The CGIAR Systemwide Program on Integrated Pest Management

Integrated Pest Management and Crop Health — bringing together sustainable agroecosystems and people's health





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White Paper to provide guidance to the CGIAR Consortium, its research partners, donor agencies, and other institutions and organizations working towards reducing world poverty and hunger, improving human health, and fostering agricultural ecosystems

This White Paper is the result of a workshop organized by the CGIAR's Systemwide Program on Integrated Pest Management (SP-IPM) from 3 to 5 March 2010 in Bonn, Germany, with the financial support of CropLife International, German Federal Ministry of Economic Cooperation and Development, Italian Ministry of Foreign Affairs, and Swiss Agency for Development and Cooperation. Eminent international experts in fields such as crop and post-harvest protection, technology transfer, human and institutional capacity building, and others from industry and the civil society attended the workshop.

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Cover photos: SP-IPM

Correct Citation: Integrated Pest Management and Crop Health — bringing together sustainable agroecosystems and people's health. White Paper. SP-IPM Secretariat, International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. 17 pp.

Contents

Acronyms and abbreviations

ABS	Access and Benefit Sharing
ARPPIS	African Regional Postgraduate Programme in Insect Science
CBD	Convention on Biological Diversity
CGIAR	Consultative Group on International Agricultural Research
CHM	Crop health management
CRSP	Collaborative Research Support Programs
FAO	Food and Agriculture Organization of the United Nations
GIS	Geographic Information Systems
GPS	Global Positioning Systems
IPM	Integrated Pest Management
LFD	Lateral flow device
SP-IPM	Systemwide Program on Integrated Pest Management

Executive summary

- Improvements in Integrated Pest Management (IPM) can lead to sound crop health management programs that contribute to resolving the unprecedented challenge of food security facing the international community, particularly in the wider contexts of climate change, trade globalization, environmental protection, and poverty alleviation.
- Harmful insects, fungal, viral, and bacterial pathogens, nematodes, rodents, and weeds – which are collectively referred to in this document as ***pests*** – are major constraints to agricultural production, productivity, and improved performance in agricultural systems. They cause chronic qualitative and quantitative losses of up to 40% of the attainable yield in major food and cash crops.
- Further significant losses occur after harvest because of inappropriate storage methods that fail to protect the harvest from animal pests and pathogens. In addition, toxins caused by fungi in stored produce have severe impacts on human and animal health, and are responsible for enormous losses for trade in global markets.
- Reducing pre- and post-harvest losses caused by pests is a significant contribution towards improved food security and safety, and better market access. Traditional and modern pest management technologies need to be combined in new packages to operate in different socio-economic and ecological contexts.
- Success in the near future requires a more balanced approach to the management of crop health and a significant improvement in the approaches and scientific methods of IPM used to address crop losses. There is a need to move away from isolated single-pest management towards crop health in general and an agricultural system performance that is congruent with farmers' concerns and with the broader pest situation.
- Small-scale farmers in developing countries can participate not only in domestic markets but also in international trade by producing food at international levels of quality. They can increase their yields and the quality of their produce if given the proper tools for doing so.
- Advanced pest management tools are presently not available for most of the farmers in the least developed countries because these have not been suitably adapted. Yet, many farmers have the ability and resources to implement modern IPM.
- Because of recent advances in the specific field of plant protection, but also in a range of other scientific areas (agrophysiology, breeding, biotechnology, agronomy, economics, and sociology), IPM can produce definite outputs and outcomes with practical applications for improved crop health, sustainable agriculture, and global food security and safety.
- Across CGIAR centers, however, there is a dire need for research to be strengthened so as to improve established IPM methodologies while simultaneously making use of novel methods, such as pest risk assessment, crop loss modelling, precision agriculture, biotechnology, remote sensing, and decision theory methods.
- Capacity building is needed to improve knowledge generally of what crop health is and how to adopt IPM innovations within the extension services and at the farmers' level. Conversely, national extension systems need support for their improvement and modernization to ensure the introduction and use of new IPM strategies and technologies to have an impact on the security of crop yield.
- Substantial increases in food production can be attained relatively quickly by upgrading IPM strategies and linking them to the other sciences with an impact on crop health as a whole. This, however, requires adequate long-term financial investment in measures that reduce yield losses today. Investments that are limited to promoting agronomic and germplasm improvements, and targeted only at increasing yield potential, often ignore the fact that pests are causing massive losses now – losses that could be avoided.

Background

Crop losses

The harmful insects, pathogens, nematodes, weeds, rodents, and other animals – referred to as pests – have an impact on crop cultivation through a cascade of events linking injuries they inflict on crop stands, the losses in crop quantity and quality these injuries may cause, and the economic costs this damage may generate.

These pest problems are responsible for significant losses that are estimated to vary from 26 to 40% of the attainable (uninjured) yield in major food and cash crops (Oerke 2006). Even greater crop losses occur very often, depending on the nature of the crop, the nature of the harmful organisms, and the production situations, as well as on climatic conditions favoring pest outbreaks and damage. When the proportion of food that perishes after harvest to molds, insects, and rodents is added, total losses are even greater. Worse still, another large percentage of harvested food is contaminated with mycotoxins, pesticides, and microbial pathogens, making it unfit for human consumption and trade (Leslie et al. 2008; European Commission 2005) and causing other, often undocumented, economic losses.

Crop losses amount to a double penalty on farmers, communities, consumers, and societies: first, there is the lost harvest, but then there are the wasted resources invested in the crop, including water, fertilizer, seeds, labor, and energy. Because of this second, often hidden, component of crop losses, pests have a very serious bearing on the sustainability of both agricultural systems and of the environment in which they develop. This is the importance and magnitude of the task confronting those concerned with crop protection and food security in underdeveloped countries. The task is even bigger, as farmers often use low cost, highly toxic, pesticides banned elsewhere, in the absence of other, more appropriate but costly tools that are safer for human and environmental health.

Impacts of Integrated Pest Management (IPM)

By bringing technology to farmers, IPM has been instrumental in increasing agricultural productivity and sustainability and reducing pesticide misuse in the developing world. For example, new methods for propagating virus-free seed roots and vines for sweetpotato in Shangdong Province, China, augmented annual sweetpotato production by 30%, a productivity increase valued at US$145 million annually (Fuglie et al. 1999). Meanwhile in Africa, the introduction and release of the exotic wasp *Anagyrus lopezi* succeeded in controlling the exotic and invasive cassava mealybug *Phenacoccus manihoti*. This project showed internal rates of return of US$200-500 for each dollar invested by donor organizations (Neuenschwander 2003). Without this and other interventions to control cassava pests and diseases, it is likely that cassava would have all but ceased to exist in Africa years ago, and with it would have gone the food security of millions of Africans. IPM in potato and sweetpotato in Latin America has shown an internal rate of return on investment of 27-49%, a very high level when compared with other types of investment in agricultural research; moreover, the adoption of IPM brought additional net benefits to farmers ranging from US$100 to 536/ha (Ortiz et al. 2009). Pretty et al. (2006) have also shown that IPM technologies have effected a decline of 71% in pesticide use, while yields increased by 42%. Different approaches based on IPM have been developed in the French West Indies in banana cultivation and have led to a 65% decrease in pesticide use over the last 10 years (Côte et al. 2009).

Host plant resistance is a pro-poor, extremely efficient, environmentally friendly, and sustainable foundation of any attempt to mitigate pest losses. However, breeding, like any other single technology, has not solved and cannot solve all pest problems on its own. For many pests no adequate sources of resistance have been identified in crops or their wild relatives, or these have not been successfully incorporated into advanced breeding lines and varieties. IPM is needed to protect the sources of resistance presently available and to supplement situations where only lower levels of resistance or tolerance are available.

Seldom, if ever, are solutions durable over time in an evolutionary sense. This can be seen in the breakdown of resistance to pests in a number of crops, and the constant development of insect and fungal resistance to pesticides. Crops do not suffer from one pest alone. Examples are abundant of cultivars resistant to a particular pest but susceptible to others far more difficult to control. Silver bullets are rare occurrences in plant protection. Considering the approaching food insecurity, there is an urgent need to modernize IPM programs and to continually integrate established and new technologies for the improvement of crop, environmental, and human health.

Change in approach

The sustainable production of nutritious and healthy food at levels that keep pace with the growth of world population urgently requires a change in mindset. Efforts that address crop production, crop protection, and sustainable agriculture separately and deliver independent component technologies should be supplanted by integrated multidisciplinary approaches that deal with the following.

1) Effect sustainable increases in food production
2) Counteract the impacts of climate change on pest spread and damage potential
3) Reduce contaminants in the food chain, from the field to post-harvest global trade
4) Increase agroecosystem resilience
5) Improve farmers' access to decision-making tools that support specific IPM practices.

These disciplines need to work more closely together in an approach that looks at crop health management (CHM) as a whole (Savary et al. 2006). CHM builds on past successes in individual component sciences and aims at their integration across crops. Crop health is dependent on maintenance of soil fertility and prudent water management as well as the use of varieties suited to local conditions. A major element in maintaining crop health is the naturally occurring ecosystem services, such as predators, parasites, and antagonists for all pests, especially insects. Other control interventions are standard practices in crop protection such as rotation, planting form, trap cropping, mulching, biorationals, pheromones, alleomones, and the judicious use of safe pesticides.

During the past decade, higher education institutes, research managers, and investors have shifted focus away from traditional crop protection towards crop resistance with a subsequent decline in resources for broader plant health and IPM. This has reduced the ability of crop protectionists to take full advantage of the many new technologies available today for managing crop health. The momentum and impact that IPM has had in the past on pests, especially insects, diseases, and weeds as they affect crop health and food security need to be expanded and taken to a new level. A potential exists for yields to increase well beyond those attained by the Green Revolution while reducing human and environmental costs.

Crop health is a major element in the highly productive systems of modern agriculture. Developing countries, where modernization has not yet taken complete hold, will continue to be deprived of adequate food and access to global markets if they do not deploy the wide range of IPM technologies available for crop health stability. The fact that a vast proportion of food produced is still lost to pests or contaminated by mycotoxins and pesticides is having a serious impact on basic needs and has prevented many countries from entering overseas markets and earning desperately needed foreign income. If the least developed countries are to be part of the global community, this situation needs major correction, and improved IPM systems are the key to achieving it. Farmers in developing countries can be part of the big picture and benefit from a wide range of IPM technologies that promote crop health and domestic food security (Table 1).

Table 1. Relative returns from selected crop health management options to land owners and farm laborers (3 = high, 2 = medium, 1 = low).

Source: G. Norton 2010, modified

	Crop health management options					
Factor owners	Cultural practices[1]	Physical control[2]	Biological control[3]	Biopesticides[4]	Host plant resistance[5]	Chemical pesticides[6]
Small land owners	3	2	2	2	3	1
Medium land owners	2	2	3	3	3	2
Large land owners	1	3	3	3	3	2
Laborers	3	2	1	2	1	1

1. Mulching, pruning, early harvesting and planting, grafting, roguing, host-free period, hand weeding
2. Soil solarization, hot water treatment, pheromone traps, sticky traps, bagging fruits, hand picking insects, irradiation
3. Classical biocontrol, augmentative release, exchange or redistribution of natural enemies between regions
4. *Trichoderma, Pseudomonas*, *Bacillus subtilis*, nuclear polyhedrous virus, Bt, Neem, entomopathogenic fungi, and nematodes
5. Conventional and marker assisted breeding, genetically modified crops
6. Synthetic insecticides, nematicides, fungicides, herbicides. (Relative returns in the short and long run may differ, and these ratings are short run. They also differ by pesticide class.)

This document emphasizes how improvements in IPM can lead to sound CHM programs that contribute towards resolving the unprecedented challenge to food security facing the international community. This, however, requires looking at CHM in the wider context of climate change, trade globalization, environmental protection, and the role of agriculture for economic growth to alleviate poverty. This document also analyzes the policy and structural environment that has to be in place to reap the benefits of improved crop health.

Crop health and Integrated Pest Management in the context of greater challenges

Food security has reemerged as a core development concern as increasingly severe droughts and flooding, rising energy prices, low global food stocks, changing urban diets, and growth in biofuels converge to push up the prices of basic commodities around the globe. Future climate change and spikes in energy prices could further disrupt food production and bring more uncertainty and volatility to food prices, with disproportionate effects on the world's poor. Moreover, increasing population pressure and the degradation of ecosystem services that underlie long-term agricultural sustainability will bring into sharp focus the prospect of greater political conflict in the most food insecure regions of the world. Although it is impossible to quantify exactly how strongly climate change will influence the global food supply, the consensus is emerging about the likelihood of the following impacts:

- Frequency and intensity of extreme events (heat waves, droughts, and floods) are likely to increase, leading to reduced yield levels and disruptions in production.
- Night-time temperature rises and changes in timing, and magnitude and distribution of precipitation are likely to increase moisture and heat stress on crops, with the subtropical regions being among those most affected.
- Long-term agricultural productivity will be increasingly threatened by heightened risks of soil erosion, runoff, landslides, and pest invasions.
- Climate change impacts are magnified where poverty is pervasive and social safety nets are weak.

Sensitivity to climate change is magnified in agricultural systems that contend with a high degree of non-climatic stresses, including low and declining soil fertility, soil and water degradation, and new, changing, and shifting pest pressures.

Meeting the challenges that agriculture will face as it adapts to climate change and other global drivers of change – trade, population growth, ecosystem degradation, and urbanization – will require significantly greater expenditure on agricultural research and development. Also policies will have to be formulated to integrate natural resource management better with agricultural production and measures to increase household access to new production and crop protection technologies.

One area where increased investment in science would significantly enhance efforts to more effectively manage current and future risks from pests is CHM. For example, climate change could impair the reliability of current CHM strategies, requiring additional resources to develop new knowledge systems and appropriate IPM measures to counter new pests or the intensification of existing ones. A two-pronged strategy, therefore, needs to be developed that would aim at managing current pest threats more effectively while at the same time laying a foundation for addressing future threats. Such a strategy will produce a strong adaptation-development synergy (as described in Box 1), particularly in the developing world where adequate resources to manage pests are lacking.

In developing long-term investment strategies for adapting CHM systems to meet future challenges, the priority should be to undertake comprehensive research and assessment of how pest threats could evolve under climate change and whether current and emerging IPM technologies will be adequate to offset these threats to crop health. This information is notably absent in the most recent assessment by the Intergovernmental Panel on Climate Change, despite the threat that biotic stresses pose to future food production and food security. In addition, investments in infrastructure, training, and education are needed in order to manage existing pest problems better, as well as to develop sufficient knowledge and capacity to aid the plant protection specialist – and finally the farmer – in responding to new threats.

Box 1. Major issues to which crop health management will contribute

Economic sustainability	Reduces sanitary and phytosanitary risks. Provides a framework for the payment of ecosystem services. Improves profitability. Reduces externalities.
Environmental sustainability	Conserves natural resources including fossil fuels, soils, water, and biodiversity. Provides ecosystem services: pollination, clean waterways, watershed protection, diverse landscapes, biodiversity-rich ecosystems. Reduces the recurrence of pests and resurgence of secondary pests.
Social/cultural sustainability	Changes the attitudes of farmers towards stewardship. Increases farmers' knowledge of ecosystem function. Is locally adaptable and compatible with social and cultural values. Allows different weighting of desired outcomes based on social norms.
Poverty alleviation	Generates local input markets. Generates economic growth through increased production.
Climate change/land use	Mitigates climate change through reduced carbon emissions and increased sequestration. Reduces the need to convert forest land into agricultural land. Provides a framework for adaption to pest outbreaks and changes for risk distribution.
Food safety and health	Reduces the risk of mycotoxin exposure. Protects the efficacy of pesticides in the control of vectors of human diseases. Reduces the risks of pesticide residues in food, feed, and fiber. Improves water quality through reduced pesticide runoff. Minimizes the risk of contamination by human pathogens.
Food security	Reduces the risks of pre- and post-harvest losses. Increases productivity. Reduces food prices to benefit consumers. Improves the availability of food at all levels of consumption.

Improving the impact of IPM on crop health management

Science-based solutions

Despite the obvious gains from IPM, the adoption rates of many new and effective technologies are still low. Many of the reasons are described below in the chapter on policies and other factors.

The CGIAR centers and their associated research institutions have decades of experience in IPM, soil fertility research, plant breeding, agronomy, and socio-economic research, and are very well positioned to provide science-based solutions for CHM in developing countries. To build and expand on past successes, collaboration among centers, in partnerships with advanced research institutions and private industry, has been fostered and harnessed within the CGIAR Systemwide Program on Integrated Pest Management (SP-IPM).

Together these partners are focusing on three major cross-cutting research areas: *Climate Change; Food, feed, and environmental safety*; and *Agroecosystem resilience* (see Box 2). Within these areas the newest research methodologies are being employed to obtain a better understanding of the nature and extent of abiotic and biotic stresses to crops in a range of agroecological zones and production systems. This will ultimately support the development of advanced technologies for a sustainable increase in crop yields at the farm level in developing countries. This team of IPM scientists also engages in capacity development at the policy-maker, research manager, scientist, and extension agent levels to improve the capacity for innovation, adaptation, and adoption in partner countries. This collaborative research within SP-IPM fits squarely into the emerging concept of Consortium Research Programs developed as a new mode of delivery for cutting-edge CGIAR research.

Box 2. Major areas of collaborative IPM research between CGIAR and associated centers and their contributions to the proposed Consortium Research Programs

Area 1. Climate change. The multiple impacts of climate change could significantly reduce the effectiveness of current IPM strategies, leading to higher crop losses. Better knowledge and understanding of pest behavior under different projected climatic scenarios are required to adopt and develop new IPM technologies to respond to threats resulting from climate change. It is predicted that changing climates will cause pests to spread further, covering more areas that increasingly become suitable for them, and to multiply faster in current areas. The potential effect of climate change on insects, and the responses of individual species, could lead to major shifts in biodiversity and species composition. In this respect, divergences in the thermal preferences of pests and their natural enemies might lead to a disruption of temporal or geographic synchronization, increasing the risk of pest outbreaks. Additionally, increased concentrations of CO_2 and tropospheric ozone in the atmosphere may alter the secondary chemistry of crops and their susceptibility to insects and diseases. Increased tropospheric ozone is a particular problem in many areas of the developing world and crops such as rice, wheat, soybean, mung bean, groundnut, and chickpea are already suffering the effects of high regional ozone levels. The CGIAR and associated centers respond to threats resulting from climate change by carrying out collaborative research and surveillance to evaluate the changes in cropping systems and production practices affected by it; and to find out which cropping systems are the most vulnerable to increased threats from pests and disease due to climate change. The knowledge gained in these areas will allow partners to develop and recommend new IPM options to counter current threats and future potential challenges. This area is strongly related to Consortium Research Programs 7, *"Climate change, agriculture, and food security,"* and 3, *"Sustainable staple food productivity for global food security."*

Area 2. Food, feed, and environmental safety. Pesticide residues, heavy metals, and microbial and mycotoxin contamination in food and animal feed are serious health risks. Aflatoxin, a toxin produced by fungi, is particularly dangerous to humans and animals, causing liver cancer, stunting, low weight, and high disease susceptibility. These contaminants also make it necessary to have stringent quality standards on food products, thus depriving the farmers and exporting countries of a vital income. The threat to food and feed safety is addressed by developing new varieties of crops with resistance to fungal colonization, reduced toxin production, and swifter toxin degradation. Scaling up and scaling out biological control will provide effective solutions to food and animal feed contamination. The development and application of cost-effective mycotoxin detection tools increases opportunities for exporting agricultural produce and allows for the mitigation of health risks from local food supplies. Developing alternatives to pesticides and increasing farmers' awareness and knowledge about the negative impacts of pesticides will enhance the benefits of existing and new crop health management technologies in this area. This area is strongly related to Consortium Research Programs 4, *"Agriculture for improved nutrition and health,"* and 2, *"Policies, institutions, and markets for enabling agricultural incomes for the poor."*

Area 3. Agroecosystem resilience. High genetic crop and cropping system diversity, diversified landscape structures, and appropriate agricultural practices are important to maintain long-term agricultural productivity and sustainability. Relatively little research has been conducted to understand agroecosystem resiliencies and soil health as an approach to control pests. Conservation agriculture and the enhancement of natural enemies to keep pest populations under a control threshold are major elements of CHM. Ideally, the agroecosystem is developed to function in a largely self-regulating manner to counteract a range of pests and diseases and to produce high yields of good quality with minimal impact on the environment. The use of companion cropping for the integrated management of soil fertility also forms an important part of CHM, enhancing agro-biodiversity and sustaining profitable agriculture. Diverse soil biota will not only help to prevent losses due to soil-borne pests, but also increase the rate at which organic matter and toxic compounds decompose, and improve nutrient recycling and soil structure. CGIAR centers focus on broadening the understanding of the ecological relationships in agricultural production systems to improve soil, root, and plant health in key regional or global cropping systems of the tropics and subtropics. This area is strongly related to Consortium Research Programs 1, *"Agricultural systems for the poor and vulnerable,"* and 5, *"Durable solutions for water scarcity and land degradation."*

Advances and innovations in CHM

The CGIAR centers are already at the forefront of deploying genetic resources from their in-trust germplasm collections and advanced crop breeding populations for improving the resistance of crops to biotic and abiotic stresses. However, in many cases, inadequate or no sources of resistance have been found in established crop germplasm or wild relatives. Whereas IPM supports the effective use of resistance in crops, crop protection has to act independently where adequate host plant resistance does not exist to keep pests under control.

Assessing and improving the health of agroecosystems and their resilience against potential threats, such as water shortages, heat stress, and insect and fungal pressures, can be furthered by using advanced diagnostic tools that can detect changes in the functioning of plants and systems at multiple scales. Employing these tools should enable the more targeted and efficient application of any necessary CHM strategy, thereby ensuring its longevity and effectiveness. Such diagnostic technologies may be employed at the farm level, such as pest reporting synchronized via mobile phone messages, or the precise assessment of soil health across farms. They may also be implemented on a much larger scale, as with the remote sensing of pest outbreaks or stresses.

The key to the successful implementation of any of the technologies highlighted in Box 3 will be their flexibility to integrate with and improve other aspects of the CHM strategy. It must be emphasized that enabling conditions have to be in place for farmers and food producers to take full advantage of these technologies.

Box 3. Innovative technologies for crop health management

Remote sensing: The ability to accurately assess the health of agro-ecosystems is crucial to determining the need for and effects of any CHM strategy. Remote sensing is one emerging tool available to IPM for ecosystem surveillance. Remote sensing is a very flexible tool with the potential to offer new insights into crop health at temporal and spatial scales that would have required intensive human efforts in the past. Remote sensing has the potential to be an excellent tool for large-scale assessment and management of crop health. Different forms of spectral assessment are being used in predicting the development of disease prior to symptom expression, in crop breeding for the early detection of resistance, and for pest assessment in ecosystems.

Precision crop protection: Although this is often considered expensive and primarily useful for large farm operations, it is adaptable to developing countries with the necessary infrastructure and larger farm units. Precision technology can be used to accurately determine the presence and impact of pests on a crop in a particular field or part of a field. Pests can then be mapped to GPS coordinates to target the delivery of specific resistant varieties, biocontrol agents, or pesticides. Precision technology can have an impact in extensive production systems (i.e., for rice, maize, and wheat) where it allows the optimum use of inputs for CHM and crop productivity, while reducing the need for large-scale sampling and extension input (Oerke et al. 2010). Many small farmers already practice a form of precision agriculture without any technological aides. They know the variability in their fields and try to use certain inputs on a refined scale. They are well-positioned to improve if the information is made available on what to do, where, and when, in response to the needs of small but variable land plots.

Pest risk assessment: Understanding the shifts in pest range or the intensification of pest damage and predicting where adaptation measures may be required are key goals of any strategy to manage plant health in a region. Pest phenology modelling and risk mapping using Geographic Information Systems (GIS) (Sporleder et al. 2008) are innovative tools to assess and understand how pests may spread across regions. Process-based phenology models use a number of functions to describe temperature-driven processes, such as development, mortality, and reproduction in insect species. They produce full life-table parameters to predict key population parameters such as net reproduction rate, mean generation time, intrinsic and finite rate of increase, and doubling time. For an analysis in space of the risk of pests, generic risk indices (Index for Establishment, Generation Number, and Activity Index) can be visualized in GIS maps using advanced Insect Life Cycle Modelling tools and software (Sporleder et al. 2009).

Early disease detection tools: Early detection of the appearance of diseases or their causal agents followed by rapid and accurate identification is essential if correct control measures are to be deployed. Nucleic acid sequencing and advances in DNA bar-coding, microarray technologies, and lateral flow devices promise to revolutionize plant diagnostics in the near future (Boonham et al. 2008). DNA microarrays printed on the bottom of an Eppendorf, which can be read with a regular document scanner, have the capability to detect many pathogens simultaneously. Little training is required and thus the technology can be implemented in any laboratory without the need of specialized or expensive equipment. DNA bar-coding, on the other hand, relies on the generic amplification and sequencing of a nucleic acid sequence that provides a 'bar-code' unique to any specific organism, enabling its rapid and precise identification. In-field methods for plant diagnostics are dominated by a single format: the serologically based lateral flow device (LFD). The 'pregnancy kit' type LFDs are extremely robust and easy to use and interpret, but are limited to known pathogens for which antisera are available.

Landscape management: The impact of new forms of landscape management on crop production, and especially on limited water resources, can lead to losses if this is not designed with pests in mind. Pests can bring greater reductions in crop water use efficiency under poorly designed systems. New or modified crop and landscape management approaches such as 'push and pull', intercropping, relay and sequential planting, border strips, and living mulches can be used for the management of pests while simultaneously conserving water resources. The incorporation of living mulches is an example of an innovative cropping system for integrated soil and pest management in cereal-based farming systems, minimizing pest infestation, sustaining permanent soil cover, and increasing soil fertility (Chabi-Olaye et al. 2005). Similarly, the intercropping of trees and coffee with banana can alter pest pressure and spread (Staver et al. 2001). Intercropping and mulching are effective in the management of soil-borne pests in perennial crops, by stimulating beneficial microorganisms that regulate densities of pests such as plant parasitic nematodes (Pattison et al. 2003).

Seed, seedling, and seedbed treatment: Seeds coated with chemical or biological agents protect plants from a wide range of pests and diseases in the early stages of growth, ensuring a good establishment and higher yield. Seed treatments also reduce the risk of farmers and the environment being exposed to pesticides. Advances have been made in coating maize seeds with herbicides (Kanampiu et al. 2002) and sorghum seeds with the mycoherbicide *Fusarium oxysporum* f. sp. *strigae* (Elzein et al. 2006) to combat the parasitic weed *Striga hermonthica*. Bacterial seed treatment to control soil-borne pests is marketed in many countries both the developed and the developing (Hallmann et al. 2009). The use of mutualistic fungal endophytes to manage pests and enhance plant tolerance is being tested in bananas, rice, vegetables and ornamentals (Dubois et al. 2006a, Backman and Sikora 2008, Sikora et al. 2008, Hallmann et al. 2009, Huong et al. 2009, Menjivar 2010,). Rhizobacterial treatment of potato and rice is also considered practical (Oswald et al. in press; Padgham and Sikora 2007) for pest management. The development of beneficial microorganisms as a component of seed, seedbed, and seedling treatment technology is moving forward quickly in many countries and could benefit developing countries in the near future. Partnerships with the private sector are crucial when the newest technologies are to be adapted to the needs of small-scale farmers, and ensure the structures are in place through which they receive high quality seeds and seedlings that remain protected when placed in the hostile agroecosystem environment (Dubois et al. 2006b).

Behavior modification: Semio-chemicals control the communication of insects both interspecific (allelochemicals) and intraspecific (pheromones). They are used in pest management either alone for pest monitoring and decision-making, for mass trapping or mating disruption, or in combination with insecticides, sterilants, or insect pathogens, the so-called 'attract-and-kill' strategy (El-Sayed et al. 2009). Additionally, semio-chemicals released by plants can repel insect pests from the crop ('push') and attract them into trap crops ('pull'). In this way the push-pull approach has been developed for controlling insect pests and the parasitic weed *Striga hermonthica* for subsistence farming systems in Africa, and has been adopted by over 25,000 maize smallholder farmers in East Africa. There, maize yields have subsequently increased from about 1 t/ha to 3.5 t/ha with minimal inputs (Khan et al. 2008). The potential use of semiochemicals for pest management on small-scale farms in developed countries remains underexploited. Similarly, a clearer understanding of the behavior of insects, including their migration capacities and spatial dispersal, could enable simple systems of pest management to be developed (Kroschel et al. 2009).

Policies and other factors enabling or inhibiting crop health management

For CHM a conducive policy environment is needed in addition to access to the knowledge of biotic and abiotic factors with an impact on the cropping system, and to the tools available for farmers to make correct agronomic and IPM decisions.

The Convention on Biological Diversity –a looming obstacle

The Convention on Biological Diversity (CBD) covers all forms of biodiversity, including agrobiodiversity, with the exception of those listed in the International Treaty on Plant Genetic Resources for Food and Agriculture. The forthcoming International Regime on Access and Benefit Sharing (ABS) under the CBD is the mechanism supposed to ensure that the providers of biodiversity receive a fair share of the benefits arising from the use of their biodiversity. The CBD assumes national ownership of biodiversity, and implies a bilateral system of benefit sharing.

This has already proven a major influence on the biological control of pests and on ecosystem resilience. The exchange of beneficial plants and biocontrol agents between countries has become increasingly difficult. In several instances, the transfer of potentially important living organisms has been refused, hindering the environmentally sound work conducted under IPM to find alternatives to pesticides. A background study by FAO (Cock et al. 2009) and other publications highlighted the needs of the biocontrol community and presented a number of case studies of successful work and hindrance through ABS.

The International Regime on ABS is expected to be adopted in October 2010 by the 193 member countries of the CBD, but its implementation and practicability remain unclear. Currently, ABS seems to constitute a significant obstacle for agricultural research in general, and breeding and pest control in particular. It is therefore necessary that the ABS Protocol provides room for specialized ABS arrangements for genetic resources, such as ubiquitous beneficial microorganisms for which the application of the CBD's concept of country of origin is doubtful, but which are of direct relevance to future pest management strategies imposed by climate change and intensified farming systems (SGRP 2010).

Knowledge transfer needs to be reformed to support IPM

Pest management structures and policies need to recognize that crop health is an essential element of sustainable agriculture that needs immediate improvement. Many policies are aimed at supporting pest control as a separate activity, often relying solely on the application of pesticides or the use of resistant cultivars. In the longer term, this has been shown to be unsustainable – whether as a result of pests overcoming host plant resistance and building up resistance to pesticides or the improper, excessive, or unnecessary use of pesticides with unacceptable impacts on humans, animals, and ecosystem services.

Farming has replaced diverse ecosystems with simplified cropping systems that have disruptive impacts on the services that an intact natural ecosystem provides. Therefore, a sole reliance on ecosystem services for CHM is insufficient. When pest outbreaks and devastating crop losses occur, farmers become disillusioned with the effectiveness of complex approaches for CHM and often revert to the sole use of pesticides. This underscores the need for integrating modern and traditional pest management approaches that provide appropriate tools and solutions for different situations. Structures and policies must provide incentives to adopt practices that favor ecosystem services. These policies must support extension officers and farmers in incorporating the range of options available and the positive and negative effects they carry, when not used by the farmer. Policies are needed that facilitate the development of effective and environmentally sound management technologies, as well as practices that can be made readily available to the farmers. Policymakers need to provide incentives to encourage the adoption and adaptation of IPM to local conditions through a strengthening of knowledge transfer to upgraded extension services.

Extension, the link between science and the farmer and the backbone of sustainable crop improvement, needs to be a major aspect of CHM in the future. Extension is the only effective way of promoting IPM, but in many developing countries, budget cuts and a lack of emphasis on agricultural development have left farmer-extension ratios far too large for adequate advice to be provided. This causes farmers to shift towards the promises of local pesticide salespersons when they encounter a serious pest or disease problem. Policies need to be put in place to strengthen and reform governmental and non-governmental extension services and to promote coordination and cooperation between the public, private, and not-for-profit sectors. The public and private sectors need to be trained and rewarded for the promotion of IPM principles. For local pesticide retailers and dealers, this should include training programs, certification, and monitoring schemes. These activities have to be supported by a stricter international control of the sale of cheap, fake, and internationally banned pesticides.

However, traditional linear research-extension models alone are unlikely to be successful in scaling out multi-component IPM technologies. There is a need for a shift away from the promotion of pure technology towards innovation systems. These include functioning networks of farmers, technology developers, extension workers, local business, and researchers, and facilitate the adaptation of technologies to local conditions, and farmers' decision-making on the selection and deployment of technologies in their time and place.

There is also a dire need for the introduction and adaptation of modern extension tools, such as online-decision-support systems to increase the impact of extension. These innovative systems are used in practical IPM in developed countries and can be modified to suit specific regions and cropping systems. Pest monitoring models and standard recommendations for a range of pests affecting a broad spectrum of crops based on weather data can be used to make CHM decisions in the field. This can be done centrally and the information on management can be spread by telecommunication tools to extension agents and farmers. However, these modern methods should be applied in such away that they help farmers to make more informed decisions, rather than trying to convince them to use a specific technology.

Mass media information campaigns and entertainment-education enhance traditional extension approaches by making a large audience aware of the issue at the most appropriate times (Heong et al. 2008, Huan et al. 2008). Whatever dissemination approaches are being used, there is a need for follow-up programs to sustain adoption. At the same time, information must flow both ways. An understanding of why farmers in different areas adopt certain practices or technologies, their sociological perspectives, language, culture, market principles, and decision-making necessitates the involvement of more than just experts on specific technologies or agronomic disciplines. Most research currently available focuses on either the benefits or the risks of different practices. There needs to be a holistic approach, considering all benefits and risks – including externalities and mechanisms of how these can be achieved.

Incentives to adopt new CHM methodologies

Farmers adopt new practices if they are profitable and if they improve yield. A major incentive to adoption is the demonstration that a technology is profitable. This requires that 'income distorting' subsidies on specific pest control options, such as chemical pesticides, should be replaced by educational programs on CHM and the properly integrated use of IPM inputs. In addition to training, monetary incentives promote the adoption of sustainable CHM practices.

Pesticides in many countries are treated as necessary inputs, and have been priced low through price-support systems with no externality adjustments. The externalities include adverse effects on human health, wildlife, and ecosystem services such as pollination, biological control, soil formation, and the provision of clean water. The introduction of even cheaper generic compounds will aggravate adverse impacts. Improved crop health is a public environmental good where local individual actions benefit a large community. The potential impact of adjusted policies that provide payments for environmental services to farmers for practicing CHM, and encourage the use of environmentally friendly approaches with safer pesticides should be evaluated and subsequent measures taken.

Capacity building

The Problem

Without sound human capacity to develop, adapt, understand, and apply CHM, crop losses will continue to be a major contributor to food insecurity. The multifaceted nature of CHM and the many scientific and technological progresses made require training and capacity development at many levels, from policymakers to national researchers, knowledge brokers, extension agents, and finally farmers.

Most higher education institutions in developing countries do not offer inclusive courses in plant protection. Future scientists working in CHM are poorly trained in all relevant disciplines during their university careers. This lack of training cascades through the educational system, also affecting technical high schools and their practical agricultural curricula. If we are to make an impact on food security in the coming 15 years, we have to strengthen the next generation in IPM expertise.

The Solution

A CGIAR systemwide capacity building program in CHM needs to be developed that targets the most important groups in the national programs, including management, scientists, and extension experts. Strengthened capacity among national research and extension services is needed now more than ever, to remove weak links in the knowledge chain and to upgrade applied research and technology transfer.

To make such an impact, policymakers, leaders of agricultural ministries, heads of university plant protection institutes, and leaders in extension need to be exposed to the true nature and scale of the pest and contaminant problems. In some cases, it will be necessary to retool the solutions available to solve crop health problems in the near future.

The following three capacity building programs are proposed, the first two to rotate among Africa, Asia, and South America and the third to be implemented everywhere:

1) Implementation of a Rotational Advanced Knowledge Exchange Program

The CGIAR centers, together with advanced national and international research and education institutes as well as private industry, need to develop a short but intensive training program for key national scientists, research managers, CGIAR staff, and political decision-makers to expose them to the negative impacts that pests and toxic contaminants are having on human and environmental health, food security, and trade. The course would tackle mycotoxins, pesticide residues, and microbial contamination. It would present the technologies that are already available or currently under development that could be of enormous benefit to their countries if the right policies and institutional infrastructure are in place and if the scientists are properly trained (see course 2 below).

This course would be implemented in different regions of the world by the hosting CGIAR Centers. IPM scientists in the other regions, as well as researchers at advanced institutes and representatives from the private sector, would backstop and present together the latest solutions to crop health problems across crops of the relevant food baskets and ecoregions.

2) *Implementation of an Advanced Studies Program*

As above, the CGIAR centers, advanced national and international research and education institutes, and the private sector would develop the structure for intensive advanced training courses for key national scientists, research managers, and extension experts to upgrade their expertise in the latest technologies available to enhance plant health across ecosystems and across the crops in the food basket of the growing region. It would also focus on the preservation of the gained knowledge.

By means of modern and affordable concepts of Information Technology, the participants in the program would be enabled to document their experiences in an easy and straightforward manner. Through the Internet this knowledge can be made readily accessible to others within and outside the program, and thus preserve the program's results, even when participants leave or move on to other positions. The basic course would then be fine-tuned by the CGIAR center(s) hosting the course to customize it to specific regional contexts. These would be conducted in the three major regions (sub-Saharan Africa, South Asia, and Central Asia) affected by food shortages, malnutrition, contaminants in the food chain, and climate change. The technologies presented would be selected to fit the problems, cropping systems, and food basket crops in the specific region where the course is offered. Staff from all of the CGIAR and associated centers would backstop as needed, so that all relevant technologies could be presented, and the contents of the course could be collaboratively and continuously refined.

Both the *Knowledge Exchange* and the *Advanced Studies Programs* would be automatically upgraded as experience is gained. The programs could be moved to the E-learning mode for further distribution.

3) Implementation of a Masters program in IPM and overall crop health

The concept would be to develop a sandwich (split-location) degree program with preference for extension agents and crop protection advisers. The goal is to develop highly qualified experts who have a real interest in extension and problem solving. This type of program does not exist in the developing world at this time. It is a weak link, but it is the key to the success of sustainable crop production. Training programs conducted outside the region usually lead to the training of students not necessarily interested in extension, or of students who remain in the developed world to build their careers.

The 27-year-old African Regional Postgraduate Program in Insect Science (ARPPIS) at icipe, extending to 34 African universities, stands as an example for such a program based in Africa. The Masters program in IPM would include a number of satellite universities from different countries based in a region. The national professors working in plant protection would be part of the core of the teaching and training program. The curriculum would be developed by the national program leaders together with CGIAR's training personnel and public and private institutes of higher learning. The program would target a major weakness in current food production: the lack of well-trained extension specialists. At the same time, it would upgrade national university programs in crop protection, a pre-condition for sustainability in food production. It would be economical in that the students will remain in their region and are not shipped around the world to centers of excellence in training in temperate regions. They would remain part of the online information-sharing network after graduation.

The ultimate goal of the capacity building programs is to solve plant health problems by educating the people who are in a position to make an impact on sustainable food production. This will be accomplished by placing CHM in the knowledge chain from the policymaker, through the researcher and extension expert, to the farmer.

These programs would be cost-effective for the following reasons:

(a) They would be conducted in the regions affected by poverty and not in developed countries.
(b) National expertise would be fully involved.
(c) The CGIAR would be able to tailor the training to make major impacts in specific regions on problems of economic importance.

Collaboration and partnerships to improve crop health management

The multidisciplinary nature of sound CHM requires inclusive partnerships for development, adaptation, and adoption. Potential collaborations and partnerships that should be considered in this systems approach are displayed (Fig. 1).

While the web of partnerships is complex, the hierarchy is focused first on farmers and farmers' associations, then on partners who are in direct contact with farmers, and finally on partners who influence technology or provide the enabling environment for change from component-based technologies towards a holistic agricultural paradigm.

These partners must make possible the capacity building by farmers through extension educators, input suppliers, and others. This clearly requires policymakers, regulatory agencies, and financial managers to provide an enabling environment to allow for new markets, market structures, transportation infrastructures, finance, and new IPM tools for plant health. Such an enabling environment will provide incentives for farmers to use new inputs (healthy seeds of new cultivars and crops, biological control agents, safer pesticides, pest monitoring and scouting tools, etc.,). It will take advantage of new market opportunities for new crops or those meeting specific quality or pesticide residue standards – all factors that will address food security, sustainability and poverty reduction. It is important to understand that the benefits are not just for farmers and their suppliers; the ultimate beneficiary is the consumer in both local and export markets.

Critical to the successful development of a holistic CHM paradigm is participatory project planning involving as many as possible of the partners identified in Figure 1. Such participatory planning will ensure that partners hold project ownership: they have all agreed on the objectives and proposed goals and outputs, activities and budget needs. Identification of initial project sites, documentation of the baseline situation, provision for project monitoring, impact assessment, and publicity are all critical to successful planning. The importance of planning grants to bring these diverse partners together cannot be overemphasized.

Prior to the initial planning meeting with the partners, preparatory work with stakeholders is very important to build a critical mass for participation in and commitment to the potential project. Publicity is critical to transferring successes and to inspiring others to duplicate or adopt CHM in new locations and to generate new support from donors or other financiers to promote plant health. Finally, partners in each project should develop plans for succession planning and mechanisms for sustaining the projects beyond initial funding. It is both logical and practical that the CGIAR centers should take the leadership in initiation since they are strategically located worldwide, have the research and extension faculty expertise, and possess established networks to initiate collaboration. This will, however, require the CGIAR centers and their faculties to cooperate across disciplinary and geographic lines, both internally and with other organizations involved in international agriculture.

The benefits from recognizing the diverse partners in CHM and the need for them to collaborate in project planning, implementation, and evaluation will be seen in the delivery and adoption of improved crop, soil health, improved incomes, and improvements in a diversity of environmental indicators. The inclusive participatory planning, implementation, and evaluation process should result in improved cooperation and trust between partners and donors. As a result, many synergies between partners, both foreseen and unforeseen, will be realized. At the same time, linkages and networks will begin to develop for future rural development initiatives.

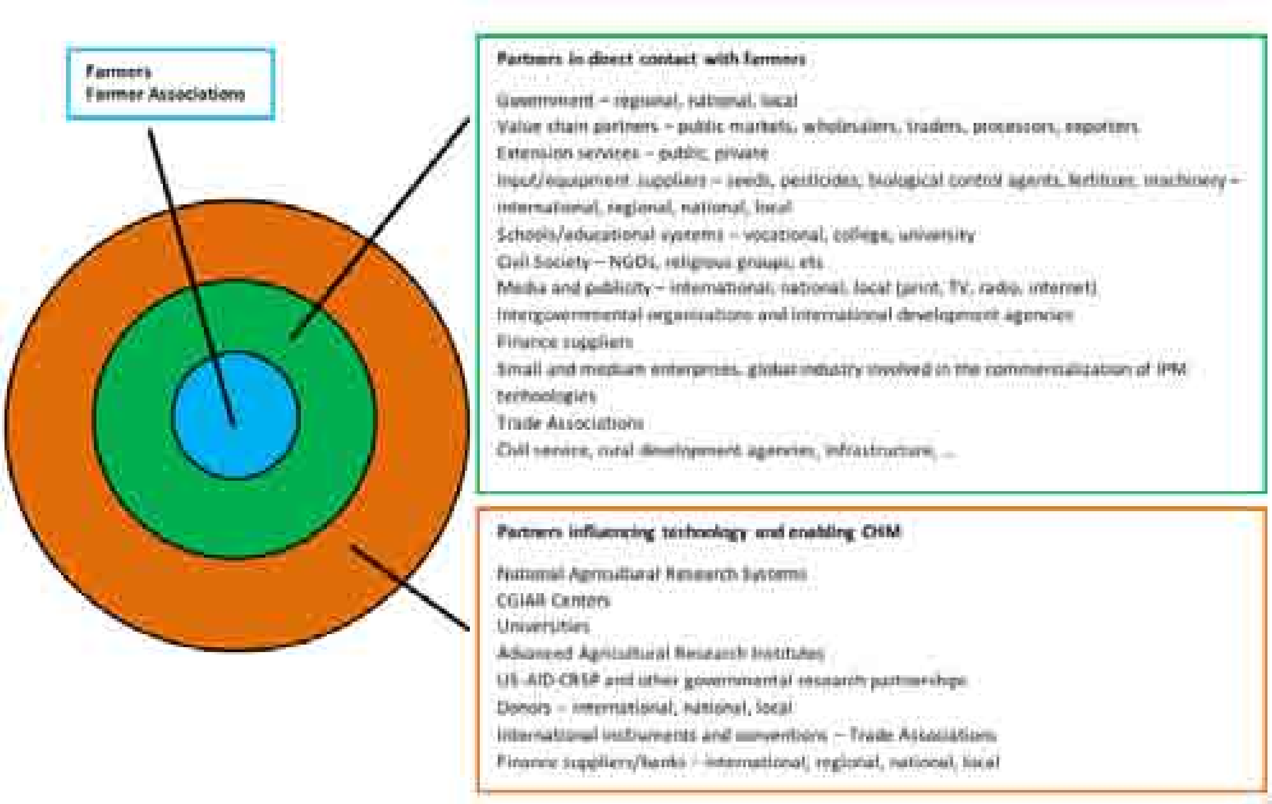

Figure 1. Partnerships in CHM.

Concluding remarks

The CGIAR and associated centers have the capacity and capability to adopt a balanced multidisciplinary approach, and they have made efforts in this direction in the past. Secure long-term funding for CHM would allow scientists to intensify inter-center and other forms of collaboration, and harness synergies better for more serious impacts on the big problems, such as food security, sustainability, and poverty reduction.

Substantial increases in food production can be attained relatively quickly by upgrading CHM strategies. However, this requires adequate financial investment in measures that reduce yield losses now. Investment only in new technologies targeted at increasing potential yields ignores the fact that significant losses are occurring now from weeds, animal pests, and diseases and that these can be reduced.

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