics, including termites (*Microtermes* spp. and *Odontotermes* spp.), white grubs (*Holotrichia* spp.), and leafhoppers (*Hilda patruelis*); factors affecting aflatoxin contamination of groundnuts; control of the fungus *Sclerotium rolfsii*; vermicomposting of crop residues and other farm wastes; use of *Gliricidia* on farm-bunds as a source of nitrogen and organic matter; biological nitrogen fixation using legumes; sequestration of carbon in subsoil through the roots of pigeonpea; use of beneficial microorganisms in agricultural systems (including phosphorus solubilizers, nitrogen fixers, cellulose degraders, plant growth promoters, and pathogens of insect pests).

3. The World Vegetable Center (AVRDC)
Research on various methods of managing bacterial wilt of tomato (caused by *Raistonia solanacearum*) and fusarium wilt of tomato (caused by *Fusarium oxysporum* f.sp. *lycopersici*), including host plant resistance, organic soil amendments, endophytic antagonistic bacteria, and flooding. Investigation of root rot of tomato caused by *Pythium aphanidermatum*, and approaches to its control.

4. Centro Internacional de Agricultura Tropical (CIAT)
Current research on soil-dwelling arthropod pests includes projects on the burrower bug (*Cyrtomenus bergi*), white grubs (*Phyllophagus* spp.), the larval stage of the bean foliage beetle (*Ootheca* spp.), and biological control with entomopathogenic fungi. Research on soil-borne diseases is focused on pathogens causing root rots, including *Pythium* spp., *Fusarium* spp., *Phytophthora* spp., *Macrophomina phaseolicola*, *Sclerotinium rolfsii*, and *Rhizcotonia solani*. Research on disease control emphasizes cultural practices, host plant resistance, and biological control.

5. International Center for Agricultural Research in the Dry Areas (ICARDA)
The main soil-borne problems of cereals currently under investigation include various root rots (caused by *Cochliobulus sativus, Gaeumannomyces graminis* var. *tritici*, and *Fusarium* spp.), cyst nematodes (*Heterodera* spp.), ground pearls (*Porphyrophora tritici*), wheat ground beetle (*Zabrus tenebrioides*), and wheat scarab beetle (*Anisoplia austraca*). For legume crops (chickpea, faba bean, and lentil), the major soil-borne pests are root rots (caused by *M. phaseolina*, *R. solani*, and *Fusarium* spp.), broomrape (*Orobanche* spp.), wilts (*Fusarium oxysporum* f. sp. *ciceris* and *F. o.* f. sp. *lentis*), and weevils (*Sitona* spp.). Research projects on these pests focus on host plant resistance, cultural practices, and biological control.

6. UMR INRA-Université de Bourgogne : Biochimie, Biologie Cellulaire et Écologie des Interactions Plante-Microorganismes (BBCE-IPM)
Research on the biological control of soil-borne plant pathogens, including the use of organic amendments to increase the level of soil suppressiveness. Studies are targeted at the most damaging soil-borne fungi, including *Pythium* spp., *Phytophthora* spp., *R. solani*, and *F. oxysporum.*

7. Centro Agronómico Tropical de Investigación y Enseñanza (CATIE)
CATIE's pest management research currently focuses on developing biological and cultural controls for key pests or diseases of vegetables (such as whitegrubs*, Phyllophaga* spp.); coffee (such as the fungus *Mycena citricolor*); plantains and bananas (black sigatoka disease and nematodes); and cacao (*Monilia* spp.). Particular attention is being paid to induced host resistance, including the use of endophytic fungi against nematodes and fusarium wilt in the *Musaceae*.

8. Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT)
Research on cultural practices and host plant resistance for the control of various soil-borne problems, including *Striga* spp., cereal cyst and lesion nematodes, crown rot, and common root rot; assessment of the effects of agronomic practices (such as reduced tillage and crop rotation) on soil microorganisms.

9. University of Jordan, Faculty of Agriculture
Research on plant-parasitic nematodes (mainly *Meloidogyne javanica* and *M. incognita*) and pathogenic fungi (including *Fusarium*, *Verticillium*, *Rhizoctonia*, and *Sclerotinia*) in relation to various vegetable crops. Studies on these pests are addressing their ecology, host-parasite relationships, and methods of control (including soil solarization, resistant cultivars, and organic soil amendments).

10. International Institute of Tropical Agriculture (IITA)
Research on the use of fungal pathogens for the control of soil-dwelling insects (e.g., *Metarhizium* spp. for termite control and *Beauvaria bassiana* for banana weevils); use of *Trichoderma harzianum* to reduce endophytic infection of maize stems by *Fusarium verticillioides*; strategies for the control of *Aspergillus flavus* and for reducing aflatoxin contamination of maize; biological control of banana weevil with hymenopteran egg parasitoids and dipteran larval parasitoids; and the pest status and management of plant parasitic nematodes.

11. CAB International
Research on weeds, fungal and bacterial plant pathogens, plant parasitic nematodes, and entomopathogenic fungi and nematodes. CAB International also has a strong farmer participatory training and research group with expertise in many different crops.

Front cover (left to right):

Top row:	*Weeding rice in the Philippines. Besides being a huge drain on farm labor, weeds can act as alternative hosts for some soil-borne pests and diseases. Photo: Chris Stowers, Panos Pictures.*
	Soil erosion in Ntcheu, Malawi.
Middle row:	*North African cereal cops afflicted with dryland root rots. Photo: ICARDA.*
	The banana weevil, Cosmopolites sordidus*, is a major pan-tropical pest of banana and plantain. Photo: Cliff Gold, IITA.*
Bottom row:	*Root-knot nematode on sweet potato.*
	Growing tomatoes in Tanzania.
	Fungus fruiting body from the forest floor in Ibadan, Nigeria.

Photos: All photos by Danny Coyne, IITA, unless otherwise indicated.

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SP-IPM members

Asian Vegetable Research and Development Center (AVRDC)
PO Box 42, Shanhua, Tainan 741, Taiwan
Centro Internacional de Agricultura Tropical (CIAT)
AA. 6713, Cali, Colombia
Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT)
Apartado Postal 6-641, 06600 Mexico D.F., Mexico
Centro Internacional de la Papa (CIP)
Apartado 1558, Lima 100, Peru
International Center for Agricultural Research in the Dry Areas (ICARDA)
PO Box 5466, Aleppo, Syria
International Centre of Insect Physiology and Ecology (ICIPE)
PO Box 30772, Nairobi, Kenya
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
Patancheru 502 324, Andhra Pradesh, India
International Institute of Tropical Agriculture (IITA)
PMB 5320, Ibadan, Oyo State, Nigeria
International Plant Genetic Resources Institute, International Network for the Improvement of Banana & Plantain (IPGRI-INIBAP)
Parc Scientifique, Agropolis 2, 34397 Montpellier, Cedex 5, France
International Rice Research Institute (IRRI)
PO Box 933, Manila, The Philippines
West Africa Rice Development Association (WARDA)
01 BP 2551, Bouaké, Côte d'Ivoire
The World Bank, Agriculture and Rural Development, Environmentally and Socially Sustainable Development Network
1818 H Street N. W., Washington, D.C. 20433, USA
CABI Bioscience
Silwood Park, Buckhurst Road, Ascot, Berkshire, SL5 7TA, UK
FAO Global IPM Facility
Viale delle Terme di Caracalla, 00100 Rome, Italy
BioNET INTERNATIONAL
Bakeham Lane, Egham, Surrey, TW20 9TY, UK
International Association for the Plant Protection Sciences (IAPPS)
NSF Center for IPM,
Box 7553, NCSU, Raleigh, NC 27695-7552, USA
Pesticide Action Network (PAN)-Africa
BP 15938, Dakar-Fann, Senegal
CropLife International
Avenue Louise 143, B-1050 Brussels, Belgium

SP-IPM Secretariat

IITA, 08 BP 0932 Tri Postal, Cotonou, Republic of Benin
www.spipm.cgiar.org

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